

MODELING THE FORMATION OF DRONE SWARMS USING COMPONENT AND AGENT-BASED APPROACHES

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The task of studying the multi-component composition of military equipment (using UAVs as an example) during the delivery and formation of the necessary stocks of weapons and their components in a military conflict zone to ensure military superiority, which contributes to the successful achievement of military operation objectives, has been formulated and is being addressed. A multi-variant, multi-criteria problem is also being solved, which is related to the modeling of the logistics process of ensuring military superiority in a military conflict zone. The aim of the study is to model actions to provide combat units with various types of UAVs when forming a drone swarm to ensure military superiority in the air in conditions of threats and vulnerabilities associated with the logistics of supplying UAVs to the military conflict zone. A component approach is used to represent weapons and their components in the process of military equipment supply. A multi-layer component structure of UAVs is proposed for the systematic representation of weapons and their components in the process of supply and stockpiling in a military conflict zone. The factors of threats associated with the supply of the required types of UAVs in the quantities necessary to form a drone swarm are investigated using qualitative assessments by military experts and lexicographic ordering of possible UAV suppliers. The selection of UAV suppliers has been optimized using integer programming. A model has been created to optimize the logistics costs of supplying weapons and their components to the combat zone. Optimization tasks are solved under conditions of conflicting criteria of time, costs, and risks associated with the logistics of forming military superiority in the combat zone. An agent-based simulation model for researching the logistics of military cargo delivery in a conflict zone has been created. The results of the research can be used to model plans and logistics for the delivery of weapons and their components to combat zones in order to create military superiority.

Introduction

In modern conditions, the success of a military operation depends on many factors, including military superiority over a potential enemy [1, 2]. The use of military equipment in a state of war requires an analysis of the necessary quantity and range of weapons, taking into account the composition of their components, in order to create military superiority in the zone of military conflict [3, 4]. Creating superiority in weapons and military equipment is one of the important tasks in preparing for a military operation [5, 6].

Building military superiority is a complex logistical task that requires the involvement of developers, suppliers of weapons and military equipment, and participants in transport logistics in a heterogeneous transport environment

with possible transshipments from one transport route to another and temporary storage of military cargo [7].

There's some tricky logistics involved in delivering small batches of weapons and their components from manufacturers and suppliers who are far away from the combat zone [8–10]. When forming stocks of military equipment, it is necessary to take into account the composition of components that ensure the effective use of weapons (ammunition, spare parts, repair kits, auxiliary equipment) [11, 12]. The logistics of training military personnel to use modern weapons requires considerable time. All of the above, in general, has an impact on the formation of the combat capability of military units and the establishment of superiority over the enemy in the zone of military conflict [13].

Today, within the Unmanned Systems Forces (USF), strike companies of UAVs are being created, as well as other units specializing in various types of unmanned aerial vehicles. Providing the USF with the necessary unmanned aerial vehicles for forming drone swarms, equipment for their control, and ammunition is an important task.

Therefore, the topic of this publication is relevant, as it addresses and solves the problem of logistics for ensuring superiority over the enemy in a military conflict zone for the successful conduct of military operations under conditions of threats and vulnerabilities associated with the logistics of supplying weapons to UAV units [14, 15], as well as the use of the component method and a precedent-based approach to analyze the logistics of supplying and forming stocks of weapons and their components in the combat zone [16, 17].

1. Analysis of current publications and setting the task

An analysis of publications on this topic showed that existing works are mainly related to individual aspects of the task at hand, such as research on requirements for establishing military parity for the successful conduct of military operations [15], logistics of military cargo transportation [18], and uncertainties related to military transportation logistics [19]. There are no publications offering a comprehensive solution to the proposed task, analyzing threats related to the violation of military parity in a zone of military conflict, or logistical threats related to the transportation of military cargo to a combat zone. In addition, the impact of possible vulnerabilities related to the logistics of military cargo delivery to the combat zone, leading to a violation of military parity and, as a result, to the death of armed forces personnel, the destruction of defense infrastructure, the transition from offensive to defensive actions, etc., has not been studied.

The existing operational and tactical logistical problems related to establishing military superiority in a war zone have been analyzed, among which the following are noteworthy:

1. The problem of the large number of weapon components and small delivery batches to the war zone. In the existing literature, the task of forming stocks of weapons and their components is considered mainly in peacetime. Army stocks of weapons and manufacturers' stocks are formed, and long-term plans are implemented to form stocks of weapons for a sufficiently long period of time [19].

2. The logistical problem associated with the supply of weapons and their components through logistical channels in conditions of military threat. In peacetime, military equipment stocks are formed according to a pre-established schedule and logistical supply chains [18].

3. The problem of military threats, which leads to disruptions and stoppages in the supply of military equipment. In peacetime, threats are associated with possible transport breakdowns, accidents on transport routes, the influence of climatic factors, and the emergence of terrorist threats [20].

4. The problem of timely delivery of weapons and their components is related to military circumstances and the nature of combat operations in the zone of military conflict. In peacetime, when supplying military equipment, the requirements for the formation of stocks of weapons and their components are taken into account in accordance with pre-established plans for the formation of stocks in army warehouses [21].

The purpose of the study is to model actions to provide units with different types of UAVs when forming a drone swarm to ensure military superiority in the air in conditions of threats and vulnerabilities associated with the logistics of supplying UAVs to a military conflict zone using the component method to represent weapons and their components in the process of supplying military equipment.

The main criteria for evaluating the achievement of the research objective are threat levels, logistical risks, and the time and costs required to establish military superiority in a military conflict zone.

To achieve the research objective, the following tasks must be solved:

1. To form a component structure of military equipment for the systematic representation of weapons and their components (using UAVs as an example).
2. To develop a component method for creating innovative UAV models.
3. To analyze threat factors in the formation of military superiority in the air in a military conflict zone.

4. To conduct threat modeling in the logistics of production and supply of weapons and military equipment to ensure air superiority in a military conflict zone.

5. To optimize logistics costs for the formation of stocks of weapons and their components in a military conflict zone.

6. To develop a method for improving the efficiency of weapons use by creating asymmetry in military parity in a military conflict zone.

7. To create an agent-based simulation model for researching the logistics of production and supply of weapons and military equipment to a military conflict zone to establish military superiority.

2. Modeling the provision of UAV units in a military conflict zone using a component-based approach

2.1 Formation of the UAV component structure for systematic representation of weapons and their components

For the effective use of weapons in a military conflict zone, it is necessary to comprehensively supply, in the required quantities, all components of military equipment (ME) related to the effective functioning of weapons:

- basic structural components (BSC);
- ammunition (A);
- spare parts and repair kits (SP);
- auxiliary equipment (AE), which for UAVs includes control, communication, power supply, transportation, and training equipment;
- mobile workshops for repairing military equipment (MME).

The lack of the necessary quantity of weapon components in the war zone (in accordance with NATO requirements and standards) leads to a reduction in the combat effectiveness of military equipment, as well as the inefficient use of weapons. Therefore, it is important to systematically present the architecture of military equipment in the form of weapons and their supporting components.

