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METHODS AND MODELS OF MILITARY LOGISTICS RESEARCH FOR EFFECTIVE COMBAT OPERATIONS IN THE CONFLICT ZONE

Fedorovich O., Pronchakov Y., Prokhorov O., Kosenko V., Lutai L.

The monograph is devoted to the problem of studying the logistics processes of supplying weapons and military equipment to combat units in a military conflict zone. The relevance of the work is associated with complex logistics processes in a heterogeneous transport environment (road, rail, sea and other modes of transport) with transshipment of military cargo, their temporary warehousing and storage in conditions of military threats and reduction of delivery time. ***The aim*** *of the study is to create models and methods for researching the logistics processes of military equipment supply to provide combat units with the necessary modern weapons, which makes it possible to create military parity of forces in a military conflict zone. The logistics processes of transportation in a heterogeneous transport environment in the face of threats are studied, which complicates the supply of weapons and can cause delays and disruption of military equipment delivery schedules. The occurrence of possible losses due to delays is modulated, which can lead to the loss of personnel, damage and destruction of military equipment, disruption of defensive structures, etc. The article solves the multivariate task of creating military parity of forces in the combat zone through the use of modern weapons with enhanced combat capability characteristics (range, accuracy, area of impact, etc.), which contributes to the establishment of asymmetry and the superiority of the quality of weapons over quantity. The article examines the impact of the variety of weapons supplied to the zone of military conflict on the effectiveness of combat operations. The logistics of training military personnel to acquire special competencies in the use of modern diverse weapons (HIMARS, PATRIOT, NASAMS, etc.) and the risks that arise from the possible incomplete knowledge and skills acquired after training are modeled. Low-quality knowledge can arise due to the short period of training and training risks. A logistics model is created for the formation of the necessary stocks of weapons and military equipment required for effective combat operations using multi-criteria optimization. A set of arms suppliers is selected that can provide the maximum level of military equipment stocks in the combat zone in an accelerated time frame. The logistics process of relocation of high-tech enterprises to the rear is modeled to establish the production of weapons and military equipment in the face of military threats and risks of relocation.* ***Scientific novelty and originality of the study*** *are related to the formation of a set of methods and models that study the complex logistics processes of supplying weapons and military equipment to the conflict zone in the context of modern hybrid warfare.* ***Mathematical methods used in the study*** *are: system analysis, multivariate choice, lexicographic ordering of options, multicriteria optimization, integer (Boolean) programming, theory of experiment, quantitative and qualitative evaluation of options, simulation modeling, agent-based modeling.*

Introduction

The globalization of the economy has led to the emergence of distributed production, the planned nature of which requires timely delivery and formation of the necessary stocks of components, materials and raw materials. Due to the changing environment, challenges and threats, there are risks to the implementation of plans to develop modern high-tech products, including weapons and military equipment. The nature and level of threats in the world has changed, as terrorist and military threats have emerged in addition to political, economic, and climate threats. This can disrupt the logistics process of building up stocks of weapons and military equipment. This is especially true during martial law, when supply logistics and production are affected by military threats. Therefore, there were problems with both supply and stockpiling of military equipment. The use of various weapons in the conflict zone requires timely planning and stockpiling, as well as the creation of relatively safe transportation and storage routes for further use during hostilities. The nature of modern military logistics requires a study of the formation of weapons stockpiles, and an assessment of the impact of the number of stockpiles on the effectiveness of combat operations. Therefore, the topic of this study is relevant, as it creates a set of models and methods for analyzing the logistics processes of stockpiling, assessing the losses that arise in the event of a delay in the supply of military equipment, and the process of developing special competencies in the military to use modern weapons.

New problems in military logistics in the context of hybrid warfare have emerged that need to be addressed to ensure the country's defense capability:

1. The problem of the diversity of military equipment entering the combat zone, for which it is necessary to ensure the timely production of ammunition, spare parts and components.

2. The problem of a heterogeneous transport environment used to deliver military cargo to the military conflict zone. There are transshipment of weapons, temporary storage, which is dangerous in the face of military threats.

3. The problem of long, sometiWME intricate supply chains that complicate the logistics of military cargo transportation, increase the time for delivery and the risks of stockpiling.

4. The problem of late delivery of weapons and military equipment. This can lead to military losses and changes in the nature of hostilities (e.g., a shift from offensive to defensive actions).

5. The problem of training personnel to use a variety of military equipment in a short time, ensuring the necessary special competencies, and conducting quality training. Insufficient knowledge in combat conditions can lead to damage to military equipment and military losses.

6. The problem of relocating high-tech enterprises that produce modern weapons and military equipment to the rear in the context of martial law.

These problems and methods of their solution are the basis of the study, the results of which are presented in this section of the collective monograph.

Modeling the logistics of military cargo and the occurrence of losses due to delays in delivery

The unit solves a multi-criteria task related to modeling the transport logistics of military cargo delivery to the combat zone. The relevance of the study is related to the analysis of losses that occur in the combat zone (loss of personnel of the Armed Forces of Ukraine, damage and destruction of military equipment, change in the nature of combat operations from offensive to defensive, etc.) due to possible delays in the supply of weapons and military equipment. The purpose of the study is to model transportation logistics in a heterogeneous transportation network to ensure timely delivery of military cargo in the face of wartime risks that affect the amount of damage in the combat zone.

Logistics is one of the most important components in wartime [1]. The untimely delivery of weapons, military equipment, ammunition and spare parts to the combat zone significantly affects the nature and course of the war. Delayed delivery of military cargoes leads to possible losses during combat clashes (loss of personnel of the armed forces, damage and destruction of military equipment, change in the nature of hostilities from offensive to defensive, etc. Therefore, it is important to solve the problem of organizing rational logistics interactions in the process of transportation of military cargoes, which are carried out in a heterogeneous transport network with transitions (transshipment) from one type of transport highway to another. For example, the delivery of military cargo can be carried out along a long logistics transport chain: air – automobile – rail – automobile modes of transport.

To organize such complex interactions, distribution logistics centers, transshipment sites, temporary storage, etc. are being formed. Such a variety of logistics components, as well as long logistics chains, lead to great risks that must be taken into account when forming wartime military cargo supply routes.

The analysis of publications on this topic has shown that the main focus of scientific papers is on the formation of cargo routes in a homogeneous (mono-) transport environment without taking into account transitions from one transport artery to another, cargo transshipment and temporary storage [3]. In addition, there are currently no studies related to the occurrence of losses (especially in wartime) as a result of logistical delays and the analysis of risks arising in supply logistics due to wartime conditions [4].

Thus, a contradiction arises between the requirements of timely delivery of military cargo, which significantly affects the amount of damage and the course of hostilities, and the capabilities of transport logistics associated with a heterogeneous transport network and long logistics chains with transshipment, which leads to increased risks of transportation in wartime.

A complex scientific and applied task of a multicriteria nature arises related to the timely delivery of military cargo, the delay of which affects the amount of damage and the course of hostilities. At the same time, it is necessary to take into account the heterogeneity of the transportation network, the availability of transshipment, and the risks of supply arising from military threats [5].

The main criteria for assessing the achievement of the research objective are the time of cargo transportation in a heterogeneous transport network, the amount of damage associated with the late delivery of military cargo, and the amount of accumulated risk in wartime supply logistics.

To realize the research goal, the following tasks need to be solved:

1) to build an agent-based simulation model to study the transportation of military cargo;

2) to develop an algorithm for minimizing the time of delivery of military cargo in a heterogeneous transportation network;

3) to create a routing algorithm to minimize the risks of military cargo delivery;

4) to develop a method for analyzing possible damage associated with the delay in the delivery of weapons and military equipment to the combat zone;

5) to formulate a method for finding compromise solutions for developing routes for the supply of weapons and military equipment to the combat zone;

6) to provide an example of modeling the supply of military cargo to a combat zone.

Agent-based simulation model for studying military cargo transportation

Due to the long logistics chains associated with the delivery of military cargo, the main aspect of the study is aimed at modeling dynamic supply processes in a complex heterogeneous transportation network. Therefore, the main research tool used is the developed agent-based simulation model, which allows simulating time delays in complex structures of transportation networks with possible parallel supply processes interconnected by synchronization conditions.

The simulation model is implemented as an agent-based representation. It is based on the classical GPSS system for modeling complex processes, which is used to simulate dynamic processes in sociotechnical systems.

The simulation model identifies a control agent that, using a given time scale, manages the main events that occur during the movement of applications (military cargo) in the transportation network. The following main events related to the movement of military cargo were used:

– formation (generation) of a request in the transportation network;

– exit of the request from the vertex of the graph G of the transport network (transport node);

– receipt of a request at a transportation hub;

– occupation of the highway section by the request;

– release of the transportation section of the highway;

– arrival of a request (military cargo) in a combat zone;

– synchronization of several requests (for example, arrival of military equipment and ammunition).

The developed simulation model allows for the study of parallel processes of request movement, each of which is associated with its own route. The processes can be synchronized, which is related to the peculiarities of using military cargo in the combat zone.

The simulation model is implemented as a set of agents in relatively isolated program modules, with its own internal decision-making structure related to the implementation of events in the simulation system. Events are modeled in system time, taking into account a given scale, using a sequential list of events. Events are realized by viewing the header of the event list. Planning of future events is based on the cause-and-effect relationship. For example, due to the occupation of a section of a transportation highway, a consequence arises – the release of this section in the process of moving military cargo. The final event in the modeling is the event of the request (military cargo) entering the combat zone.

Let us list the main agents of the simulation model.

1. Agent for describing the transportation network.

2. Order generator agent (used to generate orders in the form of military cargo entering the transportation network).

3. Transport node agent (associated with the events of arrival and departure of military cargo from the transport node).

4. Agent of a transport section of a highway (associated with events of occupation and release of a section of a highway by military cargo).

5. Agent for synchronizing the receipt of multiple requests (triggered in the event of receipt of requests related to the condition of their synchronization).

6. Agent for getting requests (military cargo) into the combat zone (CZ).

7. Agent of risk accumulation during the movement of the order (military cargo) in a heterogeneous transportation network. Risks are set in advance by experts for both transportation hubs and sections of transportation highways.

8. Agent for generating losses associated with late delivery of military cargo. The amount of damage is set by experts and depends on the specified delivery time of military cargo.

9. Agent for managing the simulation process. It generates system time in accordance with a given scale, plans and implements a list of future events, taking into account causal events.

10. Agent of modeling results. The results include: the time of arrival of military cargo to the combat zone, the time of delay in the delivery of military cargo, the amount of damage due to the delay in the arrival of military cargo, the amount of the final risk of delivery of military cargo.

Fig. 1 shows a block diagram of the agent-based model.

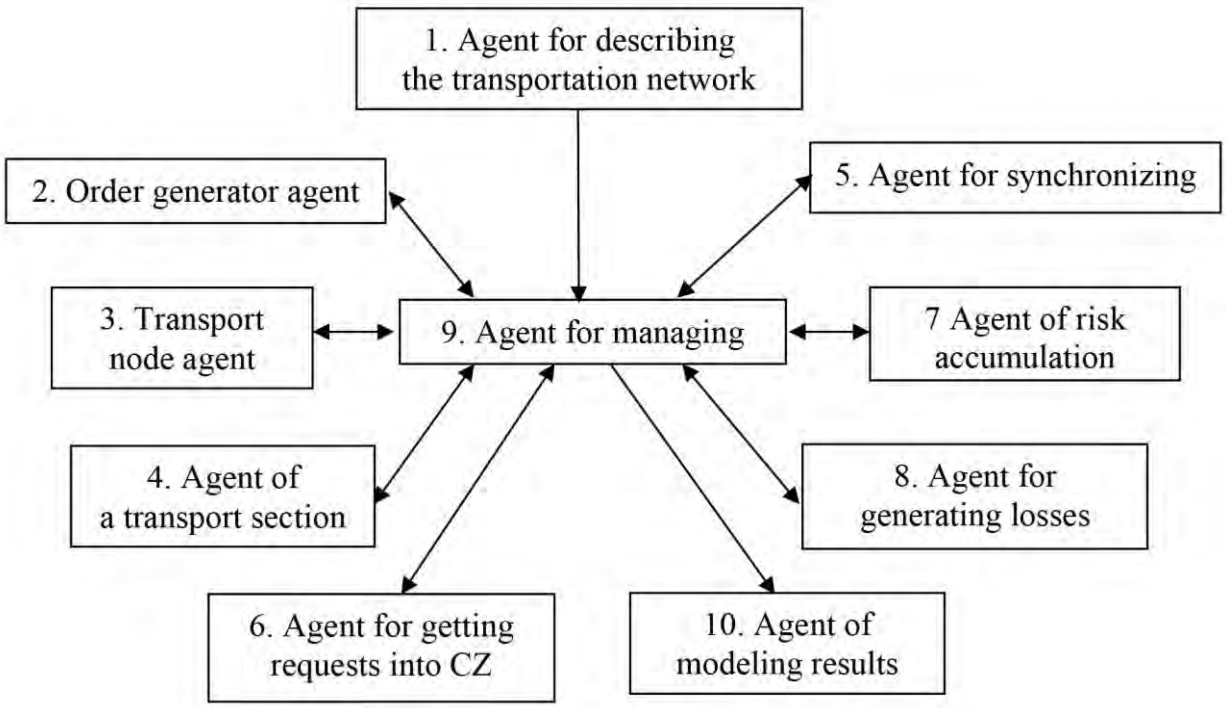

Fig. 1. Structural scheme of the agent model

Algorithm for minimizing the time of military cargo delivery in a heterogeneous transportation network

Publications discuss algorithms for minimizing cargo delivery time (for example, the well-known Dijkstra algorithm). Most of them are of an academic nature, so they cannot be used in real conditions related to the transportation of military cargo and combat operations. It is necessary to emphasize the following features of military cargo delivery in wartime:

– the use of a heterogeneous transportation network with a significant number of transitions (transshipment) from one transportation highway to another;

– use of parallel movements of military cargo from different sources of supply;

– meeting the requirements for synchronization and consolidation of military cargo;

– taking into account the military risks associated with the movement of goods both along transportation routes and at hubs;

– forced delays in the delivery of military cargo, which can lead to losses (loss of personnel of the armed forces, damage to engineering structures and destruction of military equipment, change in the nature of hostilities from offensive to defensive, etc.)

Therefore, we developed an original routing algorithm that takes into account the above features of military cargo delivery in wartime. The algorithm is implemented in the developed agent-based simulation model. Let us present the sequence of actions of the algorithm in the form of the main steps.

1. Generate requests (military cargo) related to a given batch of weapons and military equipment. Requests are generated using an agent – a request generator – based on a given schedule for the supply of weapons and military equipment.

2. Copies (clones) of applications of various types moving along all possible transportation sections of the highway associated with a particular transportation hub are sent from the transportation hub (including derivatives).

3. When a request arrives at a neighboring transport node, it is checked that no other requests are routed through that transport node. If a request (clone) occupies this transport node, it is blocked. Its movement is stopped due to the later arrival time at the already marked transport node, which was passed by another request earlier (the request is unpromising for further movement).

4. When a request (clone) arrives at a particular transport node, the synchronization (consolidation) condition is checked. If this condition exists, the request is waiting for other requests. The arrival of the last request ensures the formation of a complex request of a new type and its further movement in a heterogeneous transport network.

5. When the orders reach the combat zone (CZ), the time of their arrival is recorded.

6. From the finishing transport node of the CZ in the opposite direction, the route (routes) of movement of applications (military cargo) is formed by sequential passage through the designated transport nodes.

7. The resulting route is minimal in time and is used in the future to determine the possible delay in the arrival of military cargo to the combat zone, taking into account the specified delivery time.

8. During the movement of applications (clones) along the sections of the highway and transport nodes, risk values are accumulated, which is formed in the form of a final risk value after the arrival of all military cargo in the combat zone.

9. Depending on the time of delay of military cargoes in the CZ, military specialists form the amount of possible damage by means of expert assessment.

A routing algorithm to minimize the risks of military cargo delivery

Long supply chains become particularly vulnerable in wartime. The risks associated with the late delivery of military cargo to the war zone are growing. Therefore, it is necessary to model the accumulation of risks in long logistics chains, taking into account possible threats and vulnerabilities.

A routing algorithm has been developed to minimize the risks of supply in the face of threats and vulnerabilities. The basis for the development is an algorithm for minimizing the time of cargo delivery in a heterogeneous transport network. The peculiarity of the algorithm, unlike the developed one, is the change in the controlling action of events in the modeling. As event control, we use not time but the value of the accumulated risk in the process of movement of orders (clones) in column G, which is a heterogeneous transportation network. Therefore, the list of future events is formed not by the value of time, but by the value of the accumulated risk.

The event with the lowest value of the accumulated risk is always at the top of the event list. During the movement of orders (clones), transport nodes are marked with passed orders (clones). Unpromising orders (clones) with a higher value of accumulated risk are discarded.

The final transport node (combat zone) receives the application (clone) in the form of a military cargo consignment with the minimum value of the accumulated risk. In the reverse phase of the algorithm (movement from the CZ to the derivative transport hubs), a route for the movement of applications is formed and thus the task of routing is solved to minimize the risks of supplying military cargo in the face of threats and vulnerabilities.

A method for assessing the possible damage associated with the delayed delivery of military equipment to the combat zone

The success of combat operations in a particular area of military conflict depends primarily on the timeliness of the logistics supply of the necessary weapons and military equipment. Delay in the supply of certain components for weapons and military equipment leads to damage (loss of personnel of the armed forces, damage and destruction of military equipment and defensive structures, change in the nature of hostilities from offensive to defensive, etc.), the amount of which depends on the importance of certain types of weapons that are essential for the successful execution of military operations in the combat zone. An urgent task arises – to investigate the delay of certain types of weapons and military equipment that should be delivered to the combat zone. These delays affect the amount of damage during combat operations. To solve this problem, it is necessary to analyze possible (alternative) variants of delays for certain types of weapons and military equipment. Next, it is necessary to assess the impact of the delay on the amount of damage. The task is to search through the set of delay options associated with certain types of weapons and military equipment. For example, for three types $(n=3)$ of weapons, the total number of possible delay options is $N=2^n=2^3=8$.

You can generate all possible options using a binary counter, in the form:

1. 000
2. 001
3. 010
4. 011
5. 100
6. 101
7. 110
8. 111,

where the first option, for example, means no delays, i.e., timely arrival of all three types of weapons in the combat zone, which corresponds to no (or minimal) damage. The last, eighth, option means that there are delays for all types of weapons, which means the maximum value of damage in the combat zone. To assess the damage, the opinions of military experts are used, who can estimate the value of damage, for example, on a ten-point scale, where the minimum value of damage is associated with the first option, and the maximum – with the last, eighth option.

To estimate the impact of delays on damage, we will use a full factorial experiment (FFE), where the row of the plan is a combination of possible delays for individual weapons, and the final column (right) is the expert estimates of possible damage.

Consider an illustrated example of studying the impact of delays on the amount of damage in a combat zone. For the purpose of the example under consideration, let's assume that three types of weapons are used to successfully perform combat missions:

1) multiple launch rocket systems (MLRS) (variable X_1);

2) artillery systems (guns, howitzers, mortars) (variable X_2);

3) anti-tank systems (variable X_3).

The plan of the virtual experiment with assessments of military specialists (experts) is presented in the form of a FFE (Fig. 2).

№	X_1	X_2	X_3	Y
1	–1	–1	–1	0
2	–1	–1	+1	2
3	–1	+1	–1	3
4	–1	+1	+1	5
5	+1	–1	–1	5
6	+1	–1	+1	7
7	+1	+1	–1	8
8	+1	+1	+1	10

Fig. 2. Using FFE for loss assessment

Here, –1 means no delay (zero value of the binary counter), and +1 means a delay (one value of the binary counter). Column Y contains the estimated values of losses in points. Further, using the known calculation formulas for FFE, the values of the parameters are determined in the form of an incomplete quadratic dependence:

$$Y = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_{12} X_1 X_2 + b_{13} X_1 X_3 + b_{23} X_2 X_3 + b_{123} X_1 X_2 X_3,$$

where b_0 corresponds to the center of the experiment;

b_1 – coefficient associated with the influence of the factor X_1;

b_2 – coefficient associated with the influence of the factor X_2;

b_3 – coefficient associated with the influence of the factor X_3;

b_{12} – coefficient for assessing the relationship of factors X_1 and X_2;

b_{13} – coefficient for assessing the relationship of factors X_1 and X_3;

b_{23} – coefficient for assessing the relationship of factors X_2 and X_3;

b_{123} – coefficient for assessing the relationship of factors X_1, X_2 and X_3.

First of all, we are interested in the linear part of this relationship, which allows us to estimate the impact of certain types of weapons on the amount of loss (Y). After performing the calculations in the example, we have:

$$Y = 3,75 + 2,5X_1 + 1,5X_2 + X_3 \ .$$

The dependence shows that the most significant impact on the amount of damage in the combat zone is caused by the late delivery of MLRS. Delayed delivery of artillery systems has a lesser impact. Late delivery of anti-tank systems has the least impact on the amount of damage in the combat zone.

