

Oleg FEDOROVYCH, Oleksandr PROKHOROV, Yurii PRONCHAKOV,
Andrei POPOV, Myroslav MOMOT

National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine

MODELING OF THE RELOCATION OF HIGH-TECH ENTERPRISES FOR THE RELEASE OF INNOVATIVE PRODUCTS

A multivariate task related to the modeling of high-tech enterprises relocation under new challenges and threats is described and solved. The relevance of the study is related to the complex solution of the complex task of moving a high-tech enterprise to a new location for the production of competitive products. The purpose of the publication is to present the created set of models that allow: to justify the choice of the location (locations) of the enterprise; to form a set of suppliers of components, considering long logistics chains; and to research the relocation of a high-tech enterprise in a special period related to martial law. The existing problems of the relocation of high-tech enterprises are analyzed: the change in the political and economic conditions of global and local production; existing long logistics supply chains of components that have vulnerabilities and are triggered when threats appear; the problem of the location of distributed production in a large area; economic losses due to complex distributed logistics of supply of components; many manufacturers of components that provide the main production process; the problem of relocation (evacuation) of enterprises in a special period, in the conditions of martial law. The model for choosing a new location for the enterprise is proposed, considering contradictory indicators: the cost (rent) of land plots for the location of the enterprise; territory preparation for the location of the enterprise; logistics costs for the enterprise moving; expenses for training (retraining) of workers; relocation project risks; etc. Taking into account the combinatorial nature of the task under consideration and the complexity of the location of the distributed enterprise (not in one, but in several locations), a model of rational placement of production was created. A method of choosing a set of suppliers of components for high-tech enterprises is developed; this method considers the length of logistics chains, the time spent on delivery, the quality of components produced by suppliers, and supply risks. A multi-criteria optimization model for choosing suppliers is created, considering some contradictory indicators. The model of relocation (evacuation) of a high-tech enterprise in a special period, in the conditions of wartime threats and risks of moving technological equipment, is proposed. A simulation model is developed to study the logistics of enterprise relocation in the form of an agent-based representation; this model simulates the events associated with the sequence of relocation actions: dismantling of technological equipment, transportation of equipment, and installation of enterprise subsystems. The emergence of threats and the consequences of their actions, which are associated with a violation of the logistics of moving the enterprise, are simulated. An illustrated example of the study of enterprise relocation in the conditions of the emergence of threats and the cessation of technological equipment movement, which leads to the search for new routes with minimal transportation risks, is given. The scientific novelty of the study is associated with the development of a complex of original optimization models, an agent-based simulation model, which allows for a scientifically justified forming requirements for the relocation of a high-tech enterprise to a new location, for ensuring the reduction of long logistics chains for the supply of components, for minimization logistics costs, for the formation of relatively dangerous logistics channels and supply routes, for minimization of risks in the conditions of new challenges and threats of a political and economic nature. The results of the study should be used for planning the relocation project of a high-tech enterprise, for the formation of measures and actions related to the relocation of a high-tech enterprise, for the creation of new safe logistics supply chains, and for the evacuation of the enterprise in a special period.

Keywords: *enterprise relocation; long logistics chains; enterprise location; logistic risks; cost optimization for enterprise relocation; agent-based simulation modeling.*

1. Introduction

Globalization of the economy has led to the creation of distributed enterprises, the logistics of which production requires the timely supply of components to create products relevant to market needs. However, long (sometimes entangled) supply chains, increased risks due to the

emergence of possible threats (climatic, terrorist, transport systems aging, etc.) as well as the occurrence of new political and economic conditions have led to the initiation of the process of relocation of high-tech enterprises to new locations to ensure sustainable production with economic benefit.

1.1. Motivation

In the context of globalization and the systemic transition of the industrialization process to the principles of Industry 4.0, the digital transformation of production ensuring stability and sustainability of the functioning of high-tech enterprises is associated with minimization and possible neutralization of the impact of negative environmental factors on the planned nature of production [1, 2]. The negative impact factors include: changing political and economic conditions in the world, increasing risks of military and terrorist threats, global climate change, and long logistics supply chains with possible vulnerabilities and bottlenecks [3]. Therefore, the topic of the proposed research is relevant; this research models the logistics of relocation of high-tech enterprises in conditions of limited opportunities, challenges, and threats from the external environment.

1.2. State of the Art

There are several problems related to the relocation of high-tech enterprises to create conditions for reliable and sustainable production of competitive products; these problems are reflected in existing publications on this topic:

1. Changes in political and economic conditions of a local and global nature have led to the necessity of relocation of enterprises [4, 5]. Relocation requires a number of costly actions [6]. In the existing publications, the development of production is considered in the conditions of a stable economy with low risks of possible threats [7, 8].

2. Long logistic supply chains have become critical [9]. Challenges and threats lead to an increase in risks (political-economic, climatic, terroristic and military threats, etc.) [10, 11]. In conditions of a stable economy, long logistics chains are economically profitable due to small threats [12, 13].

3. The distributed location of the enterprise in a stable economic environment provided a high value for the technical and economic indicators of the enterprise. Changes in the external political and economic environment and the emergence of global challenges and threats to the functioning of distributed production have led to the need for a new localization of enterprises with a reduction in logistics chains and the number of suppliers [14, 15].

4. In modern conditions of distributed production, the activities of enterprises become economically unprofitable due to large logistics costs (economic costs, time, risks) [16]. In existing publications, more attention is paid to the attractiveness of enterprises when transferring production to other countries [17, 18].