Fig. 1 shows a hierarchical diagram of types of weapons, highlighting the component structure of a particular type of military equipment.

Here, on the top level, you can see the types of weapons used in war zones, with aviation equipment, including UAVs, highlighted on the second level. The third level shows the components.

For example, a typical copter-type UAV consists of the following components:

- body or fuselage (B);
- power unit (engine) (PU) ;
- autopilot (flight controller) with sensors (AP);

- control equipment (CE);
- air screw (propeller) (AS);
- information signal and telemetry transmitter and receiver (ITR);
- onboard electronics (OE);
- power source (battery, generator) (PS);
- landing gear (chassis) (LG).

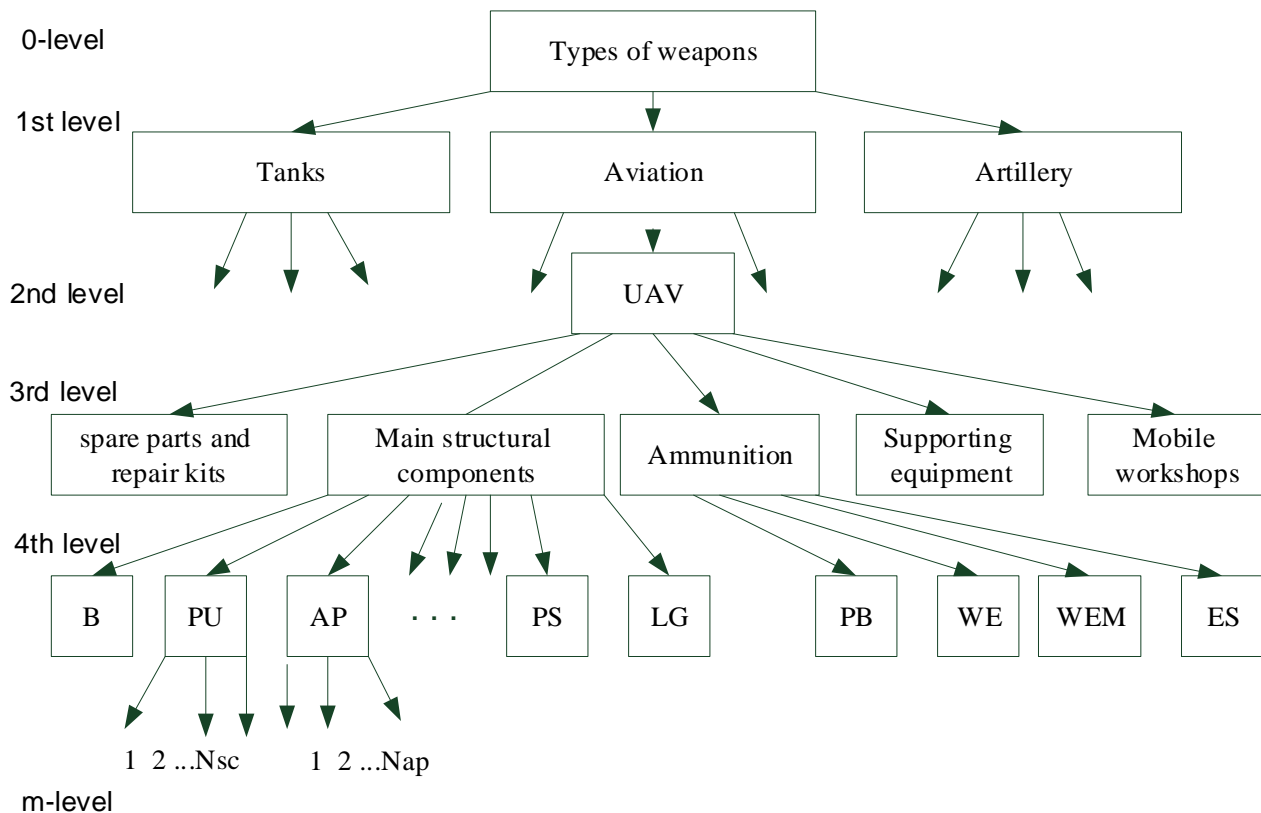


Fig. 1. Component structure of a type of military equipment (UAV)

At the next level are components that that make up the supporting elements. For strike UAVs, ammunition is an important component. Combined-type UAVs are adapted to drop combat grenades (F-1, RGD-5, RGO, RGN, RK-3) and mines (VOG-17, 82 mm for the 2B14 mortar and 120 mm for the 2B11 and 2B12) on the enemy. UAVs are transformed into high-precision weapons that simultaneously perform aerial reconnaissance tasks. In general, ammunition contains the following components:

- projectile body (PB);
- warhead elements (cone or arrow) (WE),
- warhead element mountings (WEM),
- explosive substance (ES).

The details of military equipment can be further elaborated, taking into account not only the processes of supplying weapons and their components to the zone of military conflict, but also the processes of manufacturing military equipment.

The modern approach to the creation of military equipment, based on NATO standards and regulations, allows new weapons to be created by combining existing components (reusable components). Therefore, it is advisable to use the component method when modeling the creation of new types of weapons.

The following typical components can be identified for the creation of new military equipment:

- reusable components (RC), which can be used in various types and kinds of weapons;
- components that, through the adaptation of RC (AC), can be used in the creation of new types of weapons;
- new components (IC) of an innovative nature. These components must be used to create innovative models of military equipment.

The creation of innovative types of UAVs with the predominant use of RCC allows minimizing risks, development time, and costs. However, the tactical and technical characteristics of UAVs and their combat effectiveness will not differ significantly from existing ones. The predominant use of innovative components allows for improving the tactical and technical characteristics for combat use of UAVs (accuracy, range, kill zone, etc.), but at the same time increases the risks, time, and costs of an innovative project. A compromise lies in the combined use of RC, AC, and NC components in the military equipment being developed. This allows for the creation of innovative UAV models with improved characteristics while keeping project time and cost risks at a satisfactory level.

The use of the component method to represent the multilayered structure of military equipment allows for a systematic analysis of the logistics of supplying and forming comprehensive stocks of UAVs and their components in a military conflict zone, taking into account two main areas [20]:

1. Supply of UAVs from army warehouses and manufacturers' warehouses.
2. Production of UAVs for delivery and formation of necessary stocks in the zone of military conflict.

The logistics of forming stocks of military equipment in the zone of military conflict belongs to the «pull» type of logistics system. In this case, the requirements for UAV stockpiles are determined at the operational-tactical level, taking into account the situation and objectives of military operations in the war zone. These requirements are initially analyzed at the army depot level. If army depots

do not have sufficient stockpiles, the possibility of supplying them from manufacturers' warehouses is analyzed. If the requirements for the comprehensive formation of UAV stocks in the zone of military conflict cannot be met using army warehouses and manufacturers' warehouses, production plans are drawn up to eliminate the shortage of UAVs and their components.