If a group of experts rather than a single military specialist is involved in assessing the damage (related to delays) when certain types of weapons and military equipment arrive in the combat zone, then the estimates are averaged to form the damage values.

If there is a significant difference in expert estimates, the ELEKTRA method can be used to generate compromise estimates. With its help, through multi-step iteration, we achieve compromise values for a group of experts.

A method of finding compromise solutions in the formation of routes for the supply of weapons and military equipment to the combat zone

The analysis of the tasks of supplying weapons and military equipment to the combat zone showed that there is a contradiction between the criteria related to the time of delivery of military cargo, risks and losses. Therefore, it is necessary to find a compromise solution related to the delay of military cargo and losses that occur in the combat zone by means of multivariate analysis.

Let's assume that a set of alternative routes for the delivery of weapons and military equipment to a combat zone has been formed using the opinions of military experts. For each k-th route option, a preliminary estimate of possible time delays t_{ik} for the i-th transport nodes of the logistics supply chain is known, t_{jk} is the delay on the highway sections during the movement of military cargo.

Then the total time associated with the supply of military cargo can be represented as:

$$T_k = \sum_{i=1}^{n_k} t_{ik} + \sum_{j=1}^{m_k} t_{jk},$$

where n_k – is the number of transport nodes in the k-th route of military cargo movement;

m_k – is the number of sections of the transportation highway in the k-th route option.

The amount of possible delay if military cargo arrives in the combat zone for the k-th route variant:

$$\Delta T_k = T_k - T_0,$$

where T_0 – the planned time of delivery of military cargo to the combat zone.

In this way, it is possible to assess the risks that accumulate during the movement of goods in the combat zone. For the k-th route:

$$R_k = \sum_{i=1}^{n_k} r_{ik} + \sum_{j=1}^{m_k} r_{jk}.$$

At the same time, it is necessary that $R_k \le R_0$, where R_0 is the acceptable risk value associated with the delivery of military cargo to the combat zone.

To find a compromise route for the delivery of military cargo to the combat zone, we will use the method of integer (Boolean) programming.

Let's introduce the variables x_k, in this case $X_k = 1$ corresponds to the use of the k-th route of delivery of military cargo to the combat zone, $X_k = 0$ corresponds to the non-use of the k-th route. In this case $\sum_{k=1}^{N} X_k = 1$, which corresponds to the selection of one alternative route to solve the routing problem, here N is the number of possible routes for the movement of military cargo specified by experts.

Then, taking into account the variables X_k, the criterion for the delay of military cargo when entering the combat zone will be as follows:

$$\Delta T = \sum_{k=1}^{N} \left(\sum_{i=1}^{n_k} t_{ik} + \sum_{j=1}^{m_k} t_{jk} \right) X_k - T_0.$$

In its turn, the amount of accumulated risk will be calculated as:

$$R = \sum_{k=1}^{N} \left(\sum_{i=1}^{n_k} r_{ik} + \sum_{j=1}^{m_k} r_{jk} \right) X_k.$$

To find a compromise solution, let's introduce a comprehensive criterion:

$$Q = \alpha_T \Delta\hat{T} + \alpha_R \hat{R} = \alpha_T \sum_{k=1}^{N} \Delta\hat{T}_k X_k + \alpha_R \sum_{k=1}^{N} \hat{R}_k X_k =$$

$$= \frac{\alpha_T}{\Delta T_{max} \left[\sum_{k=1}^{N} \left(\sum_{i=1}^{n_k} t_{ik} + \sum_{j=1}^{m_k} t_{jk} \right) X_k - T_0 \right]} + \frac{\alpha_R}{R_0} \left[\sum_{k=1}^{N} \left(\sum_{i=1}^{n_k} r_{ik} + \sum_{j=1}^{m_k} r_{jk} \right) X_k \right].$$

Here ΔT_{max} is the maximum value of the delay, which was taken after analyzing the set of possible routes for the supply of military goods to the combat zone, where $\alpha_T + \alpha_R = 1$, α_T is the significance (weight of the delay criterion), and α_R is the significance (weight of the supply risk criterion).

It is necessary to find min Q taking into account $R \le R_0$, $\sum_{k=1}^{N} X_k = 1$.

The resulting solution is a compromise and takes into account possible delays and risks in the delivery of military cargo to the combat zone

An example of modeling the supply of military cargo to a combat zone

Let's consider an illustrated example of the supply of military cargo to a combat zone for a transportation network depicted as graph G in Fig. 3.

The vertices of the graph represent transportation nodes, and the edges represent sections of the transportation network. The time delays at the nodes and sections of the transportation highway are given in hours. For the convenience of assessing risks and losses, qualitative assessments are used in the form of values of linguistic variables, which are then converted into terms of points.

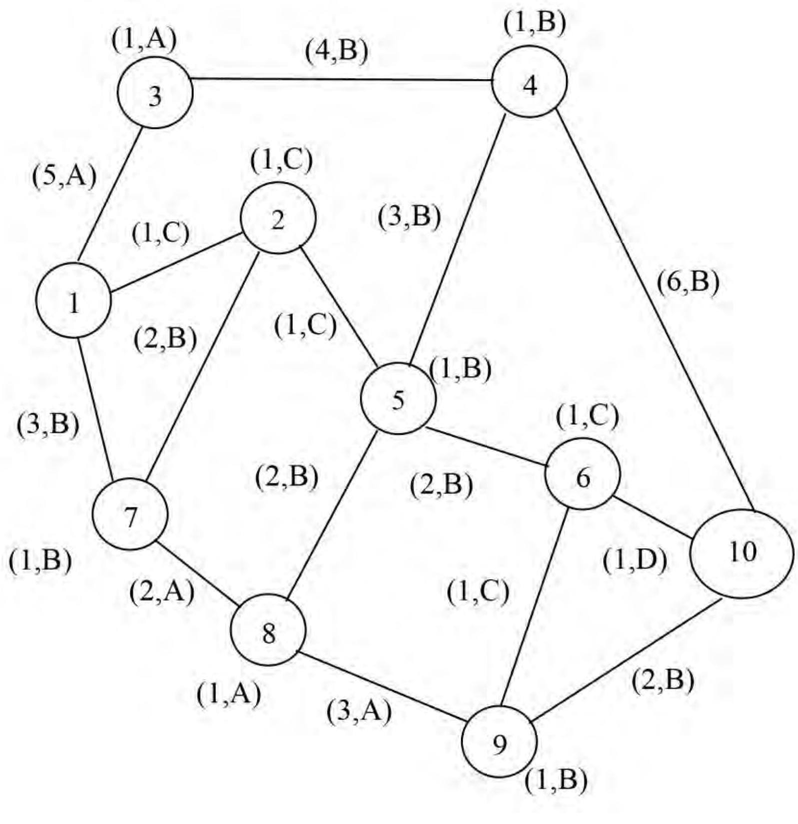

Fig. 3. Graph G of military cargo supply

We have the following qualitative assessments for risks:

A – minimum risk value;

B – satisfactory risk value;

C – acceptable risk value;

D – maximum risk.

In terms of points: $A = 3$, $B = 5$, $C = 7$, $D = 10$.

The following linguistic variables are used to estimate the loss caused by delays in the delivery of military supplies to the combat zone:

K – minimum loss;

L – satisfactory value of loss;

M – acceptable value of loss;

N – critical value of loss.

In brackets in Fig. 3 shows the values of time and risk on sections of the highway and transportation hubs. The first vertex of graph G corresponds to the transportation hub, the source of military supplies. The last, tenth vertex of graph G corresponds to the arrival of military equipment in the combat zone. Using the developed agent-based simulation model (p. 1), the algorithm for finding a route with the minimum time (p. 2) and the algorithm for finding a route with the minimum risk value (p. 3), as well as estimates from military specialists (experts), we constructed Table 1 with a set of possible routes for the supply of military equipment to the combat zone.

Table 1

An example of a study on the supply of military equipment in the CZ

№	Routes	Travel time	Time of delay		Risks		Loss
			hours	%	Linguistic variables	Points	
1	1-3-4-10	16	8	100	2A, 3B	21	N
2	1-2-5-4-10	14	6	75	4B, 3C	41	M
3	1-2-5-6-10	8	0	0	2B, 4C, D	48	K
4	1-2-5-8-9-10	13	5	63	2A, 3B, 3C	42	M
5	1-2-7-8-5-6-10	15	7	88	2A, 5B, 3C	52	M
6	1-2-5-6-9-10	11	3	38	4B, 5C	55	L
7	1-2-7-8-9-6-10	15	7	88	3A, 3B, 3C D	55	M
8	1-2-7-8-5-4-10	21	13	163	A, 7B, 2C	52	N
9	1-7-2-5-6-10	14	6	75	4B, 3C, D	51	M
10	1-7-2-5-4-10	20	12	150	A, 5B, 2C	42	N
11	1-7-2-5-6-10	14	6	75	5B, 3C, D	56	M
12	1-7-2-5-8-9-10	13	5	63	2A, 4Bb, 3C	47	M
13	1-7-2-5-8-9-10	20	12	150	3A, 5B, 3C, D	65	N
14	1-7-8-5-4-10	22	14	175	2A, 7B	41	N
15	1-7-8-5-6-10	12	6	75	2A, 6B, C, D	53	M
16	1-7-8-5-6-9-10	17	9	113	2A, 7B, 2C	55	N
17	1-7-8-9-10	13	5	63	3A, 4B	29	M
18	1-7-8-9-6-10	14	6	75	3A, 3B, 2C, D	48	M

A preliminary analysis of the modeling results showed:

1. The options for military equipment supply routes 1, 8, 10, 13, 14, 16 were eliminated in further research due to unacceptable (critical) values of damage that occurs in the combat zone.

2. Taking into account the total risk value (over 50 points) that arises and accumulates during the movement of military cargo on sections of the highway and nodes, route options 5, 6, 7, 9, 11, 15 were eliminated from further study.

3. The third route option for the supply of military equipment corresponds to the minimum time of delay, but at the same time there is a rather high risk value of R=48 points.

4. The first option of the route for the supply of military equipment to the combat zone corresponds to the minimum risk value of $R = 21$ points, but at the same time has an unacceptable value of damage – N, the time of delay corresponds to 100%, so it was also excluded from consideration.

5. It makes sense to consider the options of routes for the supply of military equipment to the combat zone with intermediate values of delay, risks and losses 2, 4, 12, 17, 18 to select a compromise solution.

The final route option for the supply of military equipment to the combat zone was chosen as route option 17 with a delay of 63%, a minimum risk of 29 points, and an acceptable value of damage of M.

The study described in this subsection is related to the modeling of logistics chains for the supply of military cargo (weapons, military equipment) to the combat zone.

The article reveals the shortcomings of existing routing methods, which are mainly related to peacetime and do not take into account delays and risks that arise in long logistics supply chains for military cargo, which leads to losses. An agent-based simulation model and an original routing algorithm have been developed that allows, by multiplying requests (request clones), to find the optimal route in a heterogeneous transportation network with minimal time and risk.

The article analyzes the losses due to late delivery using the method of theory of experiment. The method of integer (Boolean) programming is used to find compromise solutions in the problem of military cargo routing.

An example of modeling delays in the supply of military cargo to a combat zone is presented.

The proposed approach makes it possible to formulate rational routes for the transportation of military cargoes in the planning of the supply of weapons and military equipment to the combat zone, taking into account delays, losses and risks.

Modeling the logistics of establishing military parity of forces

The chapter solves a multivariate problem related to the modeling of the logistics process of creating military parity of forces in a military conflict zone, which contributes to the successful fulfillment of the objectives of a combat operation. The relevance of the study is related to the analysis of threat factors to the establishment of military parity of forces, logistical difficulties arising from the supply of weapons and military equipment, which causes damage in a military conflict zone (loss of personnel, breach of defensive structures, transition from offensive to defensive actions, etc.) The purpose of the study is to model the actions related to the logistics of forming parity of forces in the conflict zone under the threat of martial law.

Conducting a successful military operation in modern conditions depends on many factors, in particular, on the existence of military parity of forces with a possible enemy [6]. Creating parity in weapons and military equipment is one of the important tasks in preparing for a military operation [7]. The formation of military parity of forces is a complex logistical task, which should involve developers, suppliers of weapons and military equipment, logistics of transportation in a heterogeneous transport environment with possible transshipment from one transport highway to another and temporary storage of military cargo. Therefore, the task of ensuring military parity of forces in the combat zone for the successful execution of a military operation in the face of threats and vulnerabilities associated with the logistics of production and supply of weapons and military equipment is relevant. The analysis of publications on the research topic showed that the available works are mostly related to certain aspects of the task, in particular, consideration of the requirements for the formation of military parity of forces [8] for the successful execution of a military operation, the logistics of military cargo transportation, the presence of uncertainties related to the logistics of military transportation [9]. There are no publications with a comprehensive solution to the proposed task, analysis of threats caused by violation of military parity in the zone of military conflict, logistical threats related to the transportation of military cargo to the combat zone. In addition, the probability of vulnerabilities related to the problems of logistics of military cargo delivery to the combat zone, which leads to a violation of military parity of forces and, as a result, to the death of armed forces personnel, destruction of defense infrastructure, transition from offensive to defensive actions, etc. has not been studied. In order to successfully fulfill the purpose of the study, the main criteria are the levels of threats, logistical risks, time and expences required to establish military parity of forces in the zone of military conflict. To realize the research objective, it is necessary to solve the following tasks [10]:

1. To analyze the threat factors in the process of forming military parity of forces in the combat zone.

2. To model threats in the logistics of production and supply of weapons and military equipment to ensure military parity of forces in the combat zone.

3. To develop a method to increase the effectiveness of the use of zurich, which contributes to the creation of asymmetry in the military parity of forces in the combat zone.

4. To create an agent-based simulation model for studying the logistics of production and supply of weapons and military equipment to the combat zone to establish military parity of forces.

Analysis of threat factors in the process of forming military parity of forces in the combat zone

In order to form military parity of forces, it is necessary to analyze the main components of weapons and military equipment in a particular combat zone. For example, such components in the form of threat factors are the lack of specific types of weapons in the required quantity:

– aviation
– heavy weapons,
– ammunition,
– unmanned aerial systems.

Suppose that with the help of military experts for the combat zone under consideration, the necessary types of weapons and their quantity, as well as military equipment are determined in the form of a set M, $m_i \in M$, $i = \overline{1,N}$. Where m_i is the number of weapons of the i-th type required to create military parity of forces, N is the number of required types of weapons to establish military parity of forces in the CZ.

It is known, according to military experts, how many weapons of the i-th type are available in the CZ – $m_{0i} \in M_0$, where m_{0i} is the availability of weapons of the i-th type in the CZ at the moment.

Then $\Delta m_i = m_i - m_{0i}$ – is the number of weapons of the i-th type required to ensure military parity of forces in the CZ. The greater the value of , the higher the threat associated with the lack of the required number of weapons of the i-th type in the CZ. The emergence of threats associated with the lack of a certain number of certain types of weapons can lead to losses in the CZ (loss of personnel, disruption of defense infrastructure, transition from offensive to defensive actions, etc.) Therefore, it is necessary to assess the level of threats, taking into account possible factors related to the lack of weapons.

For the convenience and simplicity of analyzing the level of threats, we use the estimates of military experts for each i-th type of weapon. To do this, we will use qualitative assessments of the level of threats in the form of values of the linguistic variable:

$$x_i = \begin{cases} A - \textit{low threat level for i-th type of weapon;} \\ B - \textit{acceptable threat level;} \\ C - \textit{high threat level;} \end{cases}$$

For each i-th type of weapon and military equipment, there is a set of suppliers P_i that can supply m_{ij} number of weapons and military equipment $m_{ij} \le \Delta m_i$. The value of m_{ij} is a factor that affects the threat level x_i and is estimated with the help of military experts for each i-th type of weapon. In addition, it is necessary to take into account the time of production and delivery t_{ij} of the i-th type of weapon by the j-th supplier, w_{ij} – the expence of production and delivery of the i-th type of weapon by the j-th supplier, r_{ij} – the risks of production and delivery of the i-th type of weapon by the j-th supplier.

Where:

$$t_{ij} = \begin{cases} A - \textit{minimum delivery term;} \\ B - \textit{satisfactory delivery term;} \\ C - \textit{maximum delivery term;} \end{cases}$$

$$w_{ij} = \begin{cases} A - \textit{minimal expences;} \\ B - \textit{acceptable expenses;} \\ C - \textit{maximum expences;} \end{cases}$$

$$r_{ij} = \begin{cases} A - \textit{minimum risk;} \\ B - \textit{acceptable risk;} \\ C - \textit{maximum risk}. \end{cases}$$

To determine a possible supplier in the set P_i, we represent each j-th supplier for the i-th type of weapon as a sequence of qualitative values x_{ij}, t_{ij}, w_{ij}, r_{ij}, where x_{ij} is the level of threat determined by military experts depending on the value m_{ij} associated with the quantity of the i-th type of weapon that can be provided by the j-th supplier.

The list of qualitative values x_{ij}, t_{ij}, w_{ij}, r_{ij} will be represented conventionally as a word, for example, B A B C. Then for the set P_i of possible suppliers of the i-th type of weapons and military equipment, we will get a list of "words" that will be options for the suppliers to choose. For example, we have 10 variants:

1. A, C, B, B
2. B, A, B, B
3. B, B, A, B
4. C, A, A, B
5. B, B, C, B
6. B, A, C, C
7. C, A, A, A
8. B, B, A, C
9. C, A, A, C
10. A, B, B, C.

By organizing the options in a lexical and graphical form (as in a dictionary), you can select the option with the lowest threat level. We get:

10. A, B, B, C
1. A, C, B, B
2. B, A, B, B
6. B, A, C, C
3. B, B, A, B
8. B, B, A, C
5. B, B, C, B
7. C, A, A, A
4. C, A, A, B
9. C, A, A, C.

It is noticeable that the options with the lowest level of threat will be located in the upper half of the ordered list of possible suppliers of weapons and military equipment of the i-th type. In the above example, it is advisable to take the second option of the supplier with an acceptable level of threats, the minimum period of production and delivery of the i-th type of weapon, acceptable expence and risk.

Thus, for each i-th type of weapon and military equipment, suppliers will be selected that ensure the minimum level of threat for all weapons in the process of forming military parity of forces in the combat zone.

Given a significant number of possible suppliers of weapons and military equipment, we will use quantitative estimates to solve the optimization problem of choosing a supplier from a set of suppliers that minimizes the level of threats in the process of forming military parity of forces in the CZ.

Let z_{ij} be a Boolean variable that takes the values:

$$z_{ij} = \begin{cases} 1 - \textit{if the j-th supplier is selected for the i-th type of weapon;} \\ 0 - \textit{otherwise;} \end{cases}$$

at the same time $\sum_{j=1}^{n_i} z_{ij} = 1$.

Then the threat criterion can be presented as follows:

$$V = \sum_{i=1}^{N} \sum_{j=1}^{n_i} v_{ij} z_{ij},$$

where v_{ij} – is a quantitative assessment of the level of threat proposed by military experts (for example, on a 10-point scale) for selecting the j-th supplier of the i-th type of weapon, n_i is the number of possible suppliers of the i-th type of weapon. It should be noted that v_{ij} depends on the number of $m'_{ij} \le \Delta m_{ij}$, where m'_{ij} is the planned number of weapons of the i-th type that can be delivered by the j-th supplier.

Total time for production and delivery of weapons (pessimistic estimate of time due to the sequential nature of weapons delivery):

$$T = \sum_{i=1}^{N} \sum_{j=1}^{n_i} t_{ij} z_{ij}.$$

Expences associated with the production and supply of the necessary weapons and military equipment to establish parity of forces in the CZ:

$$W = \sum_{i=1}^{N} \sum_{j=1}^{n_i} w_{ij} z_{ij}.$$

Risks of production and supply of weapons in wartime to establish military parity of forces in CZ:

$$R = \sum_{i=1}^{N} \sum_{j=1}^{n_i} r_{ij} z_{ij}.$$

It is necessary to minimize the threat associated with lack of the required number of weapons of different types in the CZ:

$$\min V, \quad V = \sum_{i=1}^{N} \sum_{j=1}^{n_i} v_{ij} z_{ij},$$

subject to the following restrictions:

$$T \le T', \quad T = \sum_{i=1}^{N} \sum_{j=1}^{n_i} t_{ij} z_{ij},$$

$$W \le W', \quad W = \sum_{i=1}^{N} \sum_{j=1}^{n_i} w_{ij} z_{ij},$$

$$R \le R', \quad R = \sum_{i=1}^{N} \sum_{j=1}^{n_i} r_{ij} z_{ij},$$

where T', W', R' – acceptable values of the time of production and delivery of weapons, acceptable expences and risks of establishing military parity of forces in the CZ.