5. Several publications are devoted to the relocation of enterprises in peacetime [19, 20]. Threats of a military nature are local and do not lead to disruption of logistics chains [21]. Large-scale military threats can disrupt the process of enterprise relocation [22, 23]. The analysis of relocation in a special period, in the conditions of martial law, aroused interest among researchers in the logistics of distributed production [24, 25].

6. There is a problem of ensuring the resilience of the enterprise in changing political and economic conditions by giving it priority in strategic development goals [26]. However, new challenges and threats, including those of a military nature, require, in order to ensure the resilience of the enterprise, the solution of relocation problems to minimize vulnerable logistics chains and the formation of relatively safe and reliable production sites, which are not considered in modern publications [27, 28].

Thus, the emergence of new threats, primarily of a political and economic nature, led to the economic feasibility of the localization and relocation process of enterprises.

1.3. Objectives and methodology

A contradiction arises between 1) the requirements for ensuring the reliability and stable functioning of high-tech enterprises in the conditions of the variability of the external environment, and 2) the imperfection of existing methods and the lack of a systematic analysis of the problems related to the study of enterprises relocated to a new location for the production of innovative products. Thus, there is a relevant problem for high-tech enterprises to ensure the resilience of their functioning despite modern challenges and threats by moving to a new, relatively safe location and shortening long vulnerable logistics supply chains.

The purpose of the study is to increase the efficiency of production logistics of high-tech enterprises by modeling the relocation process for the location of the enterprise in a new place, considering contradictory indicators of relocation (costs, time, risks) in the conditions of possible threats from the external environment. In accordance with the research objective, the following tasks should be solved:

1. To create a model for choosing a place of relocation for a high-tech enterprise for the production of competitive products.

2. To develop a model for selecting component suppliers to ensure the production process at the new location of the enterprise.

3. To form a model of relocation of a high-tech-logical enterprise in a special period.

4. To develop an agent-based simulation model of high-tech enterprise relocation.

5. To give an example of enterprise relocation modeling.

The following mathematical methods and methods of modeling enterprise relocation were used: system analysis, multicriteria optimization, multivariate selection, and agent-based simulation modeling.

2. The model of choosing a place for high-tech enterprise relocation for the production of competitive products

The choice of a new location for the production of innovative products is one of the main tasks of relocation because its solution fulfills the strategic goal of the developing enterprise associated with the release of new competitive products. To choose a new location for the enterprise, it is necessary to analyze and evaluate contradictory relocation indicators:

1. The cost of the land plot (plots) where the enterprise is located (rent or purchase) – W.

2. Costs for the formation of supporting infrastructure for the production process organization (power supply, and water supply) – V.

3. Costs for works related to territory preparation for the placement of technological equipment and administrative buildings – E.

4. Logistics costs for moving the enterprise to a new location – L.

5. Costs for the organization of logistics for the supply of components at the new location of the enterprise – F.

6. Costs for the organization of the product sale logistics – Z.

7. Costs for the training (retraining) and the recruitment of new personnel – P.

8. Costs associated with the fulfillment of environmental requirements at the new location of the enterprise – Q.

9. Risks of enterprise relocation project implementation – R.

10. The time spent on transferring enterprises to a new location – T.

Modern high-tech enterprises consist of a set of separate divisions (branches) that require not one location but many, which complicate the task of relocation. Therefore, the solution to the problem of transferring the enterprise to new locations is combinatorial in nature, associated with the placement at multiple possible locations of the dislocation - M. Therefore, it is necessary to pre-select possible locations of the enterprise, and then form the number of dislocation options:

$$N=2^M-1.$$

For example, if the possible number of placements is $M=4$, then the number of options is: $N=2^4-1=15$. A set of options for placing the enterprise in new locations can be formed using a binary counter:

1. 0001	9. 1001
2. 0010	10. 1010
3. 0011	11. 1011
4. 0100	12. 1100
5. 0101	13. 1101
6. 0110	14. 1110
7. 0111	15. 1111.
8. 1000	

Here, '1' means the enterprise placement on the j-th possible site ($j=1, \dots, 4$), '0' means no placement.

For high-tech enterprises that have several divisions (for example: machining, plastics, composites, electronics, etc.), one placement site may not be enough. In this case, specialists should indicate the number of territories required for relocation, considering the specifics and nature of the high-tech enterprise production process.

Table 1 presents the possible options for the enterprise location ($M=4$) for a different number of possible locations. Here, n_j indicates the number of possible placement options with the j-th number of plots needed for the placement of the enterprise, "+" means using the option with the j-th specified number of placements.

Table 1

Enterprise location options

Options	Placements	$n_1=4$	$n_2=6$	$n_3=4$	$n_4=1$
1	0001	+	-	-	-
2	0010	+	-	-	-
3	0011	-	+	-	-
4	0100	+	-	-	-
5	0101	-	+	-	-
6	0110	-	+	-	-
7	0111	-	-	+	-
8	1000	+	-	-	-
9	1001	-	+	-	-
10	1010	-	+	-	-
11	1011	-	-	+	-
12	1100	-	+	-	-
13	1101	-	-	+	-
14	1110	-	-	+	-
15	1111	-	-	-	+

Each of the possible placement options corresponds to its set of indicators values: W, V, E, L, F, Z, P, Q, R, T. Due to the possible contradiction of the indicators, the

task of choosing a new place (places) for the enterprise location is of a compromise nature and depends on the priority of certain indicators.

Therefore, before choosing the location(locations) of the enterprise, it is necessary to prioritize indicators using the opinions of experts (relocation specialists).

If there is a lack of consistency in the opinions of specialists, several steps should be taken to reconcile them (for example, using the ELECTRA method). At the initial stages of the formation of the enterprise relocation project, expert assessments for some indicators may have quantitative values, and for others – to be qualitative.