The component method allows, taking into account the use of RC, AC, and NC components, to determine the logistics requirements for the comprehensive formation of military equipment stocks in a military conflict zone in the following sequence of actions:

1. First, at the operational and tactical level, using expert assessments of military specialists, requirements are formed for the required number W_j of the j -th type of UAVs for use in the zone of military conflict. At the first level, requirements for the supporting components of the weapon W_{j1} are formed.

2. The availability of the required number of certain types of UAVs W_{j1} in army warehouses is checked. If

$$W_{j1} \leq W'_{j1} \quad (1)$$

where W'_{j1} is the availability of UAVs of the j -th type in the army warehouses), then the required amount of W_{j1} is supplied to the zone of military conflict to form stocks of the j -th type of UAV.

3. If

$$W_{j1} > W'_{j1}, \quad (2)$$

then the availability of W'_{j1} in the manufacturers' warehouses is checked.

If

$$W_{j1} \leq W'_{j1} + W''_{j1}, \quad (3)$$

then W_{j1} is delivered to the military conflict zone.

4. If

$$W_{j1} > W'_{j1} + W''_{j1}, \quad (4)$$

then in this case production plans are formed for the output

$$\Delta W_{j1} \geq W_{j1} - (W'_{j1} + W''_{j1}). \quad (5)$$

5. To implement the production plans ΔW_{j1} , it is necessary to form auxiliary plans for the production of supporting components of the third level of representation of the component architecture of military equipment (see Fig. 1).

Let's introduce the following notation:

B – ammunition;
 Z – spare parts;
 V – auxiliary equipment;
 M – mobile workshops.

Given these notations, we write the following constraints:

$$\begin{aligned}
 \Delta W_{j2_B} &\geq W_{j2_B} - (W'_{j2_B} + W''_{j2_B}), \\
 \Delta W_{j2_Z} &\geq W_{j2_Z} - (W'_{j2_Z} + W''_{j2_Z}), \\
 \Delta W_{j2_V} &\geq W_{j2_V} - (W'_{j2_V} + W''_{j2_V}), \\
 \Delta W_{j2_M} &\geq W_{j2_M} - (W'_{j2_M} + W''_{j2_M}),
 \end{aligned} \tag{6}$$

where $\Delta W_{j2_B}, \Delta W_{j2_Z}, \Delta W_{j2_V}, \Delta W_{j2_M}$ is the required amount of ammunition, spare parts, auxiliary equipment, and mobile workshops for the comprehensive supply of UAVs to the military conflict zone.

6. Further, if there is a need to produce components for the i -th level of representation of the component architecture of military equipment, then in this case it is necessary:

$$\begin{aligned}
 \Delta W_{ji_B} &\geq W_{ji_B} - (W'_{ji_B} + W''_{ji_B}), \\
 \Delta W_{ji_Z} &\geq W_{ji_Z} - (W'_{ji_Z} + W''_{ji_Z}), \\
 \Delta W_{ji_V} &\geq W_{ji_V} - (W'_{ji_V} + W''_{ji_V}), \\
 \Delta W_{ji_M} &\geq W_{ji_M} - (W'_{ji_M} + W''_{ji_M}).
 \end{aligned} \tag{7}$$

Thus, the use of the component method in the integrated formation of UAV stocks of various types, using warehouses and production of components, allows to formulate requirements for the volume of stocks and production plans for different levels of component representation.

2.2 Component method for creating innovative UAV prototypes

When creating new models of military equipment, not only reusable components (RC) but also adaptive components (AC) and innovative (IC) components may be used in the product. At the initial stages of military equipment development, it is necessary to form the component architecture of the product, taking into account the tactical and technical characteristics (TTC) set out in the project specifications.

A method for synthesizing innovative UAV models has been proposed, taking into account multi-level component architecture, which is based on the active use of existing components (EC), allowing to minimize project risks and reduce the time required to create relevant weapons for use in a military conflict zone. The component method consists of the following stages:

1. At the beginning, the component composition of the ME product is formed at the subsystem level. TTCs are specified for each component. We search for existing components with the required TTCs in a database formed based on previous developments and existing weapons. The component database will be presented in the form of precedent bases (PB), which accumulate the experience of previous developments.

2. During the synthesis process, the following directions for creating the component architecture of innovative UAV models are possible:

A) the PB database contains the necessary components for forming the component architecture of the product at the first level (subsystem level). In this case, we proceed to the next stage of design;

B) the precedent database contains components whose TTC does not fully match those required in the technical specifications for the project. In this case, it is necessary to search for similar components by TTC value. That is, it is necessary to evaluate the similarity between the k -th precedent in the PB and the required p -th component of the project. In doing so, both quantitative and qualitative metrics can be used to evaluate similarity. In the simplest method of evaluating similarity (Minkowski metric), Euclidean distance is used:

$$\lambda_{kp} = \sqrt{\sum_{l=1}^L \rho_l (\lambda_{kl} - \lambda_{pl})^2}, \quad (8)$$

where $l = \overline{1, L}$ – 1st characteristic from TTC components in the project;

λ_{pl} – value of the 1st characteristic for the r -th UAV component in the project;

λ_{kl} – value of the 1st characteristic for the k -th precedent in PB;

ρ_l – significance (weight) of the 1st characteristic.

In the early stages of creating a new military product, there are characteristics whose proximity to the project can be assessed qualitatively. In this case, the proximity assessment can be carried out using a qualitative representation.

For example, in the form of letters of the Latin alphabet:

$$\partial_{kp_l} = \left\{ \begin{array}{l} A - \textit{maximum proximity of components} \\ \textit{according to the 1st characteristic;} \\ B - \textit{satisfactory proximity of components} \\ \textit{according to the 1st characteristic;} \\ C - \textit{allowable proximity of components} \\ \textit{according to the 1st characteristic;} \\ D - \textit{remoteness of components} \\ \textit{according to the 1st characteristic.} \end{array} \right. \quad (9)$$

Next, depending on the importance of the TTC UAV, an ordered list of characteristic values (in the form of «words») is compiled. For example: B, B, A, C, B for five characteristics. Then, if there is not only one possible close component available, but several in the precedent database, a list of «words» is formed. For example:

B, B, C, A, B
 B, B, D, C, B
 C, B, D, C, B
 B, B, A, C, B
 A, C, D, A, C.

The list of «words» is lexicographically sorted and takes the following form:

A, C, D, A, C
 B, B, A, C, B
 B, B, C, A, B
 B, B, D, C, B
 C, B, D, C, B.

Next, the permissible proximity indication is set in the form of a «control word». For example:

$\boxed{B, B, B, B, B}$.

The «control word» is placed in an ordered list of «words»:

A, C, D, A, C
 B, B, A, C, B
 $\boxed{B, B, B, B, B}$
 B, B, C, A, B
 B, B, D, C, B
 C, B, D, C, B.