In the case of possible parallel deliveries of weapons and military equipment to the CZ (optimistic estimate of delivery time):

$$T = \max_{i=1}^{N} \left(\sum_{j=1}^{n_i} t_{ij} z_{ij} \right).$$

If military experts have difficulties in determining threat assessments, we will use the values $\Delta m'_{ij} = \Delta m_{ij} - m'_{ij}$ that need to be minimized in the process of planning the production and supply of weapons and military equipment in the CZ. In this case, it is necessary:

$$\min \Delta m', \quad \Delta m' = \sum_{i=1}^{N} \sum_{j=1}^{n_i} \Delta m'_{ij} z_{ij},$$

taking into account the allowed values:

$$T \le T', \quad T = \sum_{i=1}^{N} \sum_{j=1}^{n_i} t_{ij} z_{ij},$$

$$W \le W', \quad W = \sum_{i=1}^{N} \sum_{j=1}^{n_i} w_{ij} z_{ij},$$

$$R \le R', \quad R = \sum_{i=1}^{N} \sum_{j=1}^{n_i} r_{ij} z_{ij}.$$

If for the i-th type of weapon it is possible to use not one supplier, but a group of suppliers, then it is necessary to evaluate each k-th group of possible suppliers for the j-th option of choosing suppliers of the i-th type of weapon:

$$v_{ij} = \sum_{k=1}^{l_j} v_{ijk},$$

$$t_{ij} = \sum_{k=1}^{l_j} t_{ijk},$$

$$w_{ij} = \sum_{k=1}^{l_j} w_{ijk},$$

$$r_{ij} = \sum_{k=1}^{l_j} r_{ijk},$$

where l_j – is the number of possible suppliers in the group for the j-th option of choosing possible suppliers.

Then, to assess the level of threats:

$$\min V, \quad V = \sum_{i=1}^{N} \sum_{j=1}^{n_i} \left(\sum_{k=1}^{l_j} v_{ijk} \right) z_{ij},$$

subject to the restrictions:

$$T \le T', \quad T = \sum_{i=1}^{N} \sum_{j=1}^{n_i} \left(\sum_{k=1}^{l_j} t_{ijk} \right) z_{ij},$$

$$W \le W', \quad W = \sum_{i=1}^{N} \sum_{j=1}^{n_i} \left(\sum_{k=1}^{l_j} w_{ijk} \right) z_{ij},$$

$$R \le R', \quad R = \sum_{i=1}^{N} \sum_{j=1}^{n_i} \left(\sum_{k=1}^{l_j} r_{ijk} \right) z_{ij}.$$

If difficulties arise in quantifying the military level of v_{ijk} threats, it is necessary:

$$\min \Delta m', \quad \Delta m' = \sum_{i=1}^{N} \sum_{j=1}^{n_i} \left(\sum_{k=1}^{l_j} \Delta m'_{ijk} \right) z_{ij},$$

subject to the restrictions:

$$T \le T', \quad T = \sum_{i=1}^{N} \sum_{j=1}^{n_i} \left(\sum_{k=1}^{l_j} t_{ijk} \right) z_{ij},$$

$$W \le W', \quad W = \sum_{i=1}^{N} \sum_{j=1}^{n_i} \left(\sum_{k=1}^{l_j} w_{ijk} \right) z_{ij},$$

$$R \le R', \quad R = \sum_{i=1}^{N} \sum_{j=1}^{n_i} \left(\sum_{k=1}^{l_j} r_{ijk} \right) z_{ij}.$$

Modeling threats in the logistics of production and supply of weapons and military equipment

In wartime, the logistics chains used for the production and supply of weapons and military equipment to the conflict zone may be disrupted by threats related to the aggressor's actions. In this case, the realization of threats leads to possible vulnerabilities in production and supply logistics, which can ultimately cause damage in the combat zone (loss of personnel, disruption of defense infrastructure, transition from offensive to defensive actions, etc.)

The chain that needs to be investigated is: threat – vulnerability – damage. Vulnerabilities, for example, may be related to the state and shortcomings of the heterogeneous transport network used to transport weapons and military equipment (moral and physical obsolescence of the transport system, a large number of bridges and interchanges, bottlenecks in the form of places of transshipment of military cargo from one transport highway to another, warehousing and temporary storage of military cargo in certain places of the transport network, transportation of ammunition that may explode due to the actions of the aggressor, violation of the requirements for dimensions and weights). In the event of a threat from the aggressor (air raids, missile attacks, long-range artillery, etc.), vulnerabilities are perturbed, which lead to damage in the combat zone.

Therefore, there is an urgent task of determining the impact of threats on the perturbation of vulnerabilities that cause damage. This affects the nature of hostilities in a military conflict zone (transition from offensive to defensive actions, retreat from previously occupied positions, etc.) To analyze the sequence: threat – vulnerabilities – losses, we will use the estimates of military experts, which are formed using a full factorial experiment (FFE).

As an example of such an analysis, consider the impact of an air raid on a section of railroad that is used to transport artillery weapons. Suppose military experts who know the specific route of the military cargo have identified three possible transportation vulnerabilities in the form of factors x_j FFE:

– cargo transshipment (x_1),

– temporary storage (x_2),

– violation of the special transportation regime (x_3).

Fig. 4 shows the FFE plan, where the rows correspond to possible vulnerabilities (no vulnerabilities – the first row (–1, –1, –1), the presence of all vulnerabilities – the last row of the plan (+1, +1, +1)).

	x_1	x_2	x_3	y
1	–1	–1	–1	0
2	–1	–1	+1	5
3	–1	+1	–1	3
4	–1	+1	+1	8
5	+1	–1	–1	2
6	+1	–1	+1	7
7	+1	+1	–1	5
8	+1	+1	+1	10

Fig. 4. FFE plan for loss assessment

The right column of the FFE plan contains military experts' estimates of the levels of damage that would result from the vulnerabilities due to an air attack (for example, on a 10-point scale). The FFE plan can be used to build a regression relationship that allows you to estimate the impact of individual factors (vulnerabilities) on damage, provided that the vulnerabilities are perturbed in the event of a threat (air raid):

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_2 + b_{23}x_2x_3 + b_{123}x_1x_2x_3,$$

where b_0, b_1, b_2, b_3, b_{12}, b_{13}, b_{23}, b_{123} – coefficients associated with the impact of factors x_1, x_2, x_3 on the value of the loss (y). We are interested in the linear part of the regression relationship, which is related to the impact of individual factors (vulnerabilities) on the amount of loss. After simple calculations, we have:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 = 5 + x_1 + 1{,}5x_2 + 2{,}5x_3.$$

The dependence obtained in the illustrated example with a virtual experiment indicates the influence of three factors (vulnerabilities).

1. According to experts, the most important vulnerability that is triggered during an air raid is the violation of the special regime during the transportation of military cargo $(b_3 = 2{,}5)$.

2. Less important is the vulnerability associated with the temporary storage of military cargo $(b_2 = 1{,}5)$.

3. In terms of damage caused, the smallest vulnerability in an air raid is the one associated with the transshipment of military cargo $(b_1 = 1)$.

A method of increasing the effectiveness of the use of weapons by creating asymmetry in the military parity of forces in the combat zone

Military parity of forces is most often associated with the use of approximately the same types of weapons by adversaries in the combat zone. The emergence of new types of weapons and military equipment makes it possible to use more effective weapons in the conflict zone that far exceed the combat characteristics of their analogues (for example, the use of modern HIMARS MLRS for rocket and artillery weapons with increased range and accuracy of impact). Therefore, by creating an asymmetry in the quality and quantity of weapons for different types of weapons, it is possible to increase the overall effectiveness of the use of weapons in the CZ (quality over quantity). Therefore, it is important to develop a method to increase the effectiveness of the use of weapons in the combat zone, which contributes to the creation of asymmetry by type in the military parity of forces. Due to the multivariate nature of establishing asymmetry in military parity of forces, we will use the method of integer (Boolean) programming as a mathematical tool to solve the problem.

Let x_{ijk} be a Boolean variable with the following values:

$$x_{ijk} = \begin{cases} x_{ijk} = 1, \text{ \textit{if the j-th type of weapon}} \\ \qquad \text{\textit{and its k-th supplier are selected for the i-th type of weapon;}} \\ x_{ijk} = 0, \text{ \textit{otherwise}}. \end{cases}$$

Then, military specialists (experts) determine the effectiveness q_{ij} of its use in the combat zone for each type of weapon. Then, for each i-th type of weapon, the effectiveness of its use is as follows:

$$Q_i = \sum_{j=1}^{n_i} \sum_{k=1}^{p_j} q_{ij} m_{ijk} x_{ijk},$$

where m_{ijk} – is the number of weapons that can be developed by the k-th supplier of the j-th kind for the i-th type of weapon;

p_j – is the number of possible suppliers of the j-th type of weapon.

Then the total efficiency of the use of all types of weapons in the combat zone

$$Q = \sum_{i=1}^{N} \sum_{j=1}^{n_i} \sum_{k=1}^{p_j} q_{ij} m_{ijk} x_{ijk},$$

where N – number of types of weapons.

To ensure the success of combat operations in the conflict zone, it is necessary

$$\max Q, \quad Q = \sum_{i=1}^{N} \sum_{j=1}^{n_i} \sum_{k=1}^{p_j} q_{ij} m_{ijk} x_{ijk},$$

subject to restrictions:

$$T \leq T', \quad T = \sum_{i=1}^{N} \sum_{j=1}^{n_i} \sum_{k=1}^{p_j} t_{ijk} m_{ijk} x_{ijk},$$

where T – time expences associated with the production and supply of weapons to the combat zone;

T' – the time allowed for the production and delivery of weapons to the conflict zone;

t_{ijk} – is the time spent on the production and delivery of one sample of weapons of the i-th kind, j-th type by the k-th supplier.

$$W \leq W', \quad W = \sum_{i=1}^{N} \sum_{j=1}^{n_i} \sum_{k=1}^{p_j} w_{ijk} m_{ijk} x_{ijk},$$

where W – expenses for the production and supply of weapons to the combat zone;

W' – acceptable expenses;

w_{ijk} – are the expenses associated with the production and supply of one sample of weapons of the i-th kind, j-th type by the k-th arms supplier.

$$R \leq R', \quad R = \sum_{i=1}^{N} \sum_{j=1}^{n_i} \sum_{k=1}^{p_j} r_{ijk} m_{ijk} x_{ijk},$$

where R – risks associated with the production and supply of weapons to the combat zone;

R' – acceptable risks,

r_{ijk} – is the risk associated with the production and supply of one sample of weapons of the i-th kind, j-th type by the k-th supplier.

In this case, the following conditions must be met:

$$\sum_{k=1}^{p_j} x_{ijk} = 1,$$

which means the mandatory selection of a supplier for the i-th kind, j-th type of weapon.

An agent-based simulation model
for studying the logistics of weapons supply to establish military parity of forces

In order to calculate the time to create military parity of forces in the face of threats, a model has been created that allows simulating the logistics of military cargo transportation (applications in the simulation model), taking into account the emergence of threats and vulnerabilities, which leads to a possible stoppage of cargo movement to the combat zone. The agent-based model was created using the Any Logic simulation environment, taking into account the main events that occur during the transportation of military cargo. The transportation network for the supply of military cargo is represented as a graph G, in which the vertices are transport nodes and the edges are sections of the transportation highway. Possible transshipment and temporary storage of cargoes are considered in the form of corresponding modeling agents. The main agents in this simulation model for studying the logistics of military cargo supply to establish military parity of forces in the conflict zone are:

1) the agent describing the transportation network;
2) agent generating requests (military cargo);
3) agent of threats emergence;
4) agent of vulnerability perturbation;
5) agent for the route formation for the transportation of military cargo;
6) agent of transport hubs;
7) agent of the transportation highway sections;
8) agent of temporary storage (warehousing) of military cargo
9) transshipment agent
10) agent of time delays of military cargo (due to vulnerability perturbations);
11) risk agent
12) combat zone agent;
13) simulation control agent;
14) simulation results agent.

Fig. 5 shows a block diagram of the agent-based model.

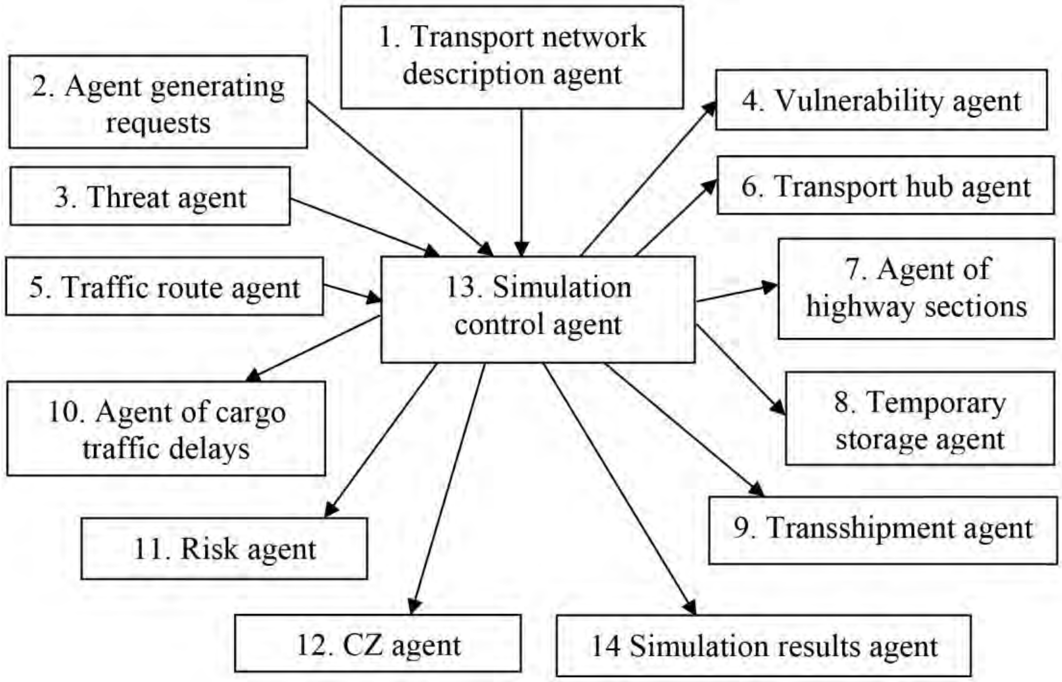

Fig. 5. Block diagram of the agent model

Let us briefly describe the simulation modeling algorithm. With the help of military experts, a transport network (or a fragment of it) is set to be used for the transportation of military cargo to the CZ in the form of sets of transport nodes and sections of a heterogeneous transport network (transport network description agent). Next, the time of the start of the military cargo movement along the transportation highway is set (agent – request generator). Then, with the help of the cargo route agent, the request (military cargo) is transported along the transport nodes and sections of the highway with the involvement of the transport node agent and the highway section agent. During the movement of the application (military cargo), vulnerabilities may be disturbed (vulnerability disturbance agent) due to the occurrence of threats (threat agent). This leads to a temporary delay in the application (military cargo) for a period related to the nature of the threat and the disturbed vulnerability. After the request (military cargo) arrives in the combat zone (CZ agent), the simulation is stopped and the results are displayed (simulation results agent) in the form of

– time of receipt of applications (military cargo) in the CZ;

– time spent on the transportation of military cargo along a given route (without perturbation / with perturbation of vulnerabilities);

– total time delays of military cargo;

– violation of the terms of delivery of military cargo to the CZ;

– time spent on transshipment;

– time spent on temporary storage (warehousing) of military cargo.

An algorithm for finding a route with the shortest possible time for the transportation of military cargo to the Czech Republic was developed. Subject to the availability of risk assessments proposed by military experts, an algorithm for the formation of accumulated risk in supply logistics in the CZ (risk agent) was developed.

The research conducted in the unit is related to the modeling of threats in the logistics process of forming military parity of forces in the combat zone. The identified shortcomings of existing methods that consider certain aspects of the process of establishing military parity do not allow a comprehensive solution to the problem. The author analyzes the threat factors associated with the lack of military parity of forces in the zone of military conflict. Military experts have evaluated various types of weapons to determine their impact on the balance of military forces in the CZ. Given the large number of possible options for choosing suppliers of weapons and military equipment, the method of integer (Boolean) programming is used. The following criteria are used to evaluate suppliers of weapons and military equipment: time, expencess and risks of production and supply. The article examines the sequence: threats – vulnerabilities – losses, which is associated with the emergence of threats in the logistics of production and supply of weapons and military equipment to establish military parity of forces in the conflict zone. It is found out how the emergence of the threat affects the perturbation of vulnerabilities in the logistics of production and supply of military equipment, which causes damage in the combat zone (deaths of personnel, disruption of defense infrastructure, transition from offensive to defensive actions, etc.) A method of increasing the efficiency of the use of weapons by means of modern types of weapons has been developed, which makes it possible to successfully achieve the goals of a combat operation in a conflict zone by creating an asymmetry in military parity of forces. An agent-based simulation model has been developed to study the logistics process of creating military parity of forces in a military conflict zone.

The proposed approach allows, when planning the objectives of a military operation, to formulate requirements for the production and supply of weapons and military equipment to establish military parity of forces in the combat zone, which contributes to the success of the military operation.

Modeling the logistics of high-tech weapons supply and military training

The subsection solves the problem of modeling logistics activities related to various military equipment and weapons entering the zone of military conflict. The relevance of the study is related to a comprehensive solution to the problem of logistics supply and the acquisition of skills in the use of modern weapons by the military to establish parity of forces in a military conflict zone. The purpose of the study is to create a method and models that allow analyzing the training of military personnel, the supply of weapons, ammunition and spare parts to the zone of military conflict for the successful achievement of the objectives of a military operation.

Establishing military parity of forces in a combat zone requires the use of various types of weapons supplied by manufacturers from different countries. This causes significant logistical difficulties and leads to problems related to the effective use of different types and types of weapons in a military conflict zone. The analysis conducted by military experts on the use of modern military equipment has revealed a number of problems that are not sufficiently covered in publications on this topic.

1. Small batches of various weapons coming from different suppliers to the area of military conflict. The available works do not consider the sources of supply of various types of military equipment [11].

2. Differences in ammunition coming from different suppliers that can be used only for specific types of weapons. Publications do not address this issue in detail [12].

3. Insufficient number of spare parts and repair kits that are supplied separately from the weapon. This problem is not addressed in published works [13].

4. Difficulties related to the repair of military equipment and routine maintenance in the area of military conflict. The removal of military equipment repair bases has not been given due attention in the current literature [14].

5. The need to conduct training of the military in a short time to acquire knowledge of the use of various types and types of new weapons. The problem of accelerated training of the military in a short time in the face of military threats is not considered in existing publications [15].

6. The problem associated with long logistics chains of supply of weapons and military equipment under martial law threats, through a heterogeneous transportation network with transshipment, temporary storage and warehousing of military cargo. Existing publications do not pay due attention to the supply of military equipment in the context of a heterogeneous transportation network and military threats [16].

An analysis of the literature on this topic has shown that there is no systematic study of the logistics problem of supplying military equipment to a military conflict zone. Insufficient attention is paid to the impact of military threats on logistics chains with critical vulnerabilities of transportation systems. The papers do not consider the modeling of military competencies necessary to acquire skills in the use of various modern weapons.

Hence the relevance of the topic of the proposed work, which models a set of logistics activities related to the supply, acquisition of skills and use of various types of modern weapons by the military in the combat zone.

There is a contradiction between the need to establish military parity of forces in the CZ through the use of modern weapons and the ineffectiveness of existing methods for studying the logistics processes of supplying, mastering, and using weapons in the combat zone. This problem is addressed in this paper [17].

In accordance with the aim of the study, the following tasks need to be solved:

1) to analyze the supply of various weapons from different manufacturers to the military conflict zone;

2) to create an optimization model for justifying and selecting suppliers of military equipment;

3) to develop a simulation model to study the logistics supply chains of military equipment;

4) to form a set of military competencies necessary for the use of new weapons systems;

5) to provide an example of choosing the composition of competencies for the use of a new combat system.

Analysis of the supply of various weapons to the military conflict zone

Let's form a systematic representation of the logistics processes associated with the supply of various types and types of weapons to a military conflict zone to establish military parity of forces.

Figure 6 shows a diagram of the logistics process of supply, which contains the main components of weapons:

– weapons

– ammunition

– spare parts.

Suppliers of different types and kinds of military equipment may be located in different countries and at a long distance from the conflict zone. An example is the geography of suppliers of various artillery weapons: M777 towed howitzers (USA, Austria, Canada), self-propelled howitzers (Caesar (France), Panzerhaubitze (Germany), M109 (USA), ANS Krab (Poland)).

Spare parts suppliers have limited capacity to produce and supply (small batches) for the needs of the frontline.