Therefore, to use mixed estimates, it is recommended to introduce linguistic variables whose value can be both quantitative and qualitative. Let the values of the indicators W, E, P, and T be represented quantitatively (in points) and be in the range from 0 to 10, where the best value of X_W , X_E , X_P , and X_T corresponds to an approximation to 0, and the worst one corresponds to an approximation to 10. For qualitative assessments of indicators V, L, F, Z, Q, and R, linguistic variables X_V , X_L , X_F , X_Z , X_Q , and X_R are used, which take the following values (in the form of letters of the Latin alphabet) A, B, C, D, where A - corresponds to the best value and D - corresponds to the worst value:

$$X_V = \begin{cases} A - \text{minimum costs;} \\ B - \text{satisfactory costs;} \\ C - \text{allowable costs;} \\ D - \text{maximum costs,} \end{cases}$$

$$X_L = \begin{cases} A - \text{minimum logistics costs for moving} \\ \quad \text{the enterprise to a new location;} \\ B - \text{satisfactory costs;} \\ C - \text{allowable costs;} \\ D - \text{maximum costs,} \end{cases}$$

$$X_F = \begin{cases} A - \text{minimum costs;} \\ B - \text{satisfactory costs;} \\ C - \text{allowable costs;} \\ D - \text{maximum costs,} \end{cases}$$

$$X_Z = \begin{cases} A - \text{minimum costs for sales logistics;} \\ B - \text{satisfactory costs;} \\ C - \text{allowable costs;} \\ D - \text{maximum costs,} \end{cases}$$

$$X_Q = \begin{cases} A - \text{minimum costs for the fulfillment} \\ \quad \text{of environmental requirements;} \\ B - \text{satisfactory costs;} \\ C - \text{allowable costs;} \\ D - \text{maximum costs,} \end{cases}$$

$$X_R = \begin{cases} A - \text{minimal risks of relocation;} \\ B - \text{satisfactory risks;} \\ C - \text{allowable risks;} \\ D - \text{maximum risks.} \end{cases}$$

Let's consider an example of choosing a new location for an enterprise dislocation. Let the set of possible locations of the enterprise be $M=4$, and the importance of relocation indicators, which was assigned by experts, has the form of a priority series: W, V, E, L, T, F, Z, P, R, Q. Let two placement sites be needed to place the enterprise. In this case, using the Table 1, the following options are obtained for $n_2=6$:

1. (0011) – 8, C, 5, B, 4, B, B, 9, C, B
5. (0101) – 5, D, 8, C, 6, A, C, 6, B, B
6. (0110) – 7, B, 6, D, 4, B, D, 4, C, D
9. (1001) – 6, C, 4, B, 5, C, B, 5, A, C
10. (1010) – 4, D, 8, A, 3, D, C, 3, B, C
12. (1100) – 4, B, 9, C, 4, B, C, 5, C, B.

Using lexicographic ordering of possible placement options, considering the priority of indicators and values of linguistic variables: X_W , X_V , X_E , X_L , X_T , X_F , X_Z , X_P , X_R , X_Q , an ordered set of options for placing the enterprise at new locations was obtained:

12. (1100) – 4, B, 9, C, 4, B, C, 5, C, B
10. (1010) – 4, D, 8, A, 3, D, C, 3, B, C
5. (0101) – 5, D, 8, C, 6, A, C, 6, B, B
9. (1001) – 6, C, 4, B, 5, C, B, 5, A, C
6. (0110) – 7, B, 6, D, 4, B, D, 4, C, D
1. (0011) – 8, C, 5, B, 4, B, B, 9, C, B.

Preferred placement options are at the top of the ordered list. Option 12 (1100) was used as the final placement option, in which two sites were selected for placement: the first and the second. This option is characterized by a relatively low cost of land (4), satisfactory costs for supporting infrastructure (B), not very high costs for preparing territories for placement (9), allowable logistic costs of relocating businesses to a new location (C), relatively not long time of transfer of the enterprise to a new place (4), satisfactory delivery logistics organization costs (B), allowable sales logistics organization costs (C) relatively low costs for retraining of personnel (5), allowable risks of implementation of the enterprise relocation project (C).

3. The model of the components suppliers choosing to ensure the production process at the new enterprise location

Modern high-tech products contain a large number of components, which complicates the task of organizing and managing supplies from multiple components manufacturers, which may be located at a great distance from the final assembly production. The relocation process in

modern political and economic conditions is aimed at reducing long logistics chains associated with high costs and risks of transportation. Choosing new components suppliers, relocating an enterprise, in addition to shortening logistics chains, it is necessary to take into account the quality of components supplied for the production of high-tech products. Choosing a set of new suppliers is a multivariate task, taking into account the values of contradictory indicators. Let's use the method of integer (Boolean) programming to select suppliers of components, using the following optimization indicators:

1. The total length of components suppliers' logistics chains is L . Reducing the value of L affects both logistics costs and supply risks.

2. Logistics costs of components supplied are W .

3. The time required for the logistics of the required number of components delivery is T .

4. The quality of products of components manufacturers is Q .

5. Logistics risks of components supply is R .

When relocating an enterprise, it should be considered that part of the suppliers of components continue to supply for several reasons (absence of other suppliers, high quality of components, sustainable supply logistics, etc.). Therefore, the set of necessary components suppliers can be entered in the form of two components: $M = M_1 \cup M_2$, where M_1 corresponds to the set of new component suppliers, M_2 to the set of previous suppliers that remained after the relocation.