Next, select the closest component by the characteristic value in PB, which is adjacent to the «control word»: B, B, A, C, B. This component will be used in further design;

C) there is no component in the PB of existing components with the required proximity in terms of characteristics. In this case, we proceed to the decomposition of the i -th level project component into possible components of the lower $(i+1)$ level of the multi-component architecture of the product and search for the required components in the PB at the $(i+1)$ level of representation. Next, we repeat the actions in step 2;

D) a possible situation is related to the design of a new innovative component. Figure 2 shows a diagram of the component synthesis of military equipment.

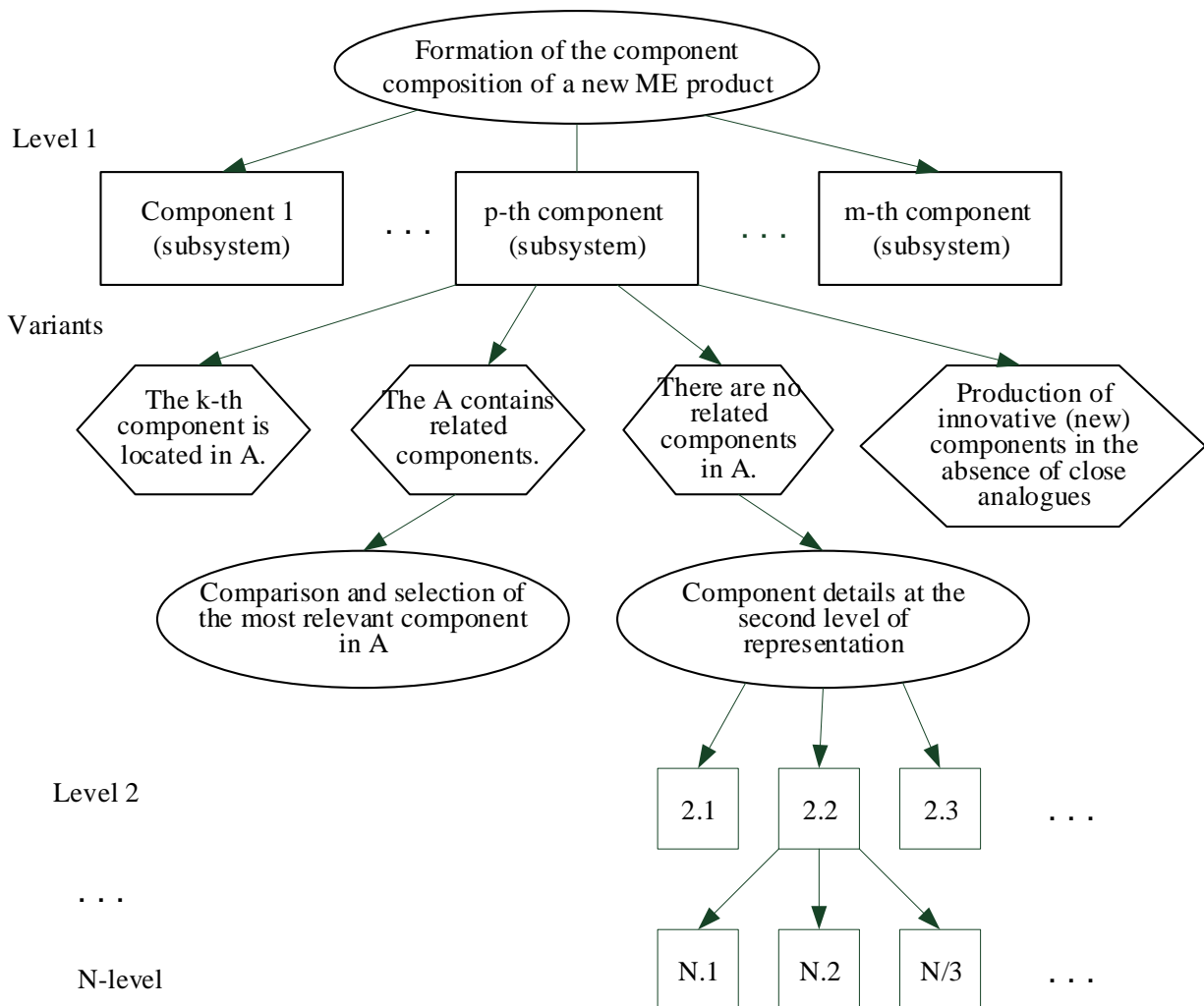


Fig. 2. Component synthesis diagram for a new military equipment product

2.3. Optimization of logistics costs for the supply of weapons and components in the combat zone

The complexity of the integrated supply of weapons to the combat zone is associated with the many supporting components of military equipment that are necessary for the effective use of weapons (ammunition, spare parts, repair kits, auxiliary equipment for maintenance, training of military personnel, etc.) Therefore, the task of optimizing logistics costs for the timely delivery of UAVs and their components to the combat zone to create a military advantage is urgent. The effectiveness of the use of a particular j -th type of UAV in the combat zone will depend on the comprehensive supply of the required number of supporting components (designated respectively as B, Z, V, M). To create a stockpile of UAVs of the j -th type in the amount of W_j , it is necessary that the number of UAVs is in the interval:

$$W_{j\min} \leq W_j \leq W_{j\max}, \quad (10)$$

here $W_{j\min}$ corresponds to the insurance stocks W_j in the combat zone, which ensure, taking into account military risks, the establishment of parity of forces for the j -th type of A (without violating the nature of hostilities).

The value of $W_{j\max}$ creates an asymmetry in the military parity of forces, which can ensure a change in the nature of hostilities (transition from defensive to offensive actions). Therefore, planning of weapons stocks within the limits of (10) is the basis for the successful fulfillment of the objectives of a military operation. Also, it is necessary to fulfill similar requirements for the formation of stocks of supporting components of the j -th type of UAV (B, Z, V, M):

$$\begin{aligned} W_{jB\min} &\leq W_{jB} \leq W_{jB\max}, \\ W_{jZ\min} &\leq W_{jZ} \leq W_{jZ\max}, \\ W_{jV\min} &\leq W_{jV} \leq W_{jV\max}, \\ W_{jM\min} &\leq W_{jM} \leq W_{jM\max}. \end{aligned} \quad (11)$$

The complex supply of UAV types and its supporting components can be carried out through a variety of logistics channels (LC). Therefore, it is relevant to solve the problem of optimizing the choice of LCs, taking into account logistics costs and requirements for the timely formation of military equipment stocks in the CZ, under conditions of possible military risks R_j . The optimization problem belongs to the class of multivariate problems using a set of indicators and constraints. To solve this optimization problem, we will use the method

of integer (Boolean) programming. Let's introduce a Boolean variable x_{jik} , which has the following values:

$$x_{jik} = \begin{cases} 1, & \text{if } k\text{-th logistics channel is selected} \\ & \text{for the supply of } i\text{-th components of } j\text{-th type of weapons;} \\ 0, & \text{other wise.} \end{cases} \quad (12)$$

Let us present the logistics indicators of military equipment supply in the combat zone as follows:

1. The volume of UAV stocks that are formed in the area of military conflict:

$$W = \sum_{j=1}^Q \sum_{i=1}^{n_j} \sum_{k=1}^{n_{ij}} w_{jik} x_{jik}, \quad (13)$$

where w_{jik} is the number of i -th components of the j -th type of UAV, which are supplied according to the k -th possible LC;

n_{ij} is the number of possible LCs from which the i -th components of the j -th UAV type are selected for supply;

n_j is the set of different components of the j -th UAV type;

Q is the number of UAV types entering the military conflict zone;

$i = 1$ corresponds to the weapon, $i = 2, \dots$, refers to the supporting components of the weapon.