Ammunition is not always interchangeable, so it can only be used for specific types of weapons. For example, different calibers of 102, 122, 105, 152, 155.

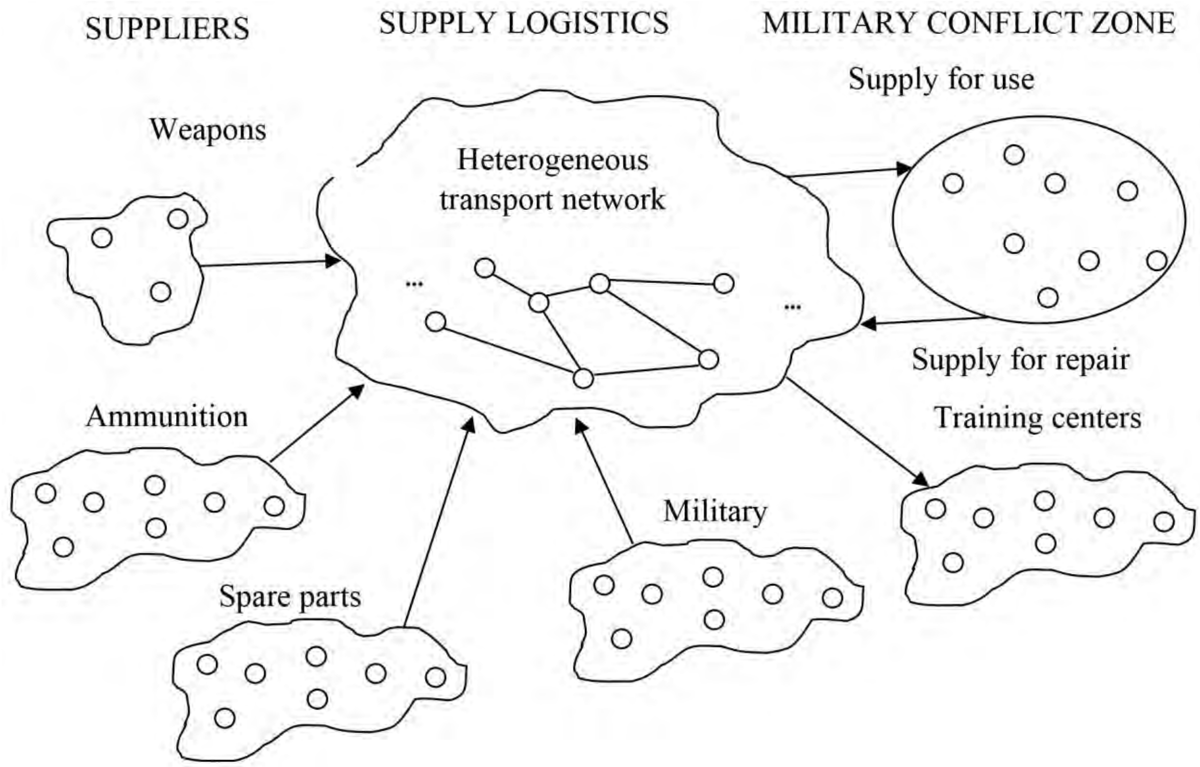

Fig. 6. Logistics scheme for the supply of weapons and military equipment

Spare parts and repair kits are not always supplied in the required quantity with weapons and military equipment. The lack of spare parts can lead to the failure of weapons in the conflict zone. To repair military equipment, it must be sent to the manufacturer.

Supply logistics is carried out in long logistics chains of a heterogeneous transportation network (air, rail, road, sea), which leads to transshipment from one transportation route to another, as well as temporary storage of military cargo.

This nature of the logistics of supplying weapons, spare parts, and ammunition to the combat zone results in

– long and complicated logistics supply chains;

– detentions during movement across state borders, as well as when changing from one mode of transportation to another;

– detentions related to the temporary storage of weapons and military equipment;

– threats to the transportation of military cargo related to the actions of the aggressor;

– the need to assess the risks that arise in elements of a long logistics supply chain in wartime. In the event of damage and failure of weapons, there are difficulties in repairing them, which requires specialists who are not available in the combat zone. Therefore, it is necessary to transport damaged military equipment to manufacturers located at a great distance from the military conflict zone.

In addition to the logistical problems of supplying weapons and military equipment, there is the task of acquiring skills in the use of new types and types of weapons in wartime. The solution to this problem is to accelerate the training of personnel in training centers. In the course of such activities, it is necessary to add new, special competencies related to modern types and types of weapons to the basic competencies of the military. At the same time, it is necessary to carry out logistical actions related to the transportation of military personnel to training centers in the face of wartime threats.

A systematic presentation of logistics activities related to the supply of weapons and preparation of the military for their use has been formed. This is the basis for solving the tasks of our study.

Optimization model for selecting military equipment suppliers

The formation of a plurality of suppliers of weapons, ammunition and spare parts to create military parity of forces in the conflict zone requires an analysis of the capacity of each supplier and consideration of logistics activities related to the transportation of military cargo in wartime.

To assess the capacity of producers, it is necessary to take into account the formation of groups of suppliers of a particular type and type of weapon, since one supplier cannot deliver the required quantity of weapons due to production limitations and financial conditions related to new defense orders. Formation of a set of possible composition of a group of suppliers for the i-th kind and j-th type of weapon is a combinatorial problem of searching for options, taking into account the limited capabilities of each manufacturer.

Suppose, for example, that military specialists (experts), after analyzing manufacturers for the i-th kind and j-th type of weapon, have identified three possible suppliers. Then the number of possible variants of the composition of suppliers in their group for $n=3$ will be $K=2^n-1=7$. For $n=3$, all variants of the composition of arms suppliers within their group can be represented as values of a binary counter:

1. 001
2. 010
3. 011
4. 100
5. 101
6. 110
7. 111

where 1 corresponds to the involvement of the manufacturer in the group of suppliers; 0 – no involvement.

Here, option 1 corresponds to the involvement of only one (third) possible arms supplier in the group of suppliers, option 3 – to the involvement of the second and third suppliers, option 7 – to the involvement of all arms suppliers.

Let's introduce an integer (boolean) variable x_{ijk} that takes the following values:

$$x_{ijk} = \begin{cases} x_{ijk} = 1, \; \textit{if the j-th type of weapon} \\ \qquad \textit{and its k-th supplier are selected for the i-th type of weapon;} \\ x_{ijk} = 0, \; \textit{otherwise}. \end{cases}$$

where $\sum_{k=1}^{P_j} x_{ijk} = 1$, which means the mandatory selection of a specific group of suppliers for the i-th kind and j-th type of weapon, P_j is the number of possible options for suppliers of the j-th type of weapon.

Let's introduce the following indicators to assess the options for the composition of the supplier group:

N – the number of weapons to be sent to the zone of military conflict:

$$N = \sum_{i=1}^{M} \sum_{j=1}^{m_i} n_{ij},$$

where n_{ij} – is the number of weapons of the i-th kind and j-th type to be used in the CZ;

m_i – number of types of weapons of the i-th type;

M – the number of types of weapons to be used in the zone of military conflict.

Taking into account the variable x_{ijk}, we obtain

$$n_{ij} = \sum_{k=1}^{P_j} n_{ijk} x_{ijk},$$

where n_{ijk} – is the number of weapons of the i-th kind and j-th type to be supplied by the k-th variant of the composition of the group of suppliers;

T – time spent on the production and logistics of transportation of weapons to the zone of military conflict:

$$T = \sum_{i=1}^{M} \sum_{j=1}^{m_i} t_{ij},$$

where $t_{ijk} = t'_{ijk} + t''_{ijk}$;

t_{ijk} – time expenses associated with the production and logistics of supply of the k-th variant of the warehouse of the group of producers of the i-th kind and j-th type of weapons;

t'_{ijk} – time for the production of a batch of weapons of the i-th kind and j-th type by the k-th manufacturer's warehouse;

t''_{ijk} – time spent on the logistics of transportation of a batch of weapons of the i-th kind and j-th type by the k-th manufacturer's warehouse.

Taking into account x_{ijk}

$$t_{ij} = \sum_{k=1}^{P_j} \left(t'_{ijk} + t''_{ijk} \right) x_{ijk}.$$

W – expenses for the production and supply of weapons:

$$W = \sum_{i=1}^{M} \sum_{j=1}^{m_i} w_{ij},$$

where w_{ijk} – expences of production and logistics of supplying weapons of the i-th kind and j-th type for the k-th variant of the supplier's warehouse:

$$w_{ijk} = w'_{ijk} + w''_{ijk},$$

where w'_{ijk} – expences of production of weapons of the i-th kind and j-th type for the k-th variant of the supplier warehouse;

w''_{ijk} – are the logistics expenses for the supply of weapons of the i-th kind and j-th type for the k-th variant of the supplier's warehouse.

Then, taking into account x_{ijk}

$$w_{ij} = \sum_{k=1}^{P_j} \left(w'_{ijk} + w''_{ijk} \right) x_{ijk}.$$

R – risks of production and supply of weapons to the military conflict zone:

$$R = \sum_{i=1}^{M} \sum_{j=1}^{m_i} r_{ij},$$

where r_{ijk} – risks of supplying the k-th variant of the warehouse of suppliers of the i-th kind and j-th type of weapons:

$$r_{ijk} = r'_{ijk} + r''_{ijk},$$

where r'_{ijk} – production risks of the i-th kind and j-th type for the k-th variant of the supplier's warehouse;

r''_{ijk} – logistics risks of supply of the i-th kind and j-th type for the k-th variant of the supplier's warehouse:

$$r_{ij} = \sum_{k=1}^{P_j} \left(r'_{ijk} + r''_{ijk} \right) x_{ijk}.$$

Taking into account all kinds and types of weapons that will be sent to the area of military conflict, we will get the following presentation of indicators for evaluating possible suppliers:

$$N = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{P_j} n_{ijk} x_{ijk},$$

$$T = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{P_j} \left(t'_{ijk} + t''_{ijk} \right) x_{ijk},$$

$$W = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{P_j} \left(w'_{ijk} + w''_{ijk} \right) x_{ijk},$$

$$R = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{P_j} \left(r'_{ijk} + r''_{ijk} \right) x_{ijk}.$$

To ensure military parity of forces in a military conflict zone, it is necessary to

$$\max N, \quad N = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{P_j} n_{ijk} x_{ijk},$$

taking into account the following restrictions:

$$T \le T', \quad T = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{P_j} \left(t'_{ijk} + t''_{ijk} \right) x_{ijk},$$

$$W \le W', \quad W = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{P_j} \left(w'_{ijk} + w''_{ijk} \right) x_{ijk},$$

$$R \le R', \quad R = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{P_j} \left(r'_{ijk} + r''_{ijk} \right) x_{ijk},$$

where T' – the time allowed for the production and logistics of arms supply to the area of military conflict;

W' – acceptable expences associated with the production and logistics of supplying weapons to the combat zone;

R' – acceptable risks associated with the production and logistics of arms supply in CZ.

It is known that new weapons (e.g. HIMARS), due to their tactical and technical characteristics (range, accuracy, etc.), can affect the effectiveness of their use in a military conflict zone by creating an asymmetry of military parity of forces (superiority of quality over quantity).

Therefore, it is necessary to take into account the combat capability of each type of weapon on the battlefield.

Let military specialists (experts) estimate the combat effectiveness e_{ij} of each sample of the i-th kind and j-th type of weapon.

Then, for all weapons that will be sent to the CZ, the combat capability is represented as:

$$E = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{P_j} n_{ijk} e_{ij} x_{ijk}.$$

To successfully achieve the objectives of a military operation in a conflict zone, it is necessary to

$$\max E, \quad E = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{P_j} n_{ijk} e_{ij} x_{ijk},$$

taking into account the restrictions:

$$T \le T', \quad T = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{P_j} \left(t'_{ijk} + t''_{ijk} \right) x_{ijk},$$

$$W \le W', \quad W = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{P_j} \left(w'_{ijk} + w''_{ijk} \right) x_{ijk},$$

$$R \le R', \quad R = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{P_j} \left(r'_{ijk} + r''_{ijk} \right) x_{ijk},$$

Note that the estimates for e_{ij}, t'_{ijk}, t''_{ijk}, w'_{ijk}, w''_{ijk}, r'_{ijk}, r''_{ijk} should be submitted by military experts for all types and types of weapons in advance in order to solve the optimisation problem.

A simulation model for studying the logistics supply chains of military equipment in a military conflict zone

To study the dynamic processes in the logistics of supplying weapons, ammunition and spare parts to a military conflict zone, a simulation model has been created that allows to form supply routes under the risks of war, estimate the time required for the transportation of military cargo, and predict the risks arising from the threats of martial law.

Supply routes are formed by military logistics specialists. If it is necessary to optimise delivery time or risks, an algorithm is created to minimise delivery time in a heterogeneous transport network and to form a rational route taking into account wartime risks. For modelling, the Any Logic system was used to create an agent-based simulation model. This model contains the following agents (Fig. 7):

1) agent "formation of the structure of the transport network" (transport hubs and sections of the transport highway);
2) agent "arms supplier"
3) agent "transport hub";
4) agent "section of the transport highway" (TH);
5) agent "time delay"
6) agent "time limit"
7) agent "temporary storage";
8) agent "time stop";
9) agent "combat zone" (CZ);
10) agent "threat";
11) agent "vulnerability"
12) agent "destruction of military munitions";
13) agent "risks"
14) "risk restriction" agent
15) agent "delivery route";
16) agent "optimisation of delivery time";
17) "delivery risk optimisation" agent;

18) simulation control agent;
19) simulation results agent.

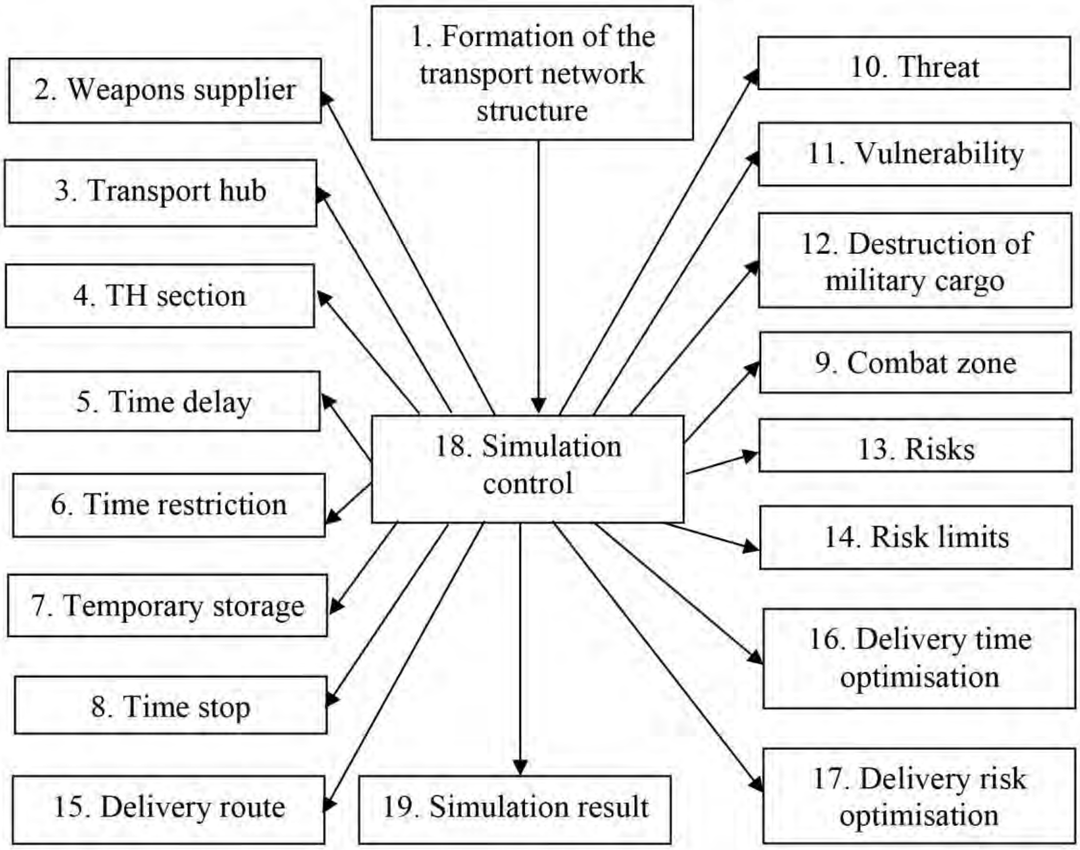

Fig. 7. Block diagram of the agent-based model

Let us briefly describe the modelling algorithm.

First, the transport network is set up using the "transport network structure formation" agent. Then, to simulate the supply route, the supply route agent sets the required route. The "supply of weapons" agent forms a batch of military cargo with weapons in the form of a request in the simulation. The next step is to create a sequence of requests through transport hubs (the "transport hub" agent) and sections of the transport network (the "transport highway section" agent) in accordance with the specified supply route, taking into account delays (the "time delay" agent), as well as stops (the "time stop" agent) and the required time for storage (the "temporary storage" agent). In the process of transporting military cargo, logistics risks are accumulated using the "risks" agent. The "threat" agent is used to study the impact of threats on the logistics of military cargo supply. The occurrence of a threat leads to a perturbation of a critical vulnerability (the "vulnerability" agent), which is associated with critical nodes and sections of the transport route, causing temporary stops of military cargo (the "temporary stop" agent), as well as possible destruction of cargo (the "destruction of military cargo" agent). To solve the optimisation problems of routing in a heterogeneous transport network, the developed route optimisation algorithms are used, which are used to:

1) search for the minimum time route in terms of wartime risks;

2) searching for the minimum risk route in terms of delivery time constraints.

In order to find the minimum time route with due regard to risks, the developed optimisation algorithm observes "waves" of orders and their clones that are formed in the transport nodes of the supply network. When developing a route that minimises the risk of delivery, the main factor taken into account is the risk of delivery. The algorithms for optimising supply routes use the delivery time optimisation and delivery risk optimisation agents, taking into account the constraints set by the time constraint and risk constraint agents.

The modelling results agent generates the following research results:

1) time of movement of military cargo (consignment of weapons) for a given delivery route to the CZ;

2) time of delay of the military cargo in terms of delivery to the conflict zone;

3) accumulated logistical risks of military cargo delivery;

4) the time-optimal route for the supply of weapons;

5) the optimal route for the delivery of military cargo in terms of risk;

6) the term of delivery of cargo to the CZ in the event of a threat;

7) military munitions that have been delayed due to threats;

8) military munitions that were destroyed due to threats.

Formation of a set of military competences for the use of new weapons systems

In order to successfully achieve the objectives of a military operation in a combat zone, it is necessary to form a set of weapons that surpasses the enemy's weapons in terms of their combat capability through the use of modern combat systems (e.g., HIMARS MLRS). This can lead to asymmetry and the advantage of forces in military parity in the zone of military conflict (quality over quantity). The use of new high-tech weapon systems requires the acquisition of new competencies in the military. A structural representation of the competences associated with the use of a new type of weapon is shown in Fig. 8. Here, the basic competences are associated with known types of military equipment and are components of the set of competences inherent in personnel. Special new competences arise in the process of using modern weapons. Acquiring new competences requires training in special training centres to acquire new knowledge (K), develop new skills (S) and strengthen their abilities (A). The training centres are located far from the combat zone, which requires transporting military personnel, especially in the face of military threats. Training centres need to develop new knowledge in a short time by using modern teaching methods (automated training systems, simulators, practical training at special training grounds, etc.). Given the martial law and active hostilities in the conflict zone, it is necessary to reduce the training time for the military to train on new weapons systems and minimise the risks of martial law.