Let's introduce the following variables to solve the optimization problem of choosing components suppliers:

$$x_{jk} = \begin{cases} 1, & \text{if the } k\text{-th warehouse of suppliers} \\ & \text{is selected for delivery of the} \\ & \text{}j\text{-th type of components;} \\ 0, & \text{in another case.} \end{cases}$$

Let's present the indicators of the choosing of components suppliers after the high-tech production relocation in the form of:

1. Total length of components suppliers' logistics chains:

$$L = L_1 + L_2 = \sum_{j=1}^{m_1} \sum_{k=1}^{m_j} l_{jk} x_{jk} + \sum_{i=1}^{m_2} l_i,$$

where L_1 - corresponds to the set of new component suppliers;

L_2 - corresponds to a set of former suppliers;

m_j - the number of possible warehouses of suppliers of the j -th type of components;

l_{jk} - the length of logistics chains for the k -th warehouse of suppliers of the j -th type of components;

l_i - the length of logistics chains for the i -th type of components that are connected to former suppliers.

$$m_1 = |M_1|, m_2 = |M_2|.$$

2. Logistics costs:

$$W = W_1 + W_2 = \sum_{j=1}^{m_1} \sum_{k=1}^{m_j} w_{jk} x_{jk} + \sum_{i=1}^{m_2} w_i,$$

where w_{jk} - the supply logistics costs for the k -th warehouse of suppliers selected for the supply of the j -th type of components;

w_i - the supply logistics costs for the i -th type of components produced by former suppliers.

3. Time spent on the supplying components logistics:

$$T = T_1 + T_2 = \sum_{j=1}^{m_1} \sum_{k=1}^{m_j} t_{jk} x_{jk} + \sum_{i=1}^{m_2} t_i,$$

where t_{jk} - the time spent on the supplying components logistics for the k -th warehouse of suppliers which produce the j -th type of components;

t_i - the time spent on the supplying logistics of the i -th type of components produced by former suppliers.

4. Components suppliers' product quality:

$$Q = Q_1 + Q_2 = \sum_{j=1}^{m_1} \sum_{k=1}^{m_j} q_{jk} x_{jk} + \sum_{i=1}^{m_2} q_i,$$

where q_{jk} - the product quality of manufacturers of the j -th type of components for the k -th supplier warehouse;

q_i - the quality of components of the i -th type, which are produced by former manufacturers of components.

5. Logistical risks associated with the supplying of components:

$$R = R_1 + R_2 = \sum_{j=1}^{m_1} \sum_{k=1}^{m_j} r_{jk} x_{jk} + \sum_{i=1}^{m_2} r_i,$$

where r_{jk} - logistics risks associated with the k -th warehouse of suppliers for the j -th type of components;

r_i – logistics risks of former manufacturers of the i -th type of components.

These formulations of the problem of the optimization of logistics chains associated with the choice of component suppliers when relocating a high-tech enterprise to a new location are possible:

1. Optimization of separate indicators in the conditions of fulfillment of restrictions on other indicators.
2. Multicriteria formulation of optimization of logistic indicators.

As an example of the optimization of separate logistics indicators, let's consider the task of optimizing the total length of logistics chains for the supply of components while transferring a high-tech enterprise to a new location:

$$\begin{aligned} \min L, \\ L = L_1 + L_2 = \\ = \sum_{j=1}^{m_1} \sum_{k=1}^{m_j} l_{jk} x_{jk} + \sum_{i=1}^{m_2} l_i, \end{aligned}$$

considering the limitations on the allowable values of other indicators:

$$W \leq W', W = \sum_{j=1}^{m_1} \sum_{k=1}^{m_j} w_{jk} x_{jk} + \sum_{i=1}^{m_2} w_i,$$

$$T \leq T', T = \sum_{j=1}^{m_1} \sum_{k=1}^{m_j} t_{jk} x_{jk} + \sum_{i=1}^{m_2} t_i,$$

$$Q \geq Q', Q = \sum_{j=1}^{m_1} \sum_{k=1}^{m_j} q_{jk} x_{jk} + \sum_{i=1}^{m_2} q_i,$$

$$R \leq R', R = \sum_{j=1}^{m_1} \sum_{k=1}^{m_j} r_{jk} x_{jk} + \sum_{i=1}^{m_2} r_i,$$

where W', T', Q', R' – allowable values of indicators W, T, Q, R .

To solve the problem of multi-criteria optimization and search for a compromise, in the conditions of contradictory indicators L, W, T, Q, R , let's use a simple, additive representation of the complex criterion:

$$K = \alpha_L \hat{L} + \alpha_W \hat{W} + \alpha_T \hat{T} + \alpha_Q \hat{Q} + \alpha_R \hat{R},$$

where $\alpha_L, \alpha_W, \alpha_T, \alpha_Q, \alpha_R$ – "weights" (importance) of criteria L, W, T, Q, R (assigned by experts).

$$\hat{L} = \frac{L-L^*}{L'-L^*}, \quad \hat{W} = \frac{W-W^*}{W'-W^*},$$

$$\hat{T} = \frac{T-T^*}{T'-T^*}, \quad \hat{Q} = \frac{Q^*-Q}{Q^*-Q'},$$

$$\hat{R} = \frac{R-R^*}{R'-R^*},$$

where L^*, W^*, T^*, Q^*, R^* are the values of indicators L, W, T, Q, R , which were obtained as a result of solving the problem of optimization of separate indicators.

It is necessary to find $\min K$, considering the fulfillment of the restrictions:

$$L \leq L', W \leq W', T \leq T', Q \geq Q', R \leq R'.$$

To solve the given task of optimizing logistics indicators of high-tech enterprise relocation, it is possible to use one of the versions of the branch and bound method, which is often used to solve this type of optimization problem with Boolean variables.