2. Time of delivery of UAVs to the zone of military conflict:

$$T = \sum_{j=1}^Q \sum_{i=1}^{n_j} \sum_{k=1}^{n_{ij}} t_{jik} x_{jik}, \quad (14)$$

where $T \leq T'$, T' is the permissible time that ensures timely delivery of weapons to the military conflict zone;

t_{jik} is the time of delivery of batches of the i -th component for the j -th type of weapon according to the selected k -th LC.

3. Risks of supplying UAVs to a military conflict zone under martial law:

$$R = \sum_{j=1}^Q \sum_{i=1}^{n_j} \sum_{k=1}^{n_{ij}} r_{jik} x_{jik}, \quad (15)$$

where $R \leq R'$, R' is the permissible risk of supplying weapons to the CZ;

r_{jik} is the risk of supplying batches of i -th components for the j -th type of weapon according to the selected k -th LC.

4. Logistical costs associated with the supply of UAVs to the zone of military conflict:

$$L = \sum_{j=1}^Q \sum_{i=1}^{n_j} \sum_{k=1}^{n_{ij}} l_{jik} x_{jik}, \quad (16)$$

where $L \leq L'$, L' is the allowable logistics costs of supply,

l_{jik} is the logistics costs associated with the supply of the i -th component for the j -th type of UAV according to the selected k -th LC.

To form the necessary UAV stocks in a military conflict zone under conditions of military risks, in order to create a military advantage, it is necessary to:

$$\max W, W = \sum_{j=1}^Q \sum_{i=1}^{n_j} \sum_{k=1}^{n_{ij}} w_{jik} x_{jik}, \quad (17)$$

taking into account

$$W_{jik_{\min}} \leq W_{jik} \leq W_{jik_{\max}} \quad \text{for all } j, i, k. \quad (18)$$

The following conditions must be met:

$$T \leq T', T = \sum_{j=1}^Q \sum_{i=1}^{n_j} \sum_{k=1}^{n_{ij}} t_{jik} x_{jik},$$

$$R \leq R', R = \sum_{j=1}^Q \sum_{i=1}^{n_j} \sum_{k=1}^{n_{ij}} r_{jik} x_{jik}, \quad (19)$$

$$L \leq L', L = \sum_{j=1}^Q \sum_{i=1}^{n_j} \sum_{k=1}^{n_{ij}} l_{jik} x_{jik}.$$

For the timely supply and formation of the necessary stocks of UAVs in the zone of military conflict, under martial law, it is necessary:

$$\min T, T = \sum_{j=1}^Q \sum_{i=1}^{n_j} \sum_{k=1}^{n_{ij}} t_{jik} x_{jik}, \quad (20)$$

Subject to the following restrictions:

$$W \geq W', W = \sum_{j=1}^Q \sum_{i=1}^{n_j} \sum_{k=1}^{n_{ij}} w_{jik} x_{jik},$$

$$R \leq R', R = \sum_{j=1}^Q \sum_{i=1}^{n_j} \sum_{k=1}^{n_{ij}} r_{jik} x_{jik}, \quad (21)$$

$$L \leq L', L = \sum_{j=1}^Q \sum_{i=1}^{n_j} \sum_{k=1}^{n_{ij}} l_{jik} x_{jik}.$$

The solution of the set optimization problems with Boolean variables can be carried out by one of the possible methods of integer optimization (for example, the modified branch-and-bound method).

3. Modeling the logistics of establishing military superiority in a combat zone

3.1 Analysis of Threat Factors in Establishing Military Superiority in the Combat Zone

In order to establish military superiority, it is necessary to analyze the main components of weapons and military equipment in a particular area of military conflict. For example, such components in the form of threat factors are the lack of the following types of weapons in the required quantity:

- aviation (including unmanned aerial vehicles)
- heavy weapons,
- ammunition.

Suppose that, with the help of military experts, the required types and number of UAVs for the area of military conflict under consideration are determined in the form of a set – M , $m_i \in M$, $i = \overline{1, N}$. Where m_i is the number of UAVs of the i -th type required to establish military superiority, N is the number of required types of UAVs to establish military superiority in the combat zone (CZ).

It is known, based on the available weapons, how many UAVs 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 at the present time.

Then

$$\Delta m_i = m_i - m_{0i} \tag{22}$$

is the number of weapons of the i -th type required to ensure military parity of forces in the CZ. The greater is the value of Δm_i , the greater is the threat associated with the lack of the required number of weapons of the i -th type. The emergence of threats associated with the required number of certain types of UAVs can lead to losses in the CZ. Therefore, it is necessary to assess the level of threats, taking into account possible factors related to the insufficient number 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 UAV.

To do this, we will use qualitative assessments of the level of threats in the form of linguistic variable values [21]:

$$x_i = \begin{cases} A - \text{low threat level} \\ \quad \text{to the } i\text{-th type of weapon;} \\ B - \text{acceptable level of threat;} \\ C - \text{high level of threat.} \end{cases} \quad (23)$$

For each i -th type of UAV, there is a set of suppliers P_i that can supply m_{ij} weapons $m_{ij} \leq \Delta m_i$. The value of m_{ij} is a factor that affects the threat level x_i and is determined 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 UAV by the j -th supplier. Let w_{ij} denote the costs of production and delivery of the i -th type of UAV by the j -th supplier, and r_{ij} denote the risks of production and delivery of the i -th type of UAV by the j -th supplier.

Let's define these values in a qualitative scale as multiples of three estimates:

$$\begin{aligned} t_{ij} &= \begin{cases} A - \text{minimum delivery term;} \\ B - \text{acceptable delivery term;} \\ C - \text{maximum delivery term;} \end{cases} \\ w_{ij} &= \begin{cases} A - \text{minimum costs;} \\ B - \text{acceptable costs;} \\ C - \text{maximum costs;} \end{cases} \\ r_{ij} &= \begin{cases} A - \text{minimum risk;} \\ B - \text{acceptable risk;} \\ C - \text{maximum risk.} \end{cases} \end{aligned} \quad (24)$$

To determine the supplier in the set P_i , we represent each possible 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 established by military experts depending on the value m_{ij} , which is associated with the number of the i -th type of UAV and can be supplied by the j -th supplier.

The list of qualitative values x_{ij} , t_{ij} , w_{ij} , r_{ij} will be represented as a «word». Then, for the set P_i of possible suppliers of the i -th type of UAV, we will get a list of «words» that will represent the options chosen by the suppliers.