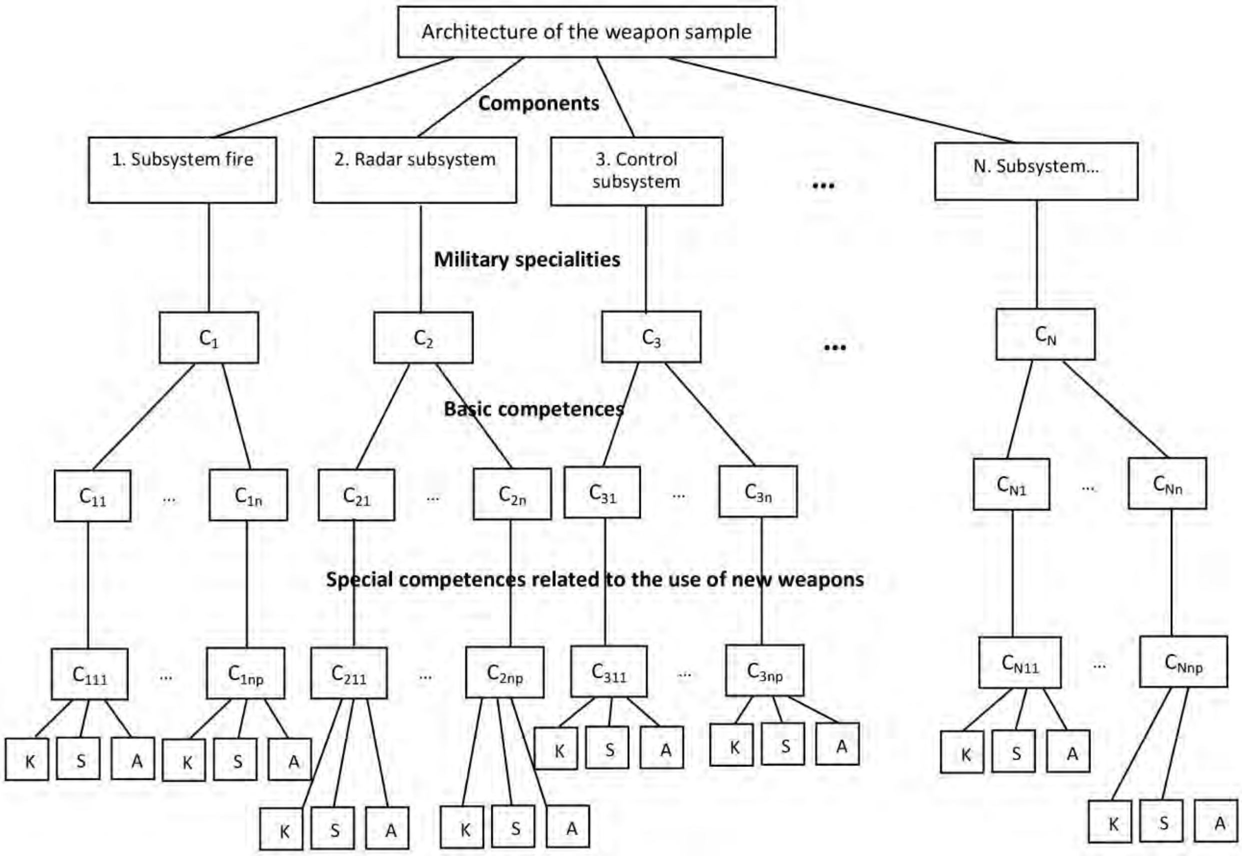

Fig. 8. Structure of competences required by the military to use new weapons

Suppose that there is a gap Δ_{ijk} in the knowledge of the military and the competences required to use modern weapons. It is important to eliminate this difference during the training of the military. It is necessary to choose the right set of competences that will provide effective training. We will measure Δ_{ijk} for the i-th kind of the j-th type of the possible k-th competence composition using military experts' estimates. For example, $\Delta_{ijk} = 0$ means there is no difference between competences, and $\Delta_{ijk} = 10$ (in points) corresponds to a complete mismatch of competences (new competences that the military did not have before). Suppose that military experts believe that after the training, there will be a difference in competences $\Delta'_{ijk} \leq \Delta_{ijk}, \Delta'_{ijk} \to 0$, for all i, j, k. Let's introduce an integer (Boolean) variable x_{ijk}, the value of which $x_{ijk} = 1$ means that for the k-th competence set, training is required to master a new type of weapon of the i-th kind of the j-th type. And for $x_{ijk} = 0$, no training is required, because such a composition will not be used or the military knows it.

As the target optimisation function, we will use the total number of points Q, which must be minimised in the process of selecting a possible composition of competences for the acquisition of military skills in the use of new types of weapons. Taking into account all types and types of weapons that will be used in a military conflict zone, we will get:

$$Q = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{s_j} \Delta'_{ijk} x_{ijk},$$

where s_j – is the number of possible variants of the composition of competences, from which one must be selected to acquire knowledge of using a new weapon of the j-th type of the i-th kind;

m_i – the number of types of the i-th kind of weapon;

M – number of types of weapons used in the area of military conflict. In this case, $\sum_{k=1}^{s_j} x_{ijk} = 1$, which means that it is mandatory to choose one k-th variant of the competence composition for training in the acquisition of the i-th kind of j-th type of weapon.

In the process of training the military, it is necessary to minimise the total difference in competences:

$$\min Q, \quad Q = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{s_j} \Delta'_{ijk} x_{ijk}.$$

When optimising Q, it is necessary to take into account the constraints on training time – T, then on wartime risks – R, and then on the expenses of training centres during training – W:

$$T \leq T', \quad T = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{s_j} t_{ijk} x_{ijk},$$

$$R \leq R', \quad R = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{s_j} r_{ijk} x_{ijk},$$

$$W \le W', \quad W = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{s_j} w_{ijk} x_{ijk},$$

where t_{ijk} – is the time to prepare the k-th possible set of competences for studying a new type of weapon of the i-th kind of the j-th type;

r_{ijk} – is the risk of preparing to acquire the k-th set of competences for a new weapon of the i-th kind of the j-th type;

w_{ijk} – is the expence of training the military and acquiring the k-th set of competences to use a new type of weapon of the i-th kind of the j-th type;

T', R', W' – acceptable time, risks and expenses for military training.

If, due to the needs of martial law, it is important to conduct accelerated training of the military, then it is necessary

$$\min T, \quad T = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{s_j} t_{ijk} x_{ijk},$$

taking into account the restrictions:

$$Q \le Q', \quad Q = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{s_j} \Delta'_{ijk} x_{ijk},$$

$$R \le R', \quad R = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{s_j} r_{ijk} x_{ijk},$$

$$W \le W', \quad W = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{s_j} w_{ijk} x_{ijk},$$

where Q' – the permissible difference in the competencies required to use new weapon systems and the competencies that military personnel will acquire through training in training centres.

The logistical task of delivering military personnel to training centres under wartime threats is solved by using the developed method of agent-based simulation modelling.

When studying and using new weapons by the military, we will pay attention primarily to the combat capability of types and types of weapons, which will further increase the effectiveness of weapons in a military conflict zone. In this case, in the formulation of the optimisation problem of military training, it is necessary to take into account the combat effectiveness e_{ij} of each sample of the i-th kind of the j-th type of weapon. At the same time, it is necessary to normalise the value of combat capability e_{ij}:

$$e'_{ij} = \frac{e_{ij}}{\sum_{i=1}^{M} \sum_{j=1}^{m_i} e_{ij}}, \qquad \sum_{i=1}^{M} \sum_{j=1}^{m_i} e'_{ij} = 1.$$

We will use e'_{ij} as a value indicating the need to train the military primarily in the use of the most effective modern weapons. Therefore, taking into account the combat capability of weapons, the following should be included in the training of the military

$$\min Q = \sum_{i=1}^{M} \sum_{j=1}^{m_i} e'_{ij} \left(\sum_{k=1}^{s_j} \Delta'_{ijk} x_{ijk} \right),$$

following the restriction:

$$T \le T', \quad T = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{s_j} t_{ijk} x_{ijk},$$

$$R \le R', \quad R = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{s_j} r_{ijk} x_{ijk},$$

$$W \le W', \quad W = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{s_j} w_{ijk} x_{ijk}.$$

An example of selecting the content of competences for the use of a new combat system

Let's consider an illustrated example of the military training for the use of a new multiple launch rocket system (HIMARS) under martial law.

A modern MLRS consists of three main subsystems:

– control

– radar;

– fire.

To use each of the subsystems, it is necessary to train military personnel of the relevant specialities. In particular, it is about acquiring new competencies in the use of modern MLRS. For the convenience and simplicity of comparing possible variants of the competencies required for training the military, we will use qualitative assessments in the form of values of linguistic variables: training time – x_1, risks associated with the logistics of training the military – x_2 and expenses required for the operation of the military training centre – x_3:

$$x_1 = \begin{cases} A - \textit{minimum training time;} \\ B - \textit{satisfactory training time;} \\ C - \textit{acceptable training time;} \\ D - \textit{maximum training time.} \end{cases}$$

$$x_2 = \begin{cases} A - \textit{minimum training risk;} \\ B - \textit{satisfactory training risk;} \\ C - \textit{acceptable training risk;} \\ D - \textit{maximum training risk.} \end{cases}$$

$$x_3 = \begin{cases} A - \textit{minimum expences} \\ B - \textit{satisfactory expences;} \\ C - \textit{acceptable expences;} \\ D - \textit{maximum expences.} \end{cases}$$

The difference in competences will be estimated as a percentage.

There are three main types of competences that military personnel need to acquire to use the new MLRS in the form of knowledge, skills and abilities:

1) basic principles of subsystem operation (knowledge);

2) detailed presentation of the subsystem's combat operation (skills);

3) regulations on the use and operation of the subsystem (abilities).

Table 2 shows the assessments of military specialists (experts) on possible variants of the content of competences for the study of the main MLRS subsystems by the military.

Let us analyse the results of the experts' assessment of possible options for the content of competences to justify and select the best option necessary for military training.

When analysing the options for the content of competences for the three main MLRS subsystems, the experts excluded from consideration options 2, 4, 6 for all subsystems. This is due to the absence of the third competence in the competence structure, related to the skills of using the subsystem in combat conditions.

In addition, due to the low and unacceptable D scores in some variants of the competence composition, the experts excluded the following variants of the competence content from further consideration:

– in the management subsystem

Option 3 due to unacceptable values of expenses (D);

Option 7 due to unacceptable values of time (D) and risks (D);

– in the radar subsystem:

Option 3 due to long training time (D);

Option 7 due to unacceptable values of time (D) and training risks (D);

– in the fire control subsystem:

Option 3 due to unacceptable values of training time (D);

Option 7 due to unacceptable values of time (D), risks (D) and training expenses (D).

Table 2

Evaluation of options for the content of competences for military training

Subsystems	Variants	Competences			Difference in competencies (%)	Training time	Training risks	Training expences
		1	2	3				
1. Control	1	–	–	+	35	A	A	A
	2	–	+	–	–			
	3	–	+	+	20	C	B	D
	4	+	–	–	–			
	5	+	–	+	25	B	B	C
	6	+	+	–	–			
	7	+	+	+	10	D	D	C
2. Radar	1	–	–	+	30	A	A	A
	2	–	+	–	–			
	3	–	+	+	20	D	C	B
	4	+	–	–	–			
	5	+	–	+	25	B	B	B
	6	+	+	–	–			
	7	+	+	+	10	D	D	C
3. Fire	1	–	–	+	25	A	A	A
	2	–	+	–	–			
	3	–	+	+	10	D	C	B
	4	+	–	–	–			
	5	+	–	+	15	B	B	B
	6	+	+	–	–			
	7	+	+	+	5	D	D	D

Furthermore, the experts noted a large unsatisfactory difference in competences:

1st variant of the competencies content in the control subsystem (35%),

1st variant of the competencies in the radar subsystem (30%).

These options were also removed from further consideration. As a result, the following options for the possible composition of competencies required for the military to study the main subsystems of the new MLRS remained:

5, 5, 1

5, 5, 5

These variants have the following scores (see Table 1):

5, 5, 1:

25 %, B, B, C;

25 %, B, B, B;

25 %, A, A, A.

5, 5. 5:

25 %, B, B, C;

25 %, B, B, B;

15 %, B, B, B.

Finally, variant 5, 5, 5 was chosen to prepare the military for the use of MLRS.

The study of this subsection is related to the modelling of the logistics process of supplying and studying new weapons by the military to successfully achieve the goals of a military operation in a combat zone. The problems of using various weapons were identified. A systematic representation of the logistics of weapons supply to a military conflict zone has been created, which is used in the future to solve the main tasks of the study. The issue of optimal selection of suppliers of weapons, spare parts and ammunition for combat operations is identified and resolved, taking into account the effectiveness of the use of weapons, time, expences and logistical risks. In this case, the use of several possible manufacturers of military equipment for the same kind and type of weapon is taken into account. An agent-based simulation model was created in the Any Logic environment, which takes into account the main components of the logistics process of supply: transport network, time delays, and supply routes. The article optimises the choice of a supply route in the face of threats and perturbations of critical vulnerabilities in the supply process in a heterogeneous transport network. Using a simulation agent model, a rational route for the supply of weapons and military equipment is formed, the time and expences of supply are estimated, and the impact of threats on the delivery time is taken into account. To ensure the effective use of new weapons and military equipment, the article examines the process of training military personnel using a set of competencies that must be mastered in training centres in a short time under the threats of martial law and logistical risks. An example of training the military to use modern weapons such as MLRS is presented.

The proposed approach makes it possible to plan the supply of new and diverse weapons to the area of military conflict in order to select a rational composition of military equipment manufacturers.

Modelling the formation of the necessary stocks of high-tech military equipment

The subsection solves a systemic problem related to the modelling of the logistics of stockpiling weapons and military equipment (WME) for the successful execution of combat operations. The relevance of the study is related to a comprehensive solution to the problem of stockpiling WME to meet the objectives of a military operation, taking into account the capabilities of arms suppliers, the complex logistics of transporting WME to the conflict zone and military threats. The purpose of the study is to create a set of models that allow to prioritise the types of WME in stockpiling; to formulate requirements for the volume of stocks; to choose a rational structure of logistics supply channels, taking into account the risks of military threats, which ensures the success of combat operations in the conflict zone.

The escalation of hostilities in a military conflict zone requires constant replenishment of the WME, which ensures effective combat operations against the aggressor. The current inventory theory, whose methods are used in the production of sophisticated equipment, is associated with the planned replenishment of components and raw materials to fulfil orders from high-tech enterprises and ensure the continuity of the production cycle.

Analysis of the problems of stockpiling in wartime

Under martial law, the availability of WME stockpiles is one of the key requirements for effective combat operations. The enemy's opposition to the formation of WME stockpiles (war of stockpiles) is one of the manifestations of the so-called hybrid warfare. Lack of the required amount of WME stocks can lead to deaths of military personnel, disruption of defence and engineering structures, transition from offensive to defensive actions, etc. Therefore, the requirements for the formation and replenishment of WME stocks and their size differ from the requirements for the formation of stocks in peacetime. The aggressor's actions in the process of stockpiling in a modern hybrid war, which uses the most advanced types of WME, are aimed at destroying both logistics and stockpiles (war of logistics and stockpiles).

There are a number of problems associated with the formation of stocks and management of WME supply logistics, which are covered in publications on this topic. Let us consider these problems.

1. WME stockpiles are formed by a large number of manufacturers (suppliers) that can supply weapons in small batches. This complicates the management of WME supply logistics. Publications consider the supply of WME in peacetime to form planned stockpiles in case of war, but not during hostilities [18].

2. The supply of WME to a military conflict zone involves long logistics chains in a heterogeneous transport environment, which require a lot of time for supply and stockpiling. In publications, planning and stockpiling is often considered in the process of supplying weapons by developers located at a short distance from the zone of military conflict, and therefore does not require the formation of long logistics chains [19].

3. In long logistics supply chains, the formation of WME stockpiles creates many possible vulnerabilities caused by the emergence of military threats. Publications consider logistics vulnerabilities that arise mainly in peacetime. Little attention has been paid to the study of the impact of military threats on logistical vulnerabilities in the supply of weapons to the CZ [20].

4. Under martial law, a number of supply risks arise due to military threats. This leads to a disruption in the formation of the necessary volumes of WME stocks for use in the CZ at the right time. The increase in the number and variety of risks associated with martial law has received little attention in existing publications [21].

5. In the heterogeneous environment of WME supply to the combat zone, a large number of transshipment of military cargo occurs, which leads to delays and increased time for the supply of weapons. Publications consider transshipment in peacetime, without the influence of military threats [22].

6. The formation of insurance and planned stocks in peacetime differs from the formation of WME stocks for use in the CZ during martial law. In the publications, insurance stockpiles are linked to peacetime arms production plans in accordance with the state's military doctrine. The size of the reserve stockpile of weapons in the CZ and its replenishment in wartime depends on the situation at the front and the objectives of the military operation [23].

Consequently, there is a contradiction between the requirements for successful operational and tactical actions by the military in the zone of military conflict using the available stocks of weapons, as well as their prompt replenishment, and the imperfection of existing methods of planning and managing WME stocks in wartime conditions. This requires the development of a set of models and applied information technology aimed at studying the formation and operational replenishment of WME stocks.

Therefore, it is relevant to create a set of models that will allow analysing the logistics of stockpiling, taking into account the required volume, justifying logistics supply channels in a heterogeneous transport environment in the face of threats during martial law in the country to ensure the effectiveness of combat operations and fulfil the objectives of a military operation in the CZ [24]. In accordance with the research objective, the following tasks need to be solved:

1) to analyse the priority of weapon types for the formation of military equipment stocks in the combat zone;

2) to develop an optimisation model for the formation of weapons stocks, taking into account the capabilities of manufacturers and suppliers;

3) to list the set and justify the structure of logistics supply channels for the formation of the necessary stocks of weapons;

4) to form the necessary stocks of weapons in the area of military conflict, taking into account the combat capability of individual models;

5) give an example of modelling the logistics of stockpiling weapons and military equipment, considering the risks of wartime.

Analysing the priority of weapons types in the process of forming stocks of military equipment in the combat zone

The requirements for the formation of WME stocks are linked to the plans of operational and tactical actions of the military, as well as the current situation at the front. Therefore, the nomenclature of WME, its quantity and the ability to train military specialists to use the weapon will be determined in each specific area of the front depending on the requirements for establishing military parity of forces.

Given that effective and powerful modern WME systems (e.g., HIMARS, NASAMS, etc.) can be used in a certain area of the frontline, by creating an asymmetry in military parity of forces (quality over quantity), it is possible to conduct successful combat operations with fewer weapons.

Therefore, it is important to determine the most effective models for the formation of WME stocks for successful use in a particular combat zone.

Let us use the method of planning an experiment, which allows us to determine the most effective weapons for use in the CZ by using expert (military) assessments and conducting virtual experiments.

Table 3 shows the plan of a full factorial experiment (FFE), in which the factors are the types of weapons that can be used in a zone of military conflict.

Each row of the plan represents a possible combination of weapons used.

In Table 3, "–" indicates the absence of a factor, "+" – its presence.

The total number of variants of factor composition: $N = 2^n$, where n is the number of factors.

The experts' ratings are presented in the rightmost column of the FFE (points or % can be used).

Table 3

Full factorial experiment to assess the combat effectiveness of weapons

№	Factors			Feedback (combat capability)
	x_1	x_2	x_3	
1	–	–	–	0
2	–	–	+	3
3	–	+	–	2
4	–	+	+	6
5	+	–	–	5
6	+	–	+	8
7	+	+	–	7
8	+	+	+	10

As a result of the virtual experiment, using expert assessments, a regression dependence is formed in the form $(n=3)$:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{123}x_1x_2x_3 .$$

The coefficient b_j, $j = \overline{1,n}$ indicates the significance of the factor x_j. We will form a series according to the decreasing significance of the coefficient b_j. This way, we can form the most priority types of weapons that should be used in a particular CZ. For example, let the factor x1 be related to the HIMARS MLRS, x_2 to the JAVELIN anti-tank system, and x_3 to the CAESAR self-propelled artillery system.

After the experts' assessment of the possible variants of the weapons composition, the following simplified linear regression relationship can be obtained:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 = 5.1 + 2.4x_1 + 1.1x_2 + 1.6x_3.$$

After analysing the obtained dependence, it can be concluded that the most important factor for use in the CZ is x_1 (HIMARS), less important is x_3 (CAESAR) and the least important is x_2 (JAVELIN).

Therefore, taking into account the priority weapons, it is necessary to build up WME stocks in the CZ.

An optimisation model of weapons stockpile formation taking into account the capabilities of manufacturers and suppliers

In peacetime, the formation of arms stocks is carried out in accordance with state defence procurement plans. To ensure successful implementation of arms production plans, stocks of components, materials and raw materials (CMRM) Z are formed in the range of:

$$Z_{\max_{\min}},$$

where $Z_{\min}$ corresponds to the CMRM safety stock, the current value of Z corresponds to the planned CMRM stock, taking into account the safety stock, and $Z_{\max}$ corresponds to the stock, the value of which is associated with minimising risks of various nature (including logistics) that may lead to possible disruptions or interruption of the production cycle.

In wartime, the formation of weapons stockpiles is carried out in the context of military threats in accordance with tactical plans and operational actions in the conflict zone. In addition, it is necessary to take into account the limited capabilities of WME suppliers (manufacturers) (small batches of manufactured weapons, long production cycle, small production stocks, etc.), which leads to difficulties in supplying the required quantity in the required time frame. In turn, this can lead to deaths of military personnel, changes in hostilities, damage to defence and engineering structures, etc. Therefore, it is important to solve the problem of forming the required level of WME stocks, taking into account the requirements for types of weapons, volumes and terms of supply. Given that for each j-th type of WME, not one supplier but a set of no suppliers can be used in the process of stockpiling, which is associated with the possibility of producing and supplying military products, the task of choosing a rational composition of suppliers to form the required level of stocks Z, where $Z_{\max_{\min}}$, arises. Here, the value of the stock $Z_{\min}$ corresponds to the insurance level of stocks in time of war, which guarantees the establishment of military parity of forces in the face of military threats. The value of the reserve $Z_{\max}$ ensures minimisation of the risks associated with military threats and creates a possible asymmetry in the military parity of forces, which contributes to the successful achievement of the objectives of the planned combat operation. The limited capabilities of arms manufacturers and suppliers (small batches) must be taken into account when forming the $Z_{\max}$ stockpile.