4. The model of a high-tech enterprise relocation in a special period

Under martial law conditions, it becomes necessary to evacuate enterprises from the front-line zone to the rear to establish the production of current products (military equipment, components of critical infrastructure, etc.). The relocation of the enterprise occurs due to a military threat (enemy attack and occupation of the territory of the enterprise location, artillery fire and missile attacks, air raids, etc.). Factors associated with military threats include:

- violation of the components supply;
- the destruction of supporting infrastructure (for example, energy one);
- a threat to the workers of the enterprise;
- failure of technological equipment.

Therefore, it is relevant to develop and solve the problem of researching the logistical process of a high-tech enterprise evacuating to the rear. The main indicators of evacuation are: the time spent on enterprise relocation, the risks of moving, and the organization of production in conditions of war threats. To evacuate the enterprise, it is necessary to choose the safest location. To choose the location of a high-tech enterprise in the rear, it is necessary to analyze the main stages of evacuation to a new place, time, and risks associated with it. The main stages include:

1. Dismantling of the company's technological equipment (time t_1 , risk r_1).
2. Preparation for the process of transporting the company's technological equipment (time t_2 , risk r_2).
3. Logistics of transportation of high-tech equipment (time t_3 , risk r_3).

4. Preparation of the site for the location of the company's technological equipment at a new location (time t_4 , risk r_4).

5. Installation of the enterprise's technological equipment on the new territory (time t_5 , risk r_5).

6. Commissioning (time t_6 , risk r_6).

7. Release of the first batch of products (time t_7 , risk r_7).

Let the military specialists and specialists of the enterprise, after considering the possible enterprise locations in the rear, mean N alternative places for the enterprise evacuation. Each i -th evacuation location is characterized by its set of values t_{ij} , r_{ij} , where t_{ij} is the time spent for the j -th stage of evacuation, considering the possible i -th location; r_{ij} is the risk associated with the j -th stage of evacuation considering the i -th possible enterprise location. To choose a rational option for the high-tech enterprise location in the rear, under conditions of military threats, let's form an optimization model in which the Boolean variable x_i is used as variables:

$$x_i = \begin{cases} 1, & \text{if } i\text{-th place of enterprise} \\ & \text{evacuation is selected;} \\ 0, & \text{in another case.} \end{cases}$$

For the i -th possible location, the time spent on evacuation is:

$$T_i = t_{i1} + t_{i2} + t_{i3} + t_{i4} + \\ + t_{i5} + t_{i6} + t_{i7} = \sum_{j=1}^7 t_{ij}.$$

The risk of locating and establishing the enterprise in the i -th possible place for the production of current products:

$$R_i = r_{i1} + r_{i2} + r_{i3} + r_{i4} + \\ + r_{i5} + r_{i6} + r_{i7} = \sum_{j=1}^7 r_{ij}.$$

Let's present indicators of time T and risks R of the enterprise evacuation, taking into account the Boolean variable x_i , as:

$$T = \sum_{i=1}^N \sum_{j=1}^7 t_{ij} x_i,$$

$$R = \sum_{i=1}^N \sum_{j=1}^7 r_{ij} x_i.$$

It is necessary to minimize the evacuation time:

$$\min T, T = \sum_{i=1}^N \sum_{j=1}^7 t_{ij} x_i,$$

considering the acceptable level of risks R' :

$$R \leq R', R = \sum_{i=1}^N \sum_{j=1}^7 r_{ij} x_i.$$

5. Agent-based simulation model of high-tech enterprise relocation

To analyze the dynamic process of a high-tech enterprise relocation an agent-based simulation model was developed using the AnyLogic platform. The sequence of the agent's actions in the model corresponds to the logistics process of a high-tech enterprise relocation (discussed in Section 4), considering the time and risks of separate stages of relocation. The agent-based simulation model includes:

1. Agent for describing the sequence of high-tech enterprises relocation stages (action sequence agent).
2. Threats emergence agent (threat agent).
3. Statistics collection agent (statistics agent).
4. Agent for forming technological equipment transportation routes (route agent).
5. Transport network agent for technological equipment transportation (transport network agent).
6. Agent of enterprise technological equipment dismantling (dismantling agent).
7. Agent of preparation for technological equipment transportation (agent of preparation for transportation).
8. Enterprise technological equipment transportation agent (transportation agent).
9. Territory preparation agent for the enterprise location (territory preparation agent).
10. Technological equipment installation agent (installation agent).
11. Commissioning agent.
12. Agent for the release of the first production batch at the enterprise's new location (product release agent).
13. Management agent (management of agents).

Figure 1 presents the structural diagram of the agent model. The goods transportation route with technological equipment in the transport network can be set by specialists in the field of transport logistics. For the automated formation of rational routes of technological equipment transportation, considering the action of possible threats, an original algorithm for finding safe routes was developed.

The sequence of actions in the safe route search algorithm:

1. The initial transport node of the transport network is specified using the transport network agent, from which the process of transporting the enterprise's technological equipment begins.