For example, we have 10 options:

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 ordering the options in the lexical and graphical sense, 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 in the top half of the ordered list of possible suppliers of UAVs of the i -th type. In this 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 UAV, the acceptable value of production and delivery costs, and the acceptable value of risk.

Thus, for each i -th type of UAV, suppliers will be selected that ensure the minimum level of threat for all weapons in the formation of military parity of forces in the area of military conflict.

Given the large number of possible UAV suppliers, we will use quantitative estimates to formulate an optimization problem of selecting a supplier from a set of suppliers that minimizes the level of threats in the formation of air superiority in the combat zone.

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

$$z_{ij} = \begin{cases} 1 - \text{if the } i\text{-th supplier is selected} \\ \quad \text{for the } j\text{-th type of weapons;} \\ 0 - \text{other wise;} \end{cases} \quad (25)$$

wherein

$$\sum_{j=1}^{n_i} z_{ij} = 1. \quad (26)$$

Then, the threat criterion can be given in the following form:

$$V = \sum_{i=1}^N \sum_{j=1}^{n_i} v_{ij} z_{ij}, \quad (27)$$

where v_{ij} is a quantitative assessment of the level of threat proposed by military experts (for example, on a 10-point scale) when choosing the j -th supplier of the i -th type of UAV,

n_i is the number of possible suppliers of the i -th type of UAV.

It should be noted that v_{ij} depends on the number of $m'_{ij} \leq \Delta m_{ij}$, where m'_{ij} is the actual number of UAVs of the i -th type that can be supplied by the j -th supplier.

The total time for the production and delivery of weapons (a pessimistic estimate of the time associated with the sequential nature of the supply) is determined by the formula:

$$T = \sum_{i=1}^N \sum_{j=1}^{n_i} t_{ij} z_{ij}. \quad (28)$$

The costs associated with the production and supply of the necessary weapons and military equipment to establish military superiority in the CZ are:

$$W = \sum_{i=1}^N \sum_{j=1}^{n_i} w_{ij} z_{ij}. \quad (29)$$

Risks of production and supply of weapons to establish military superiority in the CZ are determined by the formula:

$$R = \sum_{i=1}^N \sum_{j=1}^{n_i} r_{ij} z_{ij}. \quad (30)$$

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

$$\min V, V = \sum_{i=1}^N \sum_{j=1}^{n_i} v_{ij} z_{ij}, \quad (31)$$

if the following restrictions are met:

$$\begin{aligned} T \leq T', T &= \sum_{i=1}^N \sum_{j=1}^{n_i} t_{ij} z_{ij}, \\ W \leq W', W &= \sum_{i=1}^N \sum_{j=1}^{n_i} w_{ij} z_{ij}, \\ R \leq R', R &= \sum_{i=1}^N \sum_{j=1}^{n_i} r_{ij} z_{ij}, \end{aligned} \quad (32)$$

where T', W', R' – respectively, the permissible values of the time of production and delivery of UAVs, permissible costs and risks of establishing a military advantage in the CZ.

In the case of possible parallel deliveries of UAVs to the CZ (optimistic estimate of the delivery time), the time is defined as:

$$T = \max_{i=1}^N \left(\sum_{j=1}^{n_i} t_{ij} z_{ij} \right). \quad (33)$$

If military experts have difficulty determining threat assessments, then in this case we will use the values

$$\Delta m'_{ij} = \Delta m_{ij} - m'_{ij}, \quad (34)$$

which must be minimized during the production and delivery of UAVs to the CZ. In this case, it is necessary:

$$\min \Delta m', \Delta m' = \sum_{i=1}^N \sum_{j=1}^{n_i} \Delta m'_{ij} z_{ij}, \quad (35)$$

taking into account the permissible values;

$$\begin{aligned} T \leq T', T &= \sum_{i=1}^N \sum_{j=1}^{n_i} t_{ij} z_{ij}, \\ W \leq W', W &= \sum_{i=1}^N \sum_{j=1}^{n_i} w_{ij} z_{ij}, \\ R \leq R', R &= \sum_{i=1}^N \sum_{j=1}^{n_i} r_{ij} z_{ij}. \end{aligned} \quad (36)$$

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

$$\begin{aligned}
v_{ij} &= \sum_{k=1}^{l_j} v_{ijk}, \\
t_{ij} &= \sum_{k=1}^{l_j} t_{ijk}, \\
w_{ij} &= \sum_{k=1}^{l_j} w_{ijk}, \\
r_{ij} &= \sum_{k=1}^{l_j} r_{ijk},
\end{aligned} \tag{37}$$

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

Then, to assess the level of threats, it is necessary to minimize the level of threat:

$$\min V, \quad V = \sum_{i=1}^N \sum_{j=1}^{n_i} \left(\sum_{k=1}^{l_j} v_{ijk} \right) z_{ij}, \tag{38}$$

while fulfilling the constraints:

$$\begin{aligned}
T &\leq T', \quad T = \sum_{i=1}^N \sum_{j=1}^{n_i} \left(\sum_{k=1}^{l_j} t_{ijk} \right) z_{ij}, \\
W &\leq W', \quad W = \sum_{i=1}^N \sum_{j=1}^{n_i} \left(\sum_{k=1}^{l_j} w_{ijk} \right) z_{ij}, \\
R &\leq R', \quad R = \sum_{i=1}^N \sum_{j=1}^{n_i} \left(\sum_{k=1}^{l_j} r_{ijk} \right) z_{ij}.
\end{aligned} \tag{39}$$

If there are difficulties associated with quantifying the military threat level v_{ijk} , then it is necessary to:

$$\min \Delta m', \quad \Delta m' = \sum_{i=1}^N \sum_{j=1}^{n_i} \left(\sum_{k=1}^{l_j} \Delta m'_{ijk} \right) z_{ij}, \tag{40}$$

taking into account the fulfillment of the constraints

$$\begin{aligned}
 T \leq T', \quad T &= \sum_{i=1}^N \sum_{j=1}^{n_i} \left(\sum_{k=1}^{l_j} t_{ijk} \right) z_{ij}, \\
 W \leq W', \quad W &= \sum_{i=1}^N \sum_{j=1}^{n_i} \left(\sum_{k=1}^{l_j} w_{ijk} \right) z_{ij}, \\
 R \leq R', \quad R &= \sum_{i=1}^N \sum_{j=1}^{n_i} \left(\sum_{k=1}^{l_j} r_{ijk} \right) z_{ij}.
 \end{aligned} \tag{41}$$

3.2 Modeling threats in the logistics of UAV production and supply

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. At the same time, the realization of threats leads to the excitation of various vulnerabilities in the logistics of production and supply, which can ultimately lead to losses in the area of military conflict. The logical chain that needs to be investigated is: threat – vulnerabilities - losses.