Variants of the composition of WME suppliers can be generated by a full search of $N = 2^n - 1$, where n is the possible number of WME suppliers.

Let's introduce a Boolean variable x_{jk}:

$$x_{jk} = \begin{cases} 1, \textit{ if the k-th variant of the supplier's warehouse} \\ \quad \textit{was used for the j-th type of WME;} \\ 0, \textit{ otherwise}. \end{cases}$$

We will use the following indicators in the process of forming the WME stock Z, $Z\max_{\min}$, taking into account wartime risks:

Z is the value of the WME stock formed in the CZ;

T is the total time spent on the formation of WME stockpiles in the CZ;

R is the risk of military threats arising in the process of stockpiling WME in the CZ during martial law.

Due to the long front line, there may be not one but several CZs in the area of military conflict. Therefore, the volume of Z stocks is

$$Z = \sum_{i=1}^{M} z_i,$$

where z_i – corresponds to the WME stock for the i-th CZ;

M is the number of WME in a CZ.

Taking into account all WME in the CZ, as well as the types of weapons entering the conflict zone, we obtain the following expression:

$$Z = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{n_i} l_{ijk} m_{ijk} x_{ijk},$$

where $Z_{\max_{\min}}$;

l_{ijk} – is the size of the supply batch associated with the k-th supplier warehouse for the j-th type of WME to form stocks in the i-th CZ;

m_{ijk} – is the number of supply batches associated with the limited capacity of WME suppliers for the k-th warehouse of suppliers of the j-th type of WME for the i-th CZ.

Let us introduce the variable x_{ijk}:

$$x_{ijk} = \begin{cases} 1, \text{if the k-th supplier warehouse is selected} \\ \quad \text{for the j-th type of WME, for the i-th WBD;} \\ 0, \text{otherwise.} \end{cases}$$

Then the total time to build up WME's inventory in CZ is

$$T = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{n_i} m_{ijk} t_{ijk} x_{ijk},$$

where t_{ijk} – is the time spent on the supply of one batch of WME by the k-th supplier warehouse for the j-th type of WME for the i-th CZ.

Risks of WME stockpiling associated with possible threats of martial law:

$$R = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{n_i} m_{ijk} r_{ijk} x_{ijk},$$

where r_{ijk} – is the risk of supplying one batch of WME by the k-th supplier warehouse for the j-th type of WME to form stocks in the i-th CZ.

It is necessary to maximise the level of WME stocks in CZ

$$\max Z, \quad Z = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{n_i} l_{ijk} m_{ijk} x_{ijk},$$

subject to compliance with restrictions:

$$Z_{\max_{\min}}$$

$$T \le T', \quad T = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{n_i} m_{ijk} t_{ijk} x_{ijk},$$

$$R \le R', \quad R = \sum_{i=1}^{M} \sum_{j=1}^{m_i} \sum_{k=1}^{n_i} m_{ijk} r_{ijk} x_{ijk},$$

where R' – acceptable overall risk;

T' – acceptable time of delivery and formation of weapons stocks.

The problem can be solved by a complete search of all options for the WME's supplier warehouse, or, for a large problem dimension, by using one of the branches and boundaries methods in integer (Boolean) optimisation.

List of the set and justification of the structure of logistics supply channels in the process of forming the necessary stocks of weapons

We will conduct a structural analysis of possible supply channels for weapons and military equipment to form stocks in the zone of military conflict.

In order to form a sufficient level of WME stocks in CZ Z, $Z_{\max_{\min}}$, possible structural logistics elements are used, for example

– WME producers and suppliers;

– vehicles;

– suppliers' warehouses;

– intermediate warehouses for temporary storage of WME;

– transshipment centres;

– distribution centres;

– consolidation centres for the formation of batches of weapons and their components;

– WME warehouses in the CZ, etc.

Given the long length of the front line, the process of forming WME's stocks creates a set of possible structures for organising logistics supply channels, which requires solving the combinatorial problem of listing possible options. To analyse the set of variants of logistics supply chain structures, it is necessary to:

1) to conduct a quantitative analysis of possible options for creating logistics supply channels for WME in the CZ;

2) to form (generate) options for further analysis and comparison;

3) use the methods of combinatorics and enumeration theory to solve the task.

In the theory of enumeration, options arise when one set (e.g., A) is mapped to another (B). In our case, the set of logistics elements A is mapped to the set of vertices of the graph of the logistics structure of supply channels G. For the list of options, it is necessary to form the so-called cycle indices (CI), which characterise the peculiarities of the composition of logistics elements A, as well as the peculiarities of representing the structure of logistics supply channels in the form of a graph G:

$$Z(G) = \frac{1}{|G|} \sum_{g} \left(t_1^{c_1} t_2^{c_2} t_3^{c_3} \ldots . t_n^{c_n} \right) g,$$

where c_i is the number of cycles of length i arising from the mapping of one set to another;

t_i – an auxiliary variable related to c_i;

g – a separate component of CI.

The formation of CI for the graph of the logistics supply chain structure is associated with the analysis of the topology of the graph G. As an analysis, groups of substitutions for the vertices of graph G are used. The most commonly used groups of substitutions are as follows:

– symmetric S_n;

– cyclic C_n;

– dihedral D_n ;

– unit E_n,

where n is the number of vertices of graph G.

The obtained CIs for the groups of substitutions of the vertices of graph G are used to quantitatively analyse possible variants of the structures of logistics supply channels. In this case, the following formulas are used to recalculate the options in the form of the results of Poy and De Bruijn's theorems.

For the simplest cases of recalculation, when we are interested only in possible warehouse options, the problem is simplified and transformed into a special case – a formula for calculating combinatorial analysis. For example, we have three possible logistics elements for creating supply channels in the process of building WME stocks:

– a warehouse for temporary storage of military equipment;

– WME distribution centre;

– a consolidation point for different types of WME for further transport to the CZ.

The number of possible variants of the composition of elements in the logistics supply channel using combinatorial analysis is as follows

$$K = L^M - 1,$$

where L – number of types of logistics elements $(L = 3)$;

M – number of possible supply channels (for example, $M = 2$).

For our case, the number of possible warehouse options: $K = 3^2 - 1 = 8$.

The L-th counter can be used to form (generate) variants of the composition of WME's logistics supply channels in the CZ.

For example, this is a ternary counter. Then the set of warehouse options for WME's logistics supply channels in the CZ can be represented as follows:

1. 0 1
2. 0 2
3. 1 0
4. 1 1
5. 1 2
6. 2 0
7. 2 1
8. 2 2.

When using the graph G of the logistics supply chain structure, it is necessary to take into account the possible types of structure topologies that are used quite often (Fig. 9).

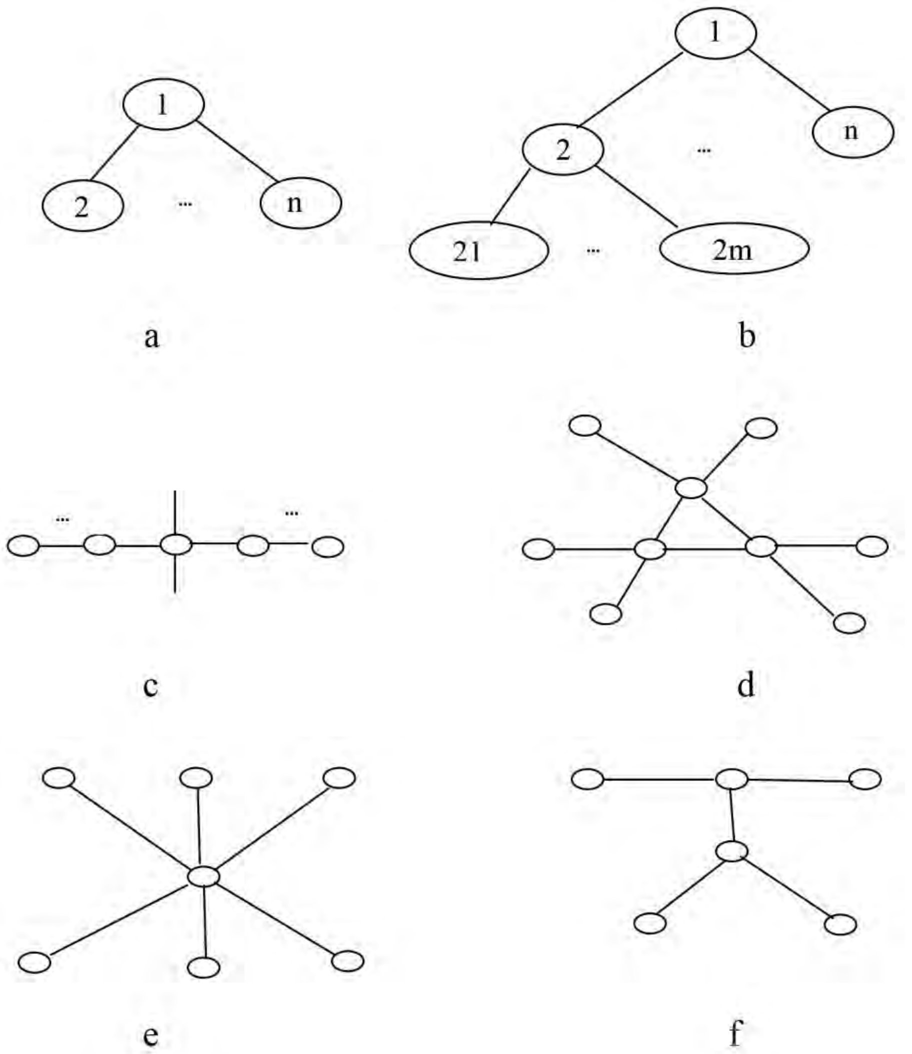

Fig. 9. Typical structures of the system topology:
a – radial structure; b – tree structure;
c – iterative; d – radial-ring structure of the first type;
e – radial-ring of the second type; f – radial-ring of the third type

In practice, mixed structures are often used, which are a combination of the types of topologies that have been considered. For any of the considered types of topologies, it is possible to form a group of vertex replacements of the graph G according to the structure topology, and then build the CI. The cycle index is the basis for recalculating the variants of logistics channels, taking into account the possible set of composition of logistics elements. In this case, one of the possible theorems of the enumeration theory is used.

As an example, let's determine the number of options associated with the mapping of possible logistics elements to the vertices of the radial structure of logistics supply channels in graph G (Fig. 9, a).

The group of substitutions of the vertices of the radial structure of graph G can be represented as follows:

$$H = E_1 + S_2,$$

where E_1 – a single group of substitutions associated with the vertex of a radial structure;

S_2 – is a symmetric replacement group associated with the two lower vertices of graph G.

The cyclic index of graph G is composed as a composition of two cyclic indices:

$$Z(H) = Z(E_1)Z(S_2) \ .$$

Let the number of types of logistics items be 3. Then

$$Z(H) = \frac{1}{2!}x_1\left(x_1^2 + x_2\right),$$

where variables x_1 and x_2 are associated with the vertices of graph G.

To recalculate the options for the structure of WME's logistics supply channels in the Czech Republic, we will use the result of the second theorem of Poy and De Bruijn:

$$K = \left\lfloor Z\left(G';\frac{\partial}{\partial z_1},\frac{\partial}{\partial z_2},\ldots\right)Z\left(H,1+z_1,1+z_2,\ldots\right)\right\rfloor_{Z_1=Z_2=\ldots=0},$$

where G' – is a group of replacements of the vertices of graph G;

H – a group of replacements associated with the composition of types of logistics supply elements;

$\frac{\partial}{\partial z_1},\frac{\partial}{\partial z_2},\ldots$ – differential operators (partial derivatives) that act on groups of vertex replacements of graph G.

In this case, the condition is met that all auxiliary variables are $z_1 = z_2 = \ldots = 0$.

For our sample:

$$K = 3\cdot\frac{1}{2}\left(3^2 + 3\right) = \frac{3\cdot 12}{2} = 18.$$

The obtained variants of WME's logistics supply chain structures in the process of inventory formation in CZs will be further evaluated and compared in order to select a rational option depending on the values of the selected logistics indicators.

We will assume that each logistics supply channel is associated with a specific CZ. It is necessary to form logistics supply chains taking into account the requirements of WME stocks in CZ $Z\{Z_{\max}\}\_\min$ for the successful completion of combat missions.

Individual links in the supply chain may include:

– transport sections of the highway;

– transport hubs;

– transport interchanges.

In order to solve the problem of choosing the rational composition of the logistics links of the arms supply channels in the CZ for the formation of WME stocks, we will use integer programming with Boolean variables y_{ik}:

$$y_{ik} = \begin{cases} 1, \textit{if the k-th warehouse of the supply chain links} \\ \quad \textit{is selected for the i-th channel to form WME stocks in CZ;} \\ 0, \textit{ otherwise}. \end{cases}$$

where $\sum_{k=1}^{l_i} y_{ik} = 1.$

In this case, the time taken to supply WME to form inventory in CZ is

$$T = \sum_{i=1}^{L} \sum_{k=1}^{l_i} t_{ik} y_{ik},$$

where L – number of WME at CZ;

l_i – is the number of possible options for the warehouse of the WME logistics supply chain for stock formation for the i-th CZ;

t_{ik} – is the time spent on supplying WME by the k-th warehouse of the logistics links of the supply chain for the i-th CZ.

Risks of military threats related to supply and stockpiling in CZ:

$$R = \sum_{i=1}^{L} \sum_{k=1}^{l_i} r_{ik} y_{ik},$$

where r_{ik} – risks of military threats associated with the use of the k-th warehouse of logistics supply chain for the i-th WME supply channel to form stocks in the CZ.

Logistics expences associated with the supply of WME for stockpiling in the CZ:

$$W = \sum_{i=1}^{L} \sum_{k=1}^{l_i} w_{ik} y_{ik},$$

where w_{ik} – logistics expences associated with the choice of the k-th variant of the composition of the logistics links of the WME supply channel in the i-th CZ.

Other formulations of the problem related to the formation of logistics links in WME's supply channels in CC are possible.

1. Minimise the delivery time for the formation of WME stocks in CZ

$$\min T, \quad T = \sum_{i=1}^{L} \sum_{k=1}^{l_i} t_{ik} y_{ik},$$

taking into account possible restriction:

$$Z_{\max_{\min}},$$

$$R \le R', \quad R = \sum_{i=1}^{L} \sum_{k=1}^{l_i} r_{ik} y_{ik},$$

$$W \le W', \quad W = \sum_{i=1}^{L} \sum_{k=1}^{l_i} w_{ik} y_{ik},$$

where R', W' – acceptable values of risks and expences.

2. Minimise supply risks for the formation of WME stocks in CZ

$$\min R, \quad R = \sum_{i=1}^{L} \sum_{k=1}^{l_i} r_{ik} y_{ik},$$

Taking into account the restrictions:

$$Z_{\max_{\min}},$$

$$T \le T', \quad T = \sum_{i=1}^{L} \sum_{k=1}^{l_i} t_{ik} y_{ik},$$

$$W \le W', \quad W = \sum_{i=1}^{L} \sum_{k=1}^{l_i} w_{ik} y_{ik}.$$

3. Minimise the logistics expences associated with the supply of WME stocks in CZ

$$\min W, \quad W = \sum_{i=1}^{L} \sum_{k=1}^{l_i} w_{ik} y_{ik}.$$

taking into account the restrictions:

$$Z_{\max_{\min}},$$

$$T \le T', \quad T = \sum_{i=1}^{L} \sum_{k=1}^{l_i} t_{ik} y_{ik},$$

$$R \le R', \quad R = \sum_{i=1}^{L} \sum_{k=1}^{l_i} r_{ik} y_{ik}.$$

Formation of the necessary stocks of weapons of certain models in the area of military conflict

Modern weapons have high combat capability (accuracy, range, area of effect, etc.). In the process of forming WME stockpiles, this allows for an asymmetry in the military parity of forces in a particular CZ (quality over quantity). Therefore, it is relevant to study the formation of WME stockpiles in a CZ in terms of the combat capability of weapons. Let us consider the formulation and solution of the problem of distributing a batch of weapons in a CZ, in which the formation of WME stocks is carried out taking into account the combat capability of individual types.

Let N be the number of WME in the CZ. As a result of the arrival of a batch of WME in the CZ, it is necessary, taking into account the types of weapons, j $\left(j=\overline{1,P}\right)$, to distribute them to individual CZs in accordance with their combat capability. In this case, it is necessary to take into account the total combat capability of all weapons in the CZ, taking into account the one we have at the moment.

Let's introduce an integer variable:

$$x_{jk}=\begin{cases}1, \textit{if for the selected } k\textit{-th warehouse of the CZ stocks} \\ \quad \textit{for the j-th type of WME are formed;} \\ 0, \textit{ otherwise.}\end{cases}$$

where $\sum\limits_{k=1}^{n_j} x_{jk}=1$ – This means that the incoming batch of weapons will definitely be used to form stocks of the j-th type of WME in the CZ. Then we have the following results.

1. Stocks formed in CZ:

$$W=\sum_{j=1}^{P}\sum_{k=1}^{n_j} w_{jk}x_{jk}\sum_{j=1}^{P}\sum_{k=1}^{n_j} w'_{jk} \ ,$$

where P – number of WME types;

n_j is the number of possible options for allocating WME to CZs to form stocks of the j-th kind of weapon;

w_{jk} is the quantity of WME of the j-th kind used for inventory formation;

w'_{jk} – is the number of weapons of the j-th kind that are currently available in the k-th warehouse in the CZ where the weapons stocks are formed.

2. Combat capability of the WME in the CZ:

$$Q = \sum_{j=1}^{P} \sum_{k=1}^{n_j} w_{jk} q_j x_{jk} + \sum_{j=1}^{P} \sum_{k=1}^{n_j} w'_{jk} q_j x_{jk},$$

where q_j – combat effectiveness of a single sample of the j-th kind of WME.

3. Time spent on the formation of WME stockpiles in CZ:

$$T = \sum_{j=1}^{P} \sum_{k=1}^{n_j} t_{jk} x_{jk},$$

where t_{jk} – is the time spent on the formation of WME stocks of the j-th kind for the k-th WME warehouse in CZ.

4. Logistical risks of WME stockpiling in the CZ related to the wartime period:

$$R = \sum_{j=1}^{P} \sum_{k=1}^{n_j} r_{jk} x_{jk},$$

where r_{jk} – the risk of military threats associated with the logistics of stockpiling the j-th type of WME for the k-th warehouse in the WME in the CZ.

In order to create military parity of forces (as well as the possibility of creating asymmetry), it is necessary to maximise the combat effectiveness of the use of WMEs, taking into account the stocks of weapons currently available in the CZ:

$$\max Q = \sum_{j=1}^{P} \sum_{k=1}^{n_j} w_{jk} q_j x_{jk} + \sum_{j=1}^{P} \sum_{k=1}^{n_j} w'_{jk} q_j x_{jk},$$

taking into account the restrictions:

$$W \sum_{j=1}^{P} \sum_{k=1}^{n_j} w_{jk} x_{jk} + \sum_{j=1}^{P} \sum_{k=1}^{n_j} w'_{jk}{}_{\max_{\min}},$$

where $W_{\min}$ – WME stocks that ensure that the nature of hostilities in the conflict zone is not disturbed, taking into account military threats;

$W_{\max}$ – WME stocks that ensure the successful achievement of the objectives of a military operation by creating an asymmetry in the military parity of forces.

$$T \le T', \quad T = \sum_{j=1}^{P} \sum_{k=1}^{n_j} t_{jk} x_{jk},$$

$$R \le R', \quad R = \sum_{j=1}^{P} \sum_{k=1}^{n_j} r_{jk} x_{jk},$$

where T', R' – acceptable values of time and risk of stockpiling weapons and military equipment.

An example of modelling
the logistics of stockpiling weapons and military equipment

Let's consider the logistics of stockpiling weapons for effective combat operations on the example of supplying the HIMARS multiple launch rocket system using four possible suppliers $(n=4)$. In this case, the number of possible options for the composition of suppliers for the formation of stocks of MLRS HIMARS in the area of military conflict is as follows $N=2^n-1=2^4-1=15$.

Table 4 shows the options for the composition of suppliers for the formation of HIMARS stocks. The following indicators are used to compare and eliminate unnecessary options for the composition of possible suppliers:

– the number of batches of HIMARS supplies from the i-th supplier for the formation of weapons stocks – n_i;

– volume of the HIMARS supply batch for the i-th supplier – l_i;

– is the volume of the HIMARS MLRS stockpile formed after using the receipts from the k-th supplier warehouse – W_k;

– is the time spent on the supply of weapons by the k-th supplier of HIMARS MLRS – T_k;

– wartime logistical risks associated with the supply of HIMARS weapons to the k-th supplier warehouse – R_k.