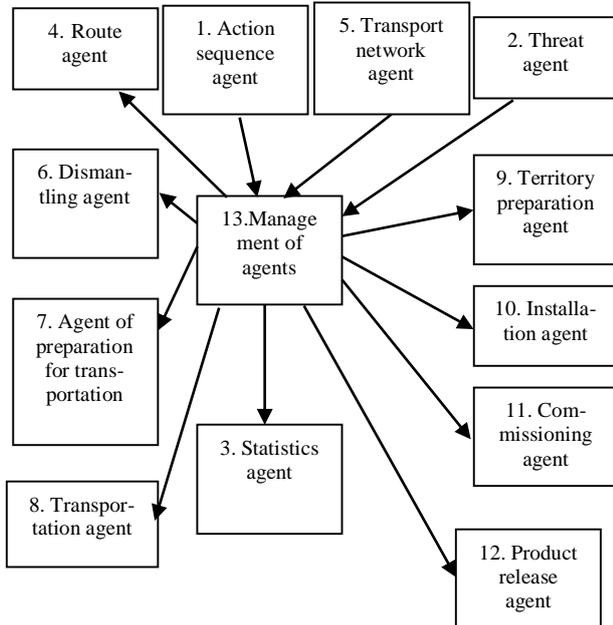


Fig. 1. Structural diagram of the agent-based model

2. All possible transport routes of the request to neighboring transport nodes are formed, requests (clones) leave the initial transport node and are distributed to neighboring ones.

3. Requests (clones) are received at the neighboring transport node (nodes), which is (are) labeled considering the accumulated risks that arise on the transport route sections and the transport node (nodes) itself (themselves).

4. If requests with a higher risk value than previous requests arrive at the transport node, they are rejected and stop moving. It is considered that they are not promising for the use of their transport routes, due to the high value of the risks.

5. A request (clone) with the minimum value of the accumulated risk is received at the transport node, which is associated with a new possible location of the enterprise.

6. Next, the safest route is formed: the route from the final node to the initial node with minimal risk of technological equipment movement (transportation agent).

Simulation modeling is carried out for all batches of the enterprise' technological equipment. In the event of a military threat (threat agent), the movement of the request (batches of technological equipment) is stopped during actions until the consequences of the threat are avoided (transportation agent). Next, after the transport

route is restored, the transportation process continues. If the threat leads to the failure of the transport route section or node, then they disappear in the description of the transport network (transport network agent), this leads to the search for new rational routes for the company's technological equipment transporting. The process of modeling the technological equipment transportation is repeated many times for statistical averaging of the simulation results. The values of the following relocation indicators are used as simulation results (statistics agent):

1. Relocation time (without considering the emergence of threats, and taking it into account).
2. The time of moving separate batches of technological equipment to the new enterprise location.
3. Accumulated time is associated with the emergence of threats and elimination of their consequences.
4. The average time of execution of individual stages of enterprise relocation, taking into account possible threats.
5. Time spent eliminating the consequences of threats to the relocation of the company's technological equipment.
6. The magnitude of the lag in the implementation of the company's relocation plan due to the emergence of possible threats.

6. The example of modeling the enterprise relocation

Let's consider an illustrated example of the logistics of transporting technological equipment of an enterprise that is evacuated during a special period. Figure 2 shows the transport network (railways) of the possible transportation of the enterprise's technological equipment during the evacuation process. Transport node 1 corresponds to the beginning of technological equipment transportation, and transport node 12 corresponds to the place where the enterprise should be located after evacuation. Intermediate transport nodes 2-11 can be used as much as possible in the process of the enterprise's technological equipment transporting. The possible time of technological equipment transportation between nodes 1-12 is presented in days: $t_{1,2}=2, t_{2,3}=1, t_{3,4}=2, t_{4,6}=2, t_{6,12}=2, t_{3,5}=2, t_{5,6}=1, t_{2,7}=1, t_{7,8}=2, t_{8,9}=1, t_{9,6}=2, t_{8,10}=2, t_{10,11}=2, t_{11,12}=2$.

With the help of the developed routing algorithm and the agent- based simulation model (discussed in Section 5), the optimal route for the transportation of the enterprise's technological equipment is found without the manifestation of possible threats. Optimal route: 1, 2, 3, 5, 6, 12. At the same time:

$$\begin{aligned}
 T^* &= t_{1,2} + t_{2,3} + t_{3,5} + t_{5,6} + t_{6,12} = \\
 &= 2+1+2+1+2 = 8 \text{ (days)}.
 \end{aligned}$$

Let the emergence of military threats and the manifestation of their action in the transport nodes (TN) of the railway network be possible: 2, 3, 5, 7 (they are indicated in Fig. 2 as risks r_2, r_3, r_5, r_7). The action of threats leads to the emergence of the necessary time to reconstruct a damaged transport node. The time for reconstructing the transport node leads to the stop cargoes transporting and corresponds to (in days): $t_2=2, t_3=3, t_5=2, t_7=2$. Let's assume that the simultaneous manifestation of military threats in nodes 2, 3, 5, 7 is unlikely (the probability of such an event tends to zero).

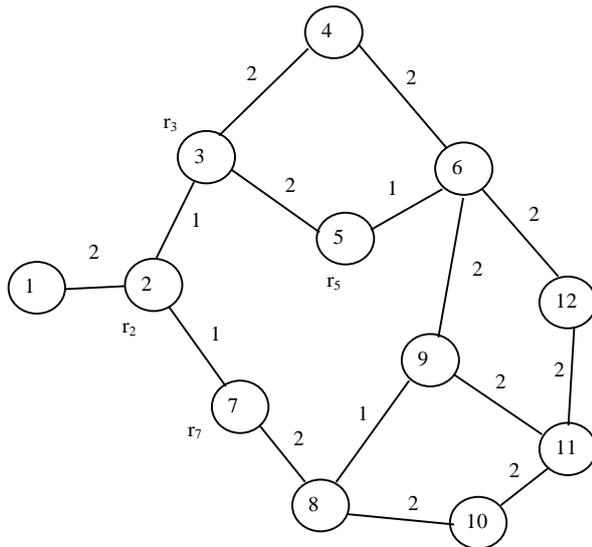


Fig. 2. Transport scheme for the enterprise evacuation

Then:

1. If the action of a military threat emerges and manifests itself in TN2, then considering the time delay due to the action of the threat $t_2=2$, the optimal route 1, 2, 3, 5, 6, 12 does not change, but the time of technological equipment moving along this route changes

$$T_2 = t_{1,2} + t_2 + t_{2,3} + t_{3,5} + t_{5,6} + t_{6,12} = 2 + 2 + 1 + 2 + 1 + 2 = 10 \text{ (days)}.$$

2. If the action of a military threat emerges and manifests itself in TN3, then considering the possible delay in the movement of transport equipment due to the threat, $t_3=3$, the optimal route changes and two possible routes of movement with the same time for moving the equipment appears:

$$1, 2, 7, 8, 9, 11, 12,$$

$$1, 2, 7, 8, 9, 6, 12.$$

Transportation time of technological equipment:

$$T_{31} = t_{1,2} + t_{2,7} + t_{7,8} + t_{8,9} + t_{9,11} + t_{11,12} = 2 + 1 + 2 + 1 + 2 + 2 = 10 \text{ (days)},$$

$$T_{32} = t_{1,2} + t_{2,7} + t_{7,8} + t_{8,9} + t_{9,6} + t_{6,12} = 2 + 1 + 2 + 1 + 2 + 2 = 10 \text{ (days)}.$$

3. If the action of a military threat emerges and manifests itself in TN5, then **considering** the possible delay of $t_5=2$, the optimal route changes and becomes:

$$1, 2, 3, 4, 6, 12.$$

Transportation time of technological equipment:

$$T_5 = t_{1,2} + t_{2,3} + t_{3,4} + t_{4,6} + t_{6,12} = 2 + 1 + 2 + 2 + 2 = 9 \text{ (days)}.$$

4. If the action of a military threat emerges and manifests itself in TN7, $t_7=2$, then the optimal route of cargo movement does not change:

$$1, 2, 3, 5, 6, 12.$$

Transportation time of technological equipment:

$$T_7 = T_{1,2} + t_{2,3} + t_{3,5} + t_{5,6} + t_{6,12} = 2 + 1 + 2 + 1 + 2 = 8 \text{ (days)}.$$

Conclusions

Conducted research related to the modeling of the complex logistics process of a high-tech enterprise relocation to a new location for the production of competitive products, which is associated with changing political and economic conditions and globalization. The existing problems related to the relocation of enterprises were analyzed: reduction of logistics supply chains of components; search for favorable locations of the enterprise; formation of a set of new components suppliers; minimization of logistics costs and risks for moving the enterprise. One of the important tasks of relocation is searching for a new location for the enterprise, this choice depends on some contradictory indicators (costs, time, risks, etc.). The formation of a set of locations is considered as a combinatorial problem, which is proposed to be solved considering the composition of the company's divisions and possible locations, using both quantitative and qualitative assessments. By a lexicographic ordering of possible options, a rational location (locations) of a high-tech enterprise is (are) formed. High-tech enterprise transfer to a new place of production requires the formation of a new composition of component suppliers, with the reduction of logistics supply chains. At the same time, it is necessary to consider the quality of component manufacturers and their ability to supply them in the required quantity. In the conditions of contradictory indicators of the choosing of suppliers, the optimization

problem of substantiating the set of components manufacturers is solved, using integer (Boolean) programming. Conducted research on high-tech enterprises relocation in a special period, when the main indicators of evacuation are the time and risks of moving the enterprise to a new location. A simulation model was created for the analysis of dynamic processes in the logistics of a high-tech enterprise relocation. With the help of the developed simulation agents, using the AnyLogic platform, an agent-based simulation model is formed for the analysis of the high-tech enterprise relocation plans. An illustrated example of enterprise relocation in a special period is presented to confirm the effectiveness of the proposed approach. The example analyzes the possible routes of transportation of the company's technological equipment to a new location under conditions of threats of martial law.

The special scientific contribution of this research is related to the development of a complex of original optimization models of enterprise location, a model of the list of enterprise relocation options, and a simulation model for the study of the dynamic process of enterprise relocation. This complex of original optimization models allows scientifically substantiating the processes of high-tech enterprise relocation in conditions of possible challenges and threats. The proposed approach allows at the initial stages of planning the enterprise relocation project to justify the enterprise location (locations), to form a set of new suppliers of components, to reduce long logistics supply chains by using simulation modeling, and to justify the terms of moving a high-tech enterprise to a new location.

Future research directions:

- the formation of a modern model of enterprise resilience due to the inclusion of the relocation process, which contributes to the reduction of long logistical and vulnerable supply chains to ensure the sustainable development of production despite new challenges and threats;
- development of a company relocation model using geoinformation technologies.

Contribution of the authors: system analysis of the relocation process of a high-tech enterprise – **Oleg Fedorovych**; simulation modeling of the logistics of moving the enterprise – **Oleksandr Prokhorov**; optimization of supplier selection – **Yurii Pronchakov**; formation of enterprise relocation indicators – **Andrei Popov**; an example of enterprise relocation modeling – **Myroslav Momot**.

All authors have read and approved the published version of the manuscript.