Vulnerabilities may be related to the condition and bottlenecks in the heterogeneous transportation network used to transport weapons and military equipment. Threats to vulnerabilities may include:

- moral and physical obsolescence of the transportation system,
- bottlenecks in the form of transshipment of military cargo from one transportation highway to another,
- necessary warehousing and temporary storage of military cargo in certain locations of the transportation network,
- transportation of ammunition that may explode due to the actions of the aggressor,
- violation of cargo size and weight requirements,
- violation of special transportation regime requirements, etc.

In the event of a threat from the aggressor (air raids, missile attacks, long-range artillery, etc.), vulnerabilities are triggered, which lead to damage in the area of military conflict. Therefore, there is an urgent task to determine the impact of threats on the exploitation of vulnerabilities that lead to losses. This affects the nature of hostilities in the zone of military conflict.

To analyze the logical 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, let's consider the impact

of a threat in the form of an air raid on a section of a railroad on which a batch of UAVs is being transported. Let's assume that military experts who know the specific route of the military cargo have identified three possible transportation vulnerabilities in the form of factors x_j of the FFE:

- cargo transshipment (x_1),
- temporary storage (x_2),
- violation of the special transportation regime (x_3).

Table 1 shows the FFE plan, where the plan lines correspond to possible vulnerabilities (no vulnerabilities – the first line $(-1, -1, -1)$, the presence of all vulnerabilities – the last line of the plan $(+1, +1, +1)$).

Table 1

FFE plan for loss assessment

	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

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

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{123}x_1x_2x_3, \quad (42)$$

where $b_0, b_1, b_2, b_3, b_{12}, b_{13}, b_{23}, b_{123}$ are the coefficients associated with the influence of factors x_1, x_2, x_3 on the value of the amount of damage (y).

Let's build the linear part of the regression dependence associated with the impact of individual factors (vulnerabilities) on the amount of damage.

After simple calculations, we get:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 = 5 + x_1 + 1,5x_2 + 2,5x_3. \quad (43)$$

The dependence obtained as a result of the virtual experiment indicates the influence of individual factors:

1. According to experts, the most important vulnerability that is triggered by an air raid is the violation of the special regime for 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. Vulnerability associated with the transshipment of military cargo is the least important in terms of the impact on damage in the event of an air raid ($b_1 = 1$).

3.3 A method of increasing the effectiveness of the use of weapons by creating an asymmetry in military parity of forces in a military conflict zone

Military parity of forces is associated with the use of almost identical types of enemy weapons in a zone of military conflict. 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 a swarm of drones with increased range and accuracy of impact). Therefore, by creating an asymmetry in the number of weapons and the use of different types of UAVs in a swarm, it is possible to increase the overall effectiveness of UAVs in a military conflict zone. Therefore, it is important to develop a method to increase the effectiveness of the use of weapons in a zone of military conflict by creating an asymmetry in the types of weapons in the military parity of forces. Due to the multivariate nature of the asymmetry in the military parity of forces, we will use the method of integer (Boolean) programming as a mathematical tool for solving the problem.

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

$$x_{ijk} = \begin{cases} x_{ijk} = 1, & \text{if the } j\text{-th type of weapon} \\ & \text{and its } k\text{-th supplier are selected} \\ & \text{for the } i\text{-th type of weapons;} \\ x_{ijk} = 0, & \text{other wise.} \end{cases} \quad (44)$$

Further, with the help of military specialists (experts), for each type of UAV, the effectiveness q_{ij} of using UAVs in a military conflict zone is determined.

Then, for each type of UAV, the efficiency of use is as follows:

$$Q_i = \sum_{j=1}^{n_i} \sum_{k=1}^{p_j} q_{ij} m_{ijk} x_{ijk}, \quad (45)$$

where m_{ijk} is the number of units of weapon components (ammunition, components, supporting elements) that can be delivered by the k -th supplier of the j -th type for the i -th type of UAV;

$p(j)$ is the number of possible suppliers of the j -th type of weapon.

Then the overall effectiveness of UAVs in a military conflict zone:

$$Q = \sum_{i=1}^N \sum_{j=1}^{n_i} \sum_{k=1}^{p_j} q_{ij} m_{ijk} x_{ijk}, \quad (46)$$

where N is the number of types of UAVs.

To ensure air superiority in the conflict zone, it is necessary to:

$$\max Q, \quad Q = \sum_{i=1}^N \sum_{j=1}^{n_i} \sum_{k=1}^{p_j} q_{ij} m_{ijk} x_{ijk}, \quad (47)$$

taking into account the limitations:

$$T \leq T', \quad T = \sum_{i=1}^N \sum_{j=1}^{n_i} \sum_{k=1}^{p_j} t_{ijk} m_{ijk} x_{ijk}, \quad (48)$$

where T is the time spent on the production and delivery of the UAV and its components to the combat zone;

T' – is the permissible time allocated for the production and delivery of the UAV and its components to the combat zone;

t_{ijk} is the time spent on the production and supply of support for one UAV of the i -th type, j -th type of components by the k -th supplier.

$$W \leq W', \quad W = \sum_{i=1}^N \sum_{j=1}^{n_i} \sum_{k=1}^{p_j} w_{ijk} m_{ijk} x_{ijk}, \quad (49)$$

where W is the cost of production and supply of weapons to the combat zone;

W' – allowable costs;

w_{ijk} – costs associated with the production and supply of one UAV of the i -th type, j -th type of components by the k -th arms supplier.

$$R \leq R', R = \sum_{i=1}^N \sum_{j=1}^{n_i} \sum_{k=1}^{p_j} r_{ijk} m_{ijk} x_{ijk}, \quad (50)$$

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 UAV of the i -th type, j -th type of components by the k -th arms supplier.

The following condition must be met:

$$\sum_{k=1}^{p_j} x_{ijk} = 1, \quad (51)$$

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

3.4 Agent-based simulation model for studying the logistics of production and supply of weapons to the combat zone to establish military superiority

To calculate the time required to provide UAV units with the necessary weapons to establish military superiority in the air in the face of threats, a model was created that allows simulating the dynamics of military cargo transportation (requests in the simulation model), taking into account the emergence of threats and the excitation of vulnerabilities, which leads to a halt in the movement of cargo 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 directed graph, in which the vertices are transport hubs 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 the simulation model for studying the production and logistics of military cargo supply to establish parity of forces in the conflict zone are:

1. Transport network description agent.
2. Request generator agent (military cargo).
3. Threat agent.
4. Vulnerability agent.
5. Military cargo transport route formation agent.
6. Transport hub agent.
7. Transport route section agent.

8. Military cargo temporary storage (warehousing) agent.
9. Transshipment agent.
10. Military cargo time delay agent (due to vulnerability excitation).
11. Risk agent.
12. Combat zone agent (CZA).
13. Simulation control agent.
14. Simulation results agent.

Figure 3 shows a block diagram of the agent-based model.