Table 4

Evaluation of options for the composition of the HIMARS MLRS supplier

№	List of suppliers				W, stock volume	T, stock formation time	R, logistics risks
	1	2	3	4			
1	–	–	–	+	6	B	A
2	–	–	+	–	4	A	A
3	–	–	+	+	10	C	B
4	–	+	–	–	3	A	A
5	–	+	–	+	9	C	B
6	–	+	+	–	7	B	B
7	–	+	+	+	13	C	C
8	+	–	–	–	3	B	A
9	+	–	–	+	9	C	C
10	+	–	+	–	7	C	B
11	+	–	+	+	13	D	D
12	+	+	–	–	6	B	B
13	+	+	–	+	12	C	D
14	+	+	+	–	10	C	C
15	+	+	+	+	16	D	D

To estimate the volume of the MLRS HIMARS stockpile being formed in the area of military conflict, we will use quantitative estimates, and to estimate time and risk, we will use qualitative estimates for the convenience of military experts:

$$T_k = \begin{cases} A - \text{ minimum time;} \\ B - \text{ satisfactory time;} \\ C - \text{ acceptable time;} \\ D - \text{ maximum time;} \end{cases}$$

$$R_k = \begin{cases} A - \text{ minimum risk;} \\ B - \text{ satisfactory risk;} \\ C - \text{ acceptable risk;} \\ D - \text{ maximum risk .} \end{cases}$$

For the example under consideration:

$$m_1 = 1, \quad l_1 = 3,$$
$$m_2 = 3, \quad l_2 = 1,$$
$$m_3 = 2, \quad l_3 = 2,$$
$$m_4 = 2, \quad l_4 = 3.$$

Table 4 was built as a result of the military experts' assessment of possible options for the formation of MLRS HIMARS stockpiles.

To analyse the results, we will take into account the fact that the most important indicator is the stockpile formation – W , $W_{\max_{\min}}$ where $W_{\min} = 6$, which corresponds to the MLRS HIMARS insurance stockpile, and $W_{\max} = 20$, which ensures the successful achievement of the objectives of the military operation due to the asymmetry in military parity of forces. The values of $W_{\min}$ and $W_{\max}$ were determined by experts in the field of military logistics.

Let the next most important indicator be the time T , which is necessary for the timely formation of MLRS HIMARS stockpiles. Possible risks in the context of military threats in the process of building up the MLRS HIMARS stockpile are taken into account using the R indicator, which, according to military experts, will be the third most important.

To compare and choose the best option for the formation of MLRS HIMARS stockpiles, we will use the options presented in Table 4, taking into account the importance of indicators.

A preliminary list of options for forming stockpiles of MLRS HIMARS (see Table 4) will look like this:

1. 6, B, A
2. 4, A, A
3. 10, C, B
4. 3, A, A
5. 9, C, B
6. 7, B, B
7. 13, C, C
8. 3, B, A
9. 9, C, C
10. 7, C, B
11. 13, D, D
12. 6, B, B
13. 12, C, D
14. 10, C, C
15. 16, D, D.

After the lexicographical ordering of the options for the formation of stockpiles of MLRS HIMARS, considering the priority of indicators, we get:

15\. 16, D, D
7\. 13, C, C
11\. 13, D, D
13\. 12, C, D
3\. 10, C, B
14\. 10, C, C
5\. 9, C, B
9\. 9, C, C
6\. 7, B, B
10\. 7, C, B
1\. 6, B, A
12\. 6, B, B
2\. 4, A, A
4\. 3, A, A
8\. 3, B, A.

After analysing the list of options, the military experts decided that the indication of the delivery time D and the value of the risk D were unacceptable for the formation of the MRLS HIMARS stockpile. Taking into account the value of the $W_{\min}$ constraint, we get a list of possible options for the formation of MLRS HIMARS stockpiles:

7. 13, C, C
14. 10, C, C
5. 9, C, B
9. 9, C, C
6. 7, B, B
10. 7, C, B
1. 6, B, A
12. 6, B, B.

After analysing the list of options and comparing them, military experts concluded that the seventh option for building up the MRLS HIMARS stockpile is the best. It corresponds to a stockpile of 13 HIMARS MLRS, and is characterised by an acceptable time and risk of stockpile formation.

The subsection examines the modelling of the logistics process of stockpiling weapons and military equipment for the successful conduct of combat operations in the conflict zone. The article analyses the problems of stockpiling weapons in wartime, which differ from stockpiling in peacetime: weapons suppliers located at a great distance from the zone of military conflict; small batches of WME supplies; long supply chains in a heterogeneous transport environment; military threats and vulnerabilities; and martial law risks. The analysis of the formation of weapons stocks has shown that the volume of stocks is formed in the interval $Z_{\max_{\min}}$, where $Z_{\min}$ corresponds to the insurance stock of weapons that will not disrupt the nature of hostilities in the context of military threats and logistical risks of the country's martial law, and $Z_{\max}$ ensures the successful achievement of the objectives of a military operation by creating an asymmetry in the military parity of forces. The article analyses the effectiveness of the use of certain types of weapons in the combat zone depending on military threats. For this purpose, the method of the theory of planning experiments is used, with the help of which priority types of weapons are selected to form the necessary stocks.

An optimisation model for the formation of WME stocks is proposed, taking into account the limited capabilities of manufacturers and suppliers and wartime logistical risks. In this case, small batches of arms supplies, delivery time and possible composition of suppliers are taken into account. A systematic analysis of logistics supply channels is carried out and options for composition and structure are listed using the methods of enumeration theory.

An optimisation model for selecting logistics links in arms supply channels was created in accordance with the expences and risks of martial law. The optimisation of the volume of weapons stocks is carried out, taking into account the combat capability of certain types, which allows creating a possible asymmetry in the military parity of forces for the successful achievement of the goals of a military operation.

An example is provided to confirm the effectiveness of the proposed approach. The example analyses possible options for the composition of suppliers for the formation of stocks of MLRS HIMARS. In this case, both quantitative estimates of weapons stocks and qualitative estimates of time and logistical risks of supply under martial law are used. To select the best option for the composition of suppliers in the formation of stockpiles of MLRS HIMARS, the composition of arms suppliers, their capabilities and the amount of required safety stocks are analysed. For this purpose, a lexicographical ordering of options for the formation of weapons stockpiles is used.

The main scientific contribution of the study is related to the development of a set of original optimisation models, models of the list of options for the structures of logistics supply channels, which allows scientifically sound formation of requirements for the volume of WME stocks.

Mathematical methods and modelling techniques used: system analysis; methods of expert evaluation of options; methods of the theory of planning experiments; integer (Boolean) optimisation; methods of Poy and De Bruijn's enumeration theory; method of lexicographic ordering of options; method of qualitative evaluation of options.

The proposed approach makes it possible to take into account the variety of weapons, their combat capability, small batches of supplies, a large number of options for the composition of suppliers, limited capabilities of suppliers, the amount of insurance stocks, delivery time and logistics of forming weapons stocks in the context of military threats in the process of forming stocks of weapons and military equipment in a military conflict zone.

Modelling the logistics of high-tech enterprises evacuation in a special period

The unit solves a complex multi-criteria task related to the justification of the location of the enterprise to be evacuated. The logistics process of evacuation is modelled in the context of wartime threats and vulnerabilities. The relevance of the study is related to the substantiation of a possible production location for a high-tech enterprise, taking into account the process of transporting technological equipment to the rear in the face of complex logistics. The article considers the process of placing and setting up the production of an evacuated enterprise at a new location. The purpose of the study is to model the logistics process of evacuating an industrial enterprise to the rear in the face of wartime threats and vulnerabilities.

Given the aggressor's military actions on the territory of the country, an acute problem arises related to the evacuation of high-tech industrial enterprises (aerospace, machine-building, instrument-making industries, etc.) from the frontline zone to the rear [25]. In this case, it is necessary to carry out a whole range of measures (dismantling of technological equipment, transportation, preparation of a new territory, placement and installation of technological equipment, etc.) in a short time with minimal risks and taking into account wartime threats. Therefore, the relevance of the study is due to the fact that it sets and solves the task of modelling the logistics process of evacuating an industrial enterprise from the frontline zone to the rear, taking into account the risks and time for moving to a new place of production. As is well known, evacuation consists of a number of stages that must be planned in advance and implemented within the required timeframe, which depends on the situation at the front [26]. The main stages to be studied:

– selection of the location of the industrial enterprise to be evacuated;

– dismantling of technological equipment;

– preparation for the transport of technological equipment;

– transporting the process equipment;

– preparation of a new territory for the location of technological facilities of the industrial enterprise;

– placement of process equipment on the new territory;

– installation of process equipment;

– establishment of communication channels for the operation and management of technological equipment;

– carrying out a set of commissioning works to resume production of the actual products of the evacuated high-tech enterprise.

The analysis of publications on this topic showed that the main attention is paid to individual stages of evacuation without a comprehensive study of the entire process [27]. The logistical nature of evacuation, risks and threats arising from wartime requirements are not taken into account [28].

Thus, there is a complex scientific and applied task of a multicriteria nature related to the successful conduct of evacuation measures in wartime [29].

To achieve the purpose of the study, the main criteria are used: evacuation time, expences, and risks arising in wartime.

To achieve this goal, it is necessary to solve the following tasks:

1) to substantiate and select the location of the evacuated enterprise, taking into account the threats and vulnerabilities of wartime;

2) to build an agent-based simulation model to study the logistics process of evacuation of a high-tech enterprise;

3) to formulate rational routes for transporting technological equipment to a new location of a high-tech enterprise;

4) to solve the problem of optimal placement of the evacuated high-tech enterprise at a new location.

Justification and selection of the location of the evacuated enterprise, taking into account the threats and vulnerabilities of wartime

The choice of a new location for a high-tech enterprise to resume production of relevant military products depends on a number of factors, including

– time spent on moving the enterprise to a new location;

– possible wartime threats and vulnerabilities at the new location of the high-tech enterprise;

– availability of engineering infrastructure for the normal operation of the high-tech enterprise at the new location (supply of the required volumes of electricity, water, gas, etc;)

– time spent on the placement and installation of high-tech equipment at the new location of the enterprise;

– expenses related to the relocation of a high-tech enterprise to a new place.

The task under consideration in this paper is multivariate in nature, taking into account the possible contradiction of criteria (time, expenses, risks) and requires a compromise solution.

Wartime threats depend on the presence of possible vulnerabilities at the new location of the industrial enterprise (availability of defence and repair plants, military command posts, storage facilities and warehouses for military equipment, ammunition, fuel, etc.) Therefore, it is necessary to assess the level of threats by evaluating the impact on existing vulnerabilities. To analyse the level of threats and vulnerabilities, we will use expert assessments (specialists in the field of military logistics). For the convenience and simplification of expert assessment, we will use qualitative assessments in the form of linguistic variables. For each possible location of the evacuated enterprise, we will form a set of threat assessments based on vulnerabilities. To assess the level of threats, we will use the qualitative values of vulnerabilities at the new location of the enterprise. For example, the qualitative values of vulnerabilities can be presented as follows:

1) presence of military command points:

A – absent;

B – present;

2) presence of weapons, military equipment, ammunition depots:

A – absent;

B – present;

3) presence of fuel storage facilities:

A – absent;

B – in a small amount;

C – in large quantities;

4) presence of defence enterprises:

A – absent;

B – in a small amount;

C – to a large extent.

Then each possible location of the evacuated high-tech enterprise can be represented as a list of linguistic variables ("word"), where the first place in importance, for example, is the value of the linguistic variable "military command posts", the second place is the presence of "weapons, military equipment and ammunition warehouses", the third place is the presence of "fuel storage facilities", and the fourth place is the presence of "defence enterprises".

Suppose that the experts offer 10 possible locations for the evacuated high-tech enterprise. For each of them, military experts assessed the impact of vulnerabilities. Let us present the options with their assessments in the form of an unordered list of "words":

1. A B A B
2. A A C B
3. B A B A
4. A B A A
5. B A A A
6. A A C C
7. A A B B
8. B A B C
9. B A A B
10. A B A C.

Given the significance of the vulnerabilities represented by the position of the corresponding linguistic variable in the "word" of the option, it is possible to identify the most promising options for the relocation of the evacuated enterprise to a new territory by lexicographically ordering the "words". We get:

7. A A B B
2. A A C B
6. A A C C
4. A B A A
1. A B A B
10. A B A C
5. B A A A
9. B A A B
3. B A B A
8. B A B C.

The options located at the top of the list have a greater advantage for choosing the location of the enterprise to be evacuated. Finally, the experts chose the seventh option for the location of the enterprise, which has no military command posts, no weapons, military equipment and ammunition depots, but small amounts of fuel storage facilities and small amounts of defence enterprises.

The analysis was limited to assessing the impact of vulnerabilities for the purpose of selecting the location of the industrial enterprise to be evacuated. To take into account such indicators as the level of threats – V, the availability of engineering infrastructure – W, the time to move – T, and the expence of moving – Z, we use the method of integer (Boolean) programming.

Let us assume that for each possible location of the evacuated high-tech enterprise, the following indicators have been quantified by military experts:

v_i – is the level of threats to the i-th location of an industrial enterprise;

w_i – engineering infrastructure for the i-th location;

t_i – is the time spent on moving an industrial enterprise to the i-th location;

z_i – expences associated with the relocation of an industrial enterprise to the i-th location.

For further optimisation, it is necessary to normalise the quantitative assessments of experts, i.e. to transfer them to a relative scale (0...1) as follows:

$$\overline{v_i} = \frac{v_i}{v_{\max}\,\overline{w_i}\,\frac{w_i}{w_{\max}\,\overline{t_i}\,\frac{t_i}{t_{\max}\,\overline{z_i}\,\frac{z_i}{z_{\max}}}}}$$

where $v_{\max_{\max_{\max_{\max}}}}$ – are the maximum values of the scores in the set of options under consideration.

Let's introduce a Boolean variable x_i:

$$x_i = \begin{cases} 1 - \textit{if the i-th variant of the enterprise location is selected,} \\ 0 - \textit{otherwise.} \end{cases}$$

In this case $\sum_{i=1}^{M} x_i = 1$, where M – is the number of possible locations for the evacuated high-tech enterprise.

For comprehensive optimisation and search for compromise solutions, we introduce the criterion Q as an additive convolution of local criteria:

$$Q = \alpha_V V + \alpha_W W + \alpha_T T + \alpha_Z Z,$$

where $\alpha_V, \alpha_W, \alpha_T, \alpha_Z$ – weights (significance) of local criteria V, W, T, Z. In this case

$$\alpha_V + \alpha_W + \alpha_T + \alpha_Z = 1,$$

$$V = \sum_{i=1}^{M} \overline{v}_i x_i,$$

$$W = \sum_{i=1}^{M} \overline{w}_i x_i,$$

$$T = \sum_{i=1}^{M} \overline{t}_i x_i,$$

$$Z = \sum_{i=1}^{M} \overline{z}_i x_i.$$

It is necessary to find min Q subject to the following constraints $V \le \hat{V}$, $W \le \hat{W}$, $T \le \hat{T}$, $Z \le \hat{Z}$, where $\hat{V}$, $\hat{W}$, $\hat{T}$, $\hat{Z}$ – acceptable values of the criteria.

Development of an agent-based simulation model to study the logistics process of evacuation of a high-tech enterprise

Given the dynamic nature of evacuation of a high-tech enterprise, the study uses simulation modelling of the main events of this process.

The main events in the simulation modelling of the logistics process of evacuation of an industrial enterprise are as follows:

– start of dismantling of technological equipment of a high-tech enterprise;

– completion of dismantling;

– start of transporting technological equipment to the rear;

– arrival of equipment (submitted as a request in the simulation) at a transport hub of a heterogeneous transport network;

– the request leaving the transport hub;

– receipt of a request to a section of a transport main line;

– the request leaving the section of the transport main line;

– commencement of the placement of technological equipment at the new location of the enterprise;

– completion of the placement of technological equipment;

– start of installation of technological equipment;

– completion of the installation of the process equipment;

– start of commissioning at the plant;

– completion of commissioning works at the enterprise;

– start of serial production of relevant military products at the new location of the high-tech enterprise (the final event).

Events are implemented in time, the scale of which is set at the beginning of the simulation (hour, day, week, etc.).

The sequence of events in the logistics process of evacuation corresponds to the cause-and-effect relationships and ensures the effectiveness of simulation modelling.

For example, the event of starting the installation of technological equipment causes a consequence. The consequence is the event of completion of the installation of technological equipment. Events are scheduled on a specified time scale in accordance with predefined cause-and-effect relationships.

The event-based simulation model is implemented in an agent-based view in the Anylogic environment, where there are agents associated with specific cause-and-effect events.

The control agent is separately identified, which provides event planning in a given time scale and generates a sequential list of events, in which the earliest event is located first.

Here are the components of the set of agents.

1. Agent for describing a diverse transport network.
2. The agent for starting the simulation (starting agent).
3. Equipment dismantling agent.
4. Agent for starting the transport of equipment.
5. Agent associated with a transport hub of a diverse transport network.
6. An agent associated with a section of a transport highway.
7. Agent for the placement of technological equipment.

8. Agent of equipment installation.
9. Agent for commissioning.
10. Risk agent.
11. Simulation control agent.
12. The agent for starting mass production (finishing agent).
13. The agent of simulation results.

The main results of the simulation are:

– time spent on evacuation of the industrial enterprise;

– time to start mass production;

– delay in the start of mass production;

– the route of technological equipment in a diverse transport network (a sequence of transport hubs and sections of a transport highway). The route can be set in advance, or an algorithm can be developed to determine the optimal route in terms of time or risk;

– the value of the final risk associated with the evacuation of the enterprise (the risk is accumulated in the case of transporting technological equipment in the hubs and sections of the transport route).

Fig. 10 shows a block diagram of the agent-based simulation model.

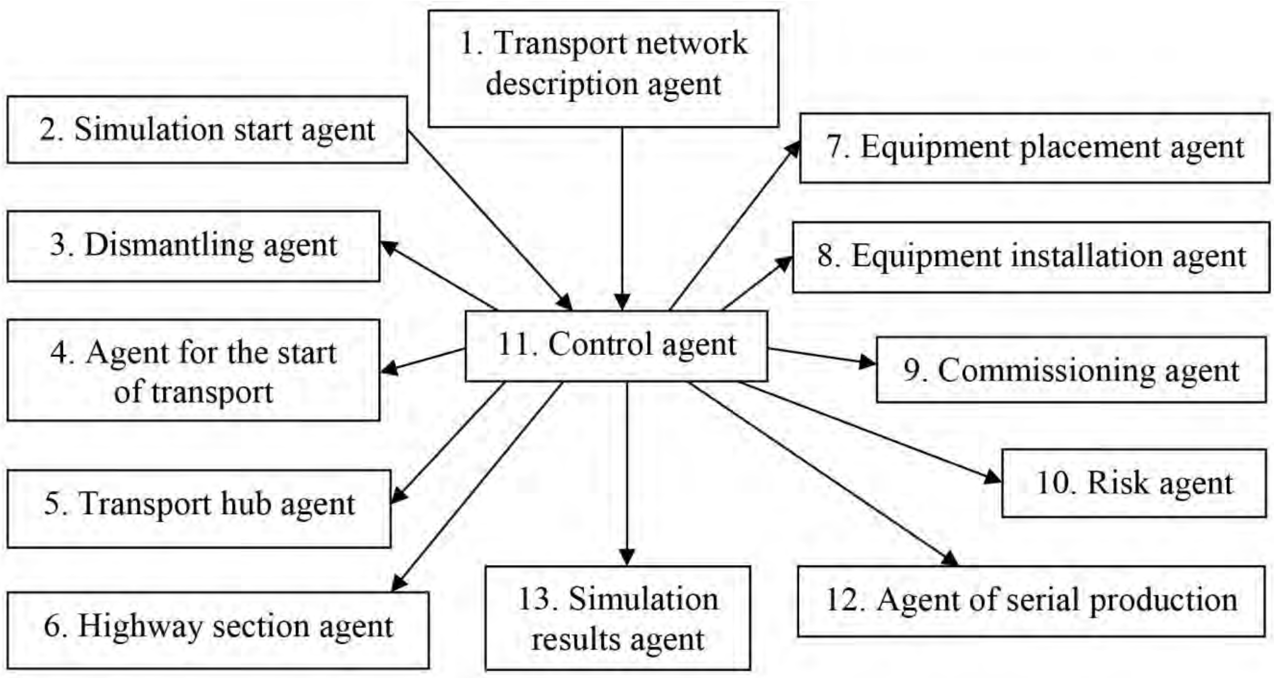

Fig. 10. Block diagram of the agent-based simulation model

A method for finding rational routes for technological equipment transportation to a new location of a high-tech enterprise

To find rational routes for transporting the technological equipment of an evacuated enterprise, an original routing algorithm was developed and implemented within an agent-based simulation model. The algorithm is based on the propagation of requests (clones) in the form of technological equipment in the graph G, which is a heterogeneous transport network used to move technological equipment to a new location of the industrial enterprise. Taking into account the special purpose of the cargo, as well as its characteristics (dimensions, weight, requirements for concealment of transportation, etc.), not all transport hubs and sections of the transport network can be used to move technological equipment. Therefore, military experts must determine in advance the permitted transport hubs and sections of the transport network that can be used to evacuate a high-tech enterprise. The movement of requests (clones) of technological equipment in column G of the transport network, taking into account the permitted nodes and sections of the transport highway, is carried out as follows: the beginning of transportation is associated with the exit of the request from the transport node to which the evacuated technological equipment was received. Then, by the method of multiplication of applications (emergence of application clones), they are transported along all possible sections of the highway associated with this transport hub. If an order (clone) enters a neighbouring transport node, it marks it with the number of this order. If a request (clone) reaches a designated node, its movement is stopped because the request (clone) has already passed through this node, so it is not promising in terms of choosing the optimal route in terms of time. Upon reaching the finishing node (arrival of the process equipment at the new location of the enterprise), the time of the end of the process equipment transportation is recorded. Then, by moving back through the designated nodes, a route is formed that is minimal in time and takes into account the features and special mode of operation of the heterogeneous transport network used to evacuate the technological equipment of a high-tech enterprise.