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МОДЕЛЮВАННЯ РЕЛОКАЦІЇ ВИСОКОТЕХНОЛОГІЧНИХ ПІДПРИЄМСТВ ДЛЯ ВИПУСКУ ІННОВАЦІЙНИХ ВИРОБІВ

*Олег Федорович, Олександр Прохоров, Юрій Прончаков,
Андрій Попов, Мирослав Момот*

Сформульована та вирішується задача багатоваріантного характеру, яка пов'язана з моделюванням релокації високотехнологічних підприємств в умовах нових викликів та загроз. Актуальність дослідження пов'язана з комплексним рішенням складної задачі переміщення високотехнологічного підприємства на нове місце розташування для виробництва конкурентоспроможної продукції. Метою публікації є наведення створеного комплексу моделей, які дозволяють: обґрунтувати вибір місця (місць) розташування підприємства; сформулювати множини постачальників комплектуючих, з урахуванням довгих логістичних ланцюгів; провести дослідження релокації високотехнологічного підприємства в особливий період, пов'язаний з воєнним станом. Проаналізовані існуючі проблеми релокації високотехнологічних підприємств: зміна політико-економічних умов виробництва глобального та локального характеру; існуючі довгі логістичні ланцюги постачання комплектуючих, які мають вразливості та збуджуються при прояві загроз; проблема розташування розподіленого виробництва на великій території; економічні втрати з-за складної розподіленої логістики постачання комплектуючих; велика кількість виробників комплектуючих, які забезпечують основний виробничий процес; проблема релокації (евакуації) підприємств в особливий період, в умовах воєнного стану. Запропонована модель вибору нового місця розташування підприємства, з урахуванням суперечливих показників: вартість (оренда) земельних ділянок під розташування підприємства; підготовка території до розташування підприємства; логістичні витрати на переміщення підприємства; витрати на підготовку (перепідготовку) робітників; ризики проекту релокації; тощо. Враховуючи комбінаторний характер задачі, яка розглядається, та складності розташування розподіленого підприємства, не в одному, а в декількох місцях розташування, створено модель раціонального розміщення виробництва. Розроблено метод вибору множини постачальників комплектуючих високотехнологічних підприємств, який враховує довжину логістичних ланцюгів, час, витрачений на постачання, якість комплектуючих, які виробляють постачальники, ризики постачання. Створена багатокритеріальна оптимізаційна модель вибору постачальників, з урахуванням множини суперечливих показників. Запропонована модель релокації (евакуації) високотехнологічного підприємства в особливий період, в умовах загроз воєнного часу та ризиків переміщення технологічного обладнання. Розроблена імітаційна модель для дослідження логістики релокації підприємства у формі агентного представлення, за допомогою якої моделюються події, які пов'язані з послідовністю дій релокації: демонтаж технологічного обладнання, перевезення обладнання, монтаж підсистем підприємства, тощо. Моделюється виникнення загроз та наслідки їх дій, які пов'язані з порушенням логістики переміщення підприємства. Наведено ілюстрований приклад дослідження релокації підприємства в умовах виникнення загроз та припинення руху переміщення технологічного обладнання, що призводить до пошуку нових маршрутів з мінімальними ризиками транспортування. Наукова новизна дослідження пов'язана з розробкою комплексу оригінальних оптимізаційних моделей, імітаційної агентної моделі, який дозволяє науково-обґрунтовано сформулювати вимоги до релокації високотехнологічного підприємства на нове місце розташування, для забезпечення скорочення довгих логістичних ланцюгів постачання комплектуючих, мінімізації логістичних витрат, формування відносно небезпечних логістичних каналів та шляхів постачання, мінімізації ризиків в умовах нових викликів та загроз політико-економічного характеру. Результати дослідження доцільно використовувати для планування проекту релокації високотехнологічного підприємства, формування заходів та дій, пов'язаних з переміщенням високотехнологічного підприємства, створення нових безпечних логістичних ланцюгів постачання, проведення евакуації підприємства в особливий період.

Ключові слова: релокація підприємства; довгі логістичні ланцюги; розташування підприємства; логістичні ризики; оптимізація витрат переміщення підприємства; агентне імітаційне моделювання.

Федорович Олег Євгенович – д-р техн. наук, проф., зав. каф. комп'ютерних наук та інформаційних технологій, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Прохоров Олександр Валерійович – д-р техн. наук, доц., проф. каф. комп’ютерних наук та інформаційних технологій, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Прончаков Юрій Леонідович – канд. техн. наук, доц., декан факультету програмної інженерії та бізнесу, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Попов Андрій Вячеславович – канд. техн. наук, доц., доц. каф. комп’ютерних наук та інформаційних технологій, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Момот Мирослав Олександрович – канд. техн. наук, доц., доц. каф. комп’ютерних наук та інформаційних технологій, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Oleg Fedorovych – Doctor of Technical Sciences, Professor, Head of Computer Science and Information Technologies Department, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine, e-mail: o.fedorovych@khai.edu, ORCID: 0000-0001-7883-1144.

Oleksandr Prokhorov – Doctor of Technical Sciences, Associate Professor, Professor of Computer Science and Information Technologies Department, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine, e-mail: o.prokhorov@khai.edu, ORCID: 0000-0003-4680-4082.

Yurii Pronchakov – Candidate of Technical Sciences, Associate Professor, Dean of the Software Engineering and Business Faculty, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine, e-mail: pronchakov@gmail.com, ORCID: 0000-0003-0027-1452.

Andrei Popov – Candidate of Technical Science, Associate Professor, Associate Professor of Computer Science and Information Technologies Department, National Aerospace University «Kharkiv Aviation Institute», Kharkiv, Ukraine, e-mail: a.popov@khai.edu; ORCID: 0000-0001-8984-731X.

Myroslav Momot – Candidate of Technical Science, Associate Professor, Associate Professor of Computer Science and Information Technologies Department, National Aerospace University «Kharkiv Aviation Institute», Kharkiv, Ukraine, e-mail: m.momot@khai.edu, ORCID: 0000-0003-2580-5908.