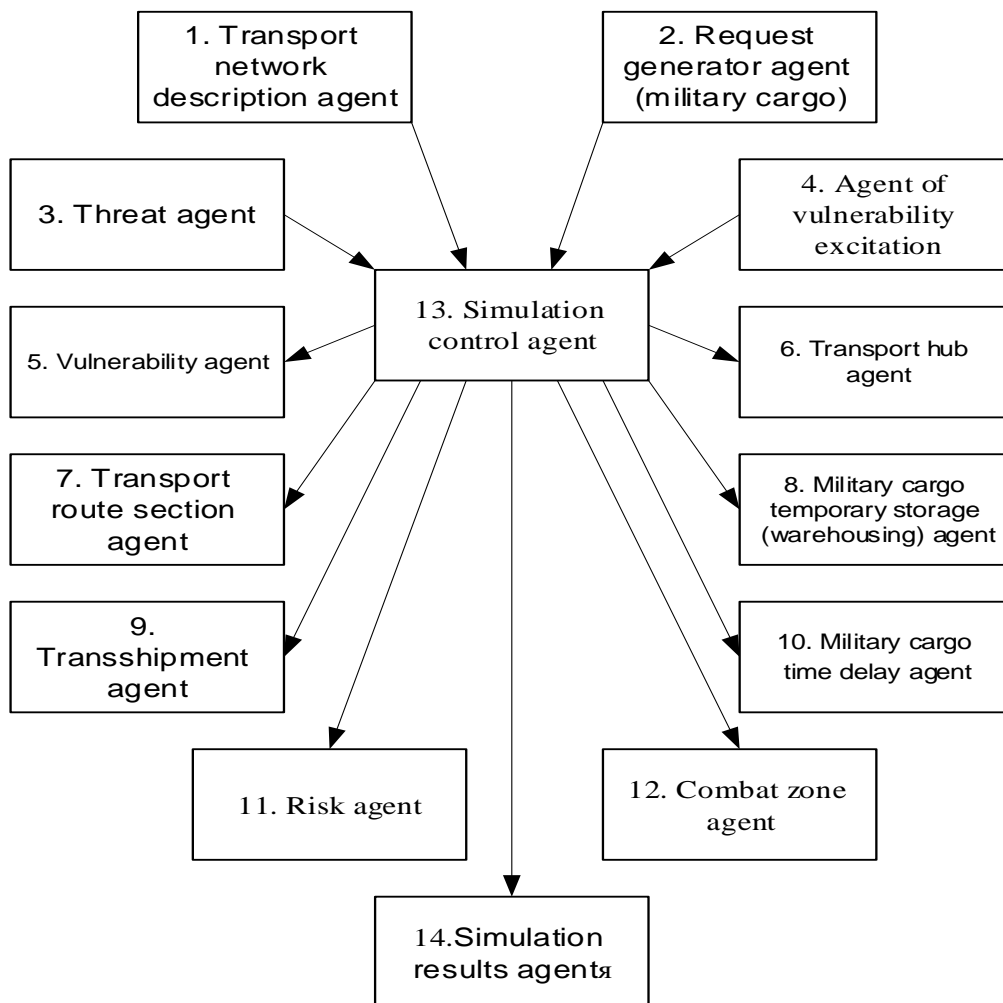


Fig. 3. Block diagram of the agent model

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 in the transportation highway is set (the request generator agent). Then, with the help of the cargo route

agent, the request (military cargo) is transported through transport nodes and sections of the highway using the transport node agent and the highway section agent. During the movement of a request (military cargo), vulnerabilities (vulnerability agent) may be triggered due to threats (threat agent). This leads to a temporary delay in the application (military cargo) for the period associated with the nature of the threat and the triggered vulnerability. When the request (military cargo) arrives in the combat zone (agent of the combat zone), the simulation stops and the results are generated (agent of the simulation results) in the form of

- the time of receipt of applications (military cargo) in the combat zone;
- time spent on the transportation of military cargo along a given route (without or with vulnerability triggering);
- total time delays of military cargo;
- violation of the terms of delivery of military cargo to the FOB;
- time spent on transshipment;
- time spent on temporary storage (warehousing) of military cargo.

An algorithm has been developed to find a route with the minimum time required to transport military cargo in the CZ. In the case of risk assessments proposed by military experts, an algorithm for the formation of accumulated risk in the logistics of supply in the CZ (risk agent) was developed.

Conclusions

The study is related to the modeling of the integrated supply of military equipment to a military conflict zone in the form of UAVs and supporting components. A representation of military equipment in the form of a component structure is formed. The problems with the integrated supply of various types of UAVs to the military conflict zone are analyzed, which are related to: the variety and multiplicity of types of UAVs and its components, small batches of supplies, complex supply logistics, risks of timely delivery for the formation of military equipment stocks. Using system analysis, a multicomponent structure of military equipment was created, which includes weapons and their main components in the form of a multilayer architecture. The main types of military equipment components are identified: reusable components that ensure unification and reusability in different types of military equipment; new components that need to be developed in projects to create modern equipment; adapted components that can be used in new military equipment by modifying reusable components. The formation of a multilayer architecture of military equipment is carried out taking into account the separate types of components. The creation of stocks of military equipment (various types

of UAV systems and components) in the zone of military conflict is carried out using: army warehouses, manufacturers' warehouses, as well as by producing the required amount of weapons.

An algorithm for the formation of UAV stocks has been developed, taking into account the values of safety stocks necessary to establish military superiority in the air. When creating modified UAV models to be used in a military conflict zone, the component architecture of a new military equipment model is formed using a precedent database that contains possible components for reuse. The search for similar components in the database of precedents required for a new project is carried out with an assessment of the proximity of components by tactical and technical characteristics. Both quantitative and qualitative proximity estimates in the form of linguistic variables are proposed.

An optimization model for selecting logistics channels for the supply of weapons and their components to a military conflict zone, taking into account logistics costs and risks, has been created.

The second part of the study is related to the modeling of threats in the logistics process of forming a military advantage. As a result of the preliminary analysis, the shortcomings of existing methods that consider certain aspects of the process of establishing military parity and advantages that are not linked in a comprehensive solution to the problem are identified. The author analyzes the threat factors associated with the lack of military superiority and parity of forces in the zone of military conflict. Military experts assessed various types of weapons to study their impact on the balance of military forces. The assessment was carried out using qualitative expert assessments in the form of linguistic variables. Given the large number of possible options for choosing suppliers of different types of UAVs, the method of integer (Boolean) programming is used. The criteria for evaluating UAV suppliers are proposed, taking into account the time, costs and risks of production and delivery. The article investigates the sequence: threats – vulnerabilities – losses, which is associated with the emergence of threats in the logistics of production and supply of UAVs to establish military superiority in the air. The author shows how the emergence of a threat affects the creation of vulnerabilities in the logistics of UAV production and supply, which leads to losses in the area of military conflict.

A method for increasing the efficiency of weapons use through innovative types of attack UAVs has been developed, which allows, by creating an asymmetry in military parity of forces, to successfully accomplish the goals of a combat operation in a conflict zone.

An agent-based simulation model was developed to study the logistics process of establishing military superiority in