In order to find a route with minimal risk of transporting technological equipment, it is necessary that before starting the modelling, military experts assess the possible risks of technological equipment passing through individual nodes and sections of the transport route. In the course of modelling, as the applications (clones) move along the nodes and sections of the transport route, individual risks accumulate and the final risk associated with the logistics of transport services for the evacuated enterprise is formed. To model risks and find a route with minimal risk, the main factor in managing simulation modelling (control agent) is the value of the accumulated risk.

The developed algorithm can be used both to find the optimal (minimum) evacuation route for technological equipment in terms of time and to find a safe route with a minimum risk value. The final choice of the route for evacuating the technological equipment of the evacuated high-tech enterprise is recognised by experts in the field of military logistics using the developed agent-based simulation model.

A method of optimal placement of an evacuated high-tech enterprise at a new location

The successful relocation of a high-tech enterprise to a new territory depends on the following factors:

1) the need for space for the placement of technological equipment;

2) earthworks to prepare the territory for the placement of technological equipment;

3) availability of engineering infrastructure on the new territory (electricity, water, gas, etc.);

4) availability of communications to organise the interaction of technological facilities and equipment management;

5) the duration and expences of preparing the new territory for the placement of the evacuated facility's technological equipment;

6) risks associated with the placement of the enterprise's technological equipment on the new territory.

The main criteria for assessing the location of an evacuated high-tech enterprise in a new territory are

– time spent on the location of the enterprise in the new territory – T ;

– expences associated with the location of the enterprise in the new territory – W ;

– risks of locating the enterprise in the new territory – R .

The availability of alternative options for the location of a high-tech enterprise, as well as the use of not one but several criteria for evaluating the location, leads to the need to formulate and solve a multi-criteria, multi-variant problem of finding a rational location option.

Suppose that military experts and the management of an enterprise determine in advance a set, M , of possible locations for a high-tech enterprise that is being evacuated to the rear. For each possible location, the time, expences, and risks associated with the location of the evacuated enterprise's technological equipment at the new location are estimated.

We present the criteria in the following form:

$$T_k = t_{k_1} + t_{k_2} + t_{k_3},$$
$$W_k = w_{k_1} + w_{k_2} + w_{k_3},$$
$$R_k = r_{k_1} + r_{k_2} + r_{k_3},$$

where T_k, W_k, R_k – are, respectively, the time, expences and risks associated with choosing the k-th option of locating the enterprise at a new location;

$t_{k_1}, w_{k_1}, r_{k_1}$ – time, costs and risks associated with earthworks to prepare the territory for the location of a high-tech enterprise for the k-th location option;

$t_{k_2}, w_{k_2}, r_{k_2}$ – time, costs and risks associated with the preparation of engineering infrastructure for the location of the enterprise, for the k-th location option;

$t_{k_3}, w_{k_3}, r_{k_3}$ – time, costs and risks associated with the organisation of communication channels for technological equipment for the k-th location option.

To find rational options for the location of a high-tech enterprise, we will use the method of integer (Boolean) programming. Let's introduce the variables x_k, the values of which are:

$$x_k = \begin{cases} 1 - \textit{if the k-th option for the placement} \\ \quad \textit{of technological equipment is selected;} \\ 0 - \textit{otherwise.} \end{cases}$$

Then, taking into account the variables x_k, the criteria for assessing the location of a high-tech enterprise will be as follows:

$$T = \sum_{k=1}^{M} \left(t_{k_1} + t_{k_2} + t_{k_3} \right) x_k,$$
$$W = \sum_{k=1}^{M} \left(w_{k_1} + w_{k_2} + w_{k_3} \right) x_k,$$
$$R = \sum_{k=1}^{M} \left(r_{k_1} + r_{k_2} + r_{k_3} \right) x_k.$$

There are two possible formulations of the problem of optimal location of an evacuated high-tech enterprise in a new territory.

1. Single-criteria optimisation. In this case, the optimisation of individual local criteria (T, W, R) is carried out, taking into account the constraints in the form of acceptable values T', W', R'.

For example, it is necessary to find:

$$\min T,\ \ T=\sum_{k=1}^{M}\left(t_{k_1}+t_{k_2}+t_{k_3}\right)x_k,$$

subject to the restrictions:

$$W\le W',\ \ W=\sum_{k=1}^{M}\left(w_{k_1}+w_{k_2}+w_{k_3}\right)x_k,$$

$$R\le R',\ \ R=\sum_{k=1}^{M}\left(r_{k_1}+r_{k_2}+r_{k_3}\right)x_k,$$

$$\sum_{k=1}^{M}x_k=1.$$

2. Multi-criteria optimisation to find a compromise solution for the location of the evacuated enterprise. In this case, we use the complex criterion P:

$$P=\alpha_T\hat{T}+\alpha_W\hat{W}+\alpha_R\hat{R},$$

where $\alpha_T+\alpha_W+\alpha_R=1,$

$$\hat{T}=\frac{T-T^*}{T'-T^*},\ \ \hat{W}=\frac{W-W^*}{W'-W^*},\ \ \hat{R}=\frac{R-R^*}{R'-R^*},$$

where T^*, W^*, R^* – are the optimal values of T, W, R determined by the previous single-criteria optimisation.

It is necessary to find:

$$\begin{aligned}\min P,\ \ P=\alpha_T\hat{T}+\alpha_W\hat{W}+\alpha_R\hat{R}=\\ =\frac{\alpha_T}{T'-T^*}\left[\sum_{k=1}^{M}\left(t_{k_1}+t_{k_2}+t_{k_3}\right)x_k-T^*\right]+\\ +\frac{\alpha_W}{W'-W^*}\left[\sum_{k=1}^{M}\left(w_{k_1}+w_{k_2}+w_{k_3}\right)x_k-W^*\right]+\\ +\frac{\alpha_R}{R'-R^*}\left[\sum_{k=1}^{M}\left(r_{k_1}+r_{k_2}+r_{k_3}\right)x_k-R^*\right],\end{aligned}$$

subject to the restrictions:

$$T\le T',\quad W\le W',\quad R\le R',$$

$$\sum_{k=1}^{M}x_k=1,$$

$$\alpha_T+\alpha_W+\alpha_R=1,$$

where $\alpha_T,\alpha_W,\alpha_R$ – the significance of the criteria T, W, R, set by experts in the field of construction of high-tech enterprises.

The study is related to modelling the logistics process of evacuating a high-tech enterprise in wartime. The preliminary analysis has revealed the shortcomings of existing approaches that study individual stages of evacuation of a high-tech enterprise without a comprehensive analysis of logistically related stages, without taking into account the dynamic nature of evacuation in the face of possible threats and vulnerabilities. The choice of a new location for the evacuated high-tech enterprise is substantiated on the basis of multivariate analysis and qualitative assessments of military experts in the form of linguistic variables. An agent-based simulation model for studying the logistics process of evacuation has been developed, which helps to determine the rational and optimal routes for transporting the technological equipment of the evacuated enterprise in the context of wartime risks. The article solves the problem of optimal placement of technological equipment of a high-tech enterprise at a new location, taking into account time, expenses and risks, using integer (Boolean) linear programming. In order to find compromise solutions in the process of placing technological equipment of a high-tech enterprise, a complex criterion in the form of an additive convolution of local criteria of time, expenses and risks is used.

The research was based on modelling the process of evacuation of an industrial enterprise in wartime, which involves justifying the new location of a high-tech enterprise through expert assessment, developing an agent-based simulation model to study the logistics of the evacuation process under conditions of risks, and optimising the placement of technological equipment of an industrial enterprise in a new territory. In the course of the study, the goal was fully achieved. The mathematical methods and modelling techniques used are: system analysis, expert evaluation using linguistic variables, agent-based simulation modelling, integer (Boolean) programming.

The proposed approach makes it possible, in the process of planning the evacuation of a high-tech enterprise, to reasonably choose a new location, to form rational (optimal) routes for transporting technological equipment during evacuation, and to rationally place technological equipment in a new territory, taking into account time, expenses and risks.

Conclusions

The chapter examines the logistics processes of production of high-tech enterprises during the special period associated with martial law in the country. The author describes the logistical problems that arose in the production and supply of high-tech defence products:

– transfer of production to the manufacture of weapons and military equipment;

– evacuation of high-tech enterprises from the frontline zone to the rear;

– the emergence of military threats and vulnerabilities related to the aggressor's actions, which affects the logistics of production;

– complications in the supply of high-tech enterprises due to long supply chains in wartime;

– delivery of high-tech components under difficult martial law conditions, as well as losses due to delays in delivery;

– supply of high-tech military equipment to the zone of military conflict to establish military parity of forces;

– formation of the necessary stocks of high-tech weapons in the area of military conflict for the successful fulfilment of the objectives of a military operation.

The logistics of military cargo supply in a heterogeneous transport network is modelled to find rational routes that will ensure timely delivery of military equipment to the combat zone, as well as minimise losses due to possible delays. A model has been created that allows analysing the logistical actions to establish military parity of forces, as well as possible asymmetry due to the use of high-tech weapons (quality over quantity). The sequence of actions related to the emergence of military threats (threat – vulnerabilities – losses) is investigated, which allows planning preventive measures to reduce the consequences of threats. With the help of an agent-based simulation model, the terms of supply of weapons and military equipment under martial law threats are determined. The method of forming rational routes for the supply of military equipment in a distributed transport environment with long logistics chains is developed. The logistics of training military personnel to acquire new competencies necessary for the use of high-tech military equipment are investigated. Considerable attention is paid to the formation of the necessary stocks of weapons in the area of military conflict, which are formed in the range from insurance stocks to the maximum, which ensures the successful achievement of the goals of a military operation in the face of complex supply logistics and limited capabilities of manufacturers and suppliers of high-tech military equipment. The author modelled the logistics processes of evacuation of high-tech enterprises in wartime by creating an optimisation model for estimating the logistics costs of transporting technological equipment and relocating the enterprise to a new location in the face of military threats.

Mathematical methods and modelling techniques were used: system analysis to present the logistics of military equipment supply under martial law; optimisation models of integer (Boolean) programming to estimate the time, risks and expenses in the production and supply of high-tech enterprises in the face of military threats;

the method of the theory of experiment to identify significant threat factors, priority of types of weapons in the area of military conflict; the method of expert evaluation using linguistic variables and lexicographic ordering of options to select the nomenclature and quantity of military equipment necessary to create military parity of forces in the combat zone; a method of simulated agent-based modelling to study long logistics chains for the supply of military equipment to a military conflict zone in the face of threats and perturbations of vulnerabilities in transport supply networks; a method of enumeration theory to form a set of possible logistics channels for the supply of weapons and military equipment to a military conflict zone.

The scientific results obtained in this section:

– the method of creating military parity of forces has been improved due to the timely supply of modern military equipment to the zone of military conflict, preparation of the military for its use in conditions of limited capabilities of manufacturers and risks of martial law;

– the method of stockpiling products of high-tech enterprises under special conditions and possible military threats has been improved, which allows planning the necessary stocks of military equipment for the successful implementation of operational and tactical actions;

– the method of logistical actions for the relocation of a high-tech enterprise was improved by optimising costs and reducing time, which allows planning the logistics of transferring production to a new location in the face of military threats.

Reference

1. Rosella Cappella Zielinski, Paul Poast (2021), "Supplying Allies: Political Economy of Coalition Warfare", *Journal of Global Security Studies*, Vol. 6, iss. 1. DOI: 10.1093/jogss/ogaa006
2. Lyu, Y., Yuan, J.-H., Sun, Y., Liu, J., Gong, C.-Y. (2019), "Optimization of vehicle routing problem in military logistics on wartime", *Kongzhi yu Juece/Control and Decision*. Vol. 34, iss. 1. P. 121–128. DOI: 10.13195/j.kzyjc.2017.0983
3. Nakonechnyi, O. (2019), "Analysis of conditions and factors influencing the efficiency of the system of logistics of the country defense forces", *Control, Navigation and Communication Systems. Academic Journal,* VOL. 3 (55). P. 48–57. doi:https://doi.org/10.26906/SUNZ.2019.3.048
4. Havryliuk, I., Matsko, O., Dachkovskyi, V. (2019), "Conceptual basis of flow management in the system of logistic support of the armed forces of Ukraine", *Modern Information Technologies in Security and Defence,* T. 34, No. 1. P. 37–44. DOI: 10.33099/2311-7249/2019-34-1-37-44
5. Fedorovich, O., Uruskiy, O., Chepkov, I., Lukhanin, M., Pronchakov, Yu., Rybka, K., Leshchenko, Yu. (2022), "Simulation of transport logistics of military cargo considering

the losses occurring in the war zone due to delays in delivery", *Radioelectronic and Computer Systems*, No. 2(102). P. 63–74.

6. Školník, M. (2018), "New trends in the management of logistics in the Armed Forces of the Slovak Republic", *Zeszyty Naukowe Akademii Sztuki Wojennej*, No. 3(112), P. 53–63. DOI: 10.5604/01.3001.0013.0878
7. Halizahari, M., Daud, M. F., Sarkawi, A. A. (2022), "The Impacts of Transportation System towards the Military Logistics Support in Sabah", *International Journal on Advanced Science, Engineering and Information Technology*, Vol. 12, Iss. 3. P. 1092–1097. DOI: 10.18517/ijaseit.12.3.14516
8. Pecina, M., Husak, J. (2018), "Application of the new NATO logistics system", *Land Forces Academy Review*, Vol. 23, No. 2. P. 121–127. DOI: 10.2478/raft-2018-0014
9. Fedorovich, O., Pronchakov, Yu., (2020), "Method to organize logistic transport interactions for the new order portfolio of distributed virtual manufacture", *Радіоелектронні і комп'ютерні системи*, No. 2. P. 102–108. DOI: 10.32620/reks.2020.2.09
10. Fedorovich, O., Uruskiy, O., Chepkov, I., Lukhanin, M., Pronchakov, Yu., Rybka, K., Leshchenko, Yu. (2022), "Simulation of the logistics to establish parity of military forces in a war zone", *Aerospace technic and technology* No. 4. P. 57–67, DOI: https://doi.org/10.32620/aktt.2022.4.07
11. Bovda, E., Stetsenko, I., Bovda, V. (2019), "Petri-object modeling of transportation of material assets in military units", *Collection of scientific papers of the Military Institute of Telecommunications and Informatization*, Issue 3. Kyiv: MITI, P. 6–15.
12. Demertzis, K., Kikiras, P., Iliadis, L. (2022), "A Blockchained Secure and Integrity-Preserved Architecture for Military Logistics Operations", *Communications in Computer and Information Science*. Vol. 1600. P. 271–283. DOI: 10.1007/978-3-031-08223-8_23
13. Lai, C.-M., Tseng, M.-L. (2022), "Designing a reliable hierarchical military logistic network using an improved simplified swarm optimization", *Computers and Industrial Engineering,* Vol. 169. No. 108153. DOI: 10.1016/j.cie.2022.108153
14. Polishchuk, Ye., Chmykhun, Ye., Solovyov, V. (2022), "Simulation of critical vulnerabilities in the logistics of supply arms and military equipment under conditions of military threat", *Aerospace technic and technology*, No. 6 (184). P. 40–49. DOI: 10.32620/aktt.2022.6.05
15. Milewski, R., Smal, T. (2018), "Decision making scenarios in military transport processes", *Archives of Transport*, Vol. 45, iss. 1. P. 65–81. DOI: 10.5604/01.3001.0012.0945
16. Nechyporuk, M., Fedorovich, O., Popov, V., Romanov, M. (2022), "Modeling of specialists' profiles for planning and implementation of projects for the creation of innovative products of aerospace techniques", *Radioelectronic And Computer Systems*, No. 1 (101). P. 23–35. DOI: 10.32620/reks.2022.1.02
17. Fedorovich, O., Chepkov, I., Lukhanin, M., Pronchakov, Yu., Rybka, K., Leshchenko, Yu. (2022), "Modeling of supply logistics and training of military personnel for the successful use of weapons in a combat area", *Radioelectronic and Computer Systems*, No. 3(103). P. 33–46. doi: 10.32620/reks.2022.3.03
18. Raskin, L., Sira, O., Parfeniuk, Y., Bazilevych, K. (2021), "Development of methods for supply management in transportation networks under conditions of uncertainty of transportation expence values", *EUREKA, Physics and Engineering*, No. 2. P. 108–123. DOI: 10.21303/2461-4262.2021.001691

19. Raskin, L., Sira, O., Sukhomlyn, L., Parfeniuk, Y. (2021), "Universal method for solving optimization problems under the conditions of uncertainty in the initial data", *Eastern-European Journal of Enterprise Technologies*, 1(4 (109), 46–53. https://doi.org/10.15587/1729-4061.2021.225515
20. Acero R, Torralba M, Pérez-Moya R, Pozo JA. (2020), "Value Stream Analysis in Military Logistics: The Improvement in Order Processing Procedure", *Applied Sciences*, No. 1, P. 106. https://doi.org/10.3390/app10010106
21. Fedorovich, O., Rubin, E., Yeremenko, N. (2016), "Study of supply and sales logistics in a heterogeneous transport infrastructure of cargo transportation", *Monogr. National Aerospace University* – 'Kharkiv Aviation Institute', 198 p.
22. Fedorovich, O., E., Yeremenko, N. (2014), "Enumeration of multiple variants of the logistics network of distribution centers of production sales", *Information processing systems: collection of science Ave. / Khark. National Air University Forces named after Ivan Kozhedub*, No. 9 (125). P. 205–208.
23. Junhai Cao, Chuang Zhang, Yantong Li, Yiming Guo, Qingyi Guo (2022), "Combinatorial Optimization Methods for Determining the Pre-storage Location and Pre-setting the Distribution of Equipment Maintenance Materials", *Acta Armamentarii*, Vol. 43, iss. 10. P. 2668–2678. – Available at: http://www.co-journal.com/CN/Y2022/V43/I10/2668. – 10.12.2022
24. Barbu, M.-L. (2019), "Theoretical considerations concerning the setting of the capability requirements specific to combat engineers structures supporting management acrivities from the airfield", *Journal of Defense Resources Management*, Vol. 10, Iss. 2(19). P. 188–196.
25. Çetinkaya, C., Haffar, S. (2018), "A Risk-Based Location-Allocation Approach for Weapon Logistics", *Logistics*, Vol. 2, Iss. 2, No. 9. DOI: 10.3390/logistics2020009
26. Liu, Y., Li, L., Tu, Y., Mei, Y. (2020), "Fuzzy TOPSIS-EW Method with Multi-Granularity Linguistic Assessment Information for Emergency Logistics Performance Evaluation", *Symmetry*, vol. 12, iss. 8, No. 1331. DOI: 10.3390/sym12081331
27. Andrews, W. S., Hurley W. J. (2004), "Approaches To Determining Army Operational Stockpile Levels", *Canadian Military Journal*, P. 37–46. Available at: http://www.journal.forces.gc.ca/vo5/no2/doc/technology-technologi-eng.pdf. (accessed 12.11.2022).
28. Fedorovich, O., Chepkov, I., Lukhanin, M., Pronchakov, Yu., Rybka, K., Leshchenko, Yu. (2022), "Simulation of the logistic process of the industrial enterprise evacuation in wartime", *Aerospace Technic And Technology*, No. № 3(179). P. 84–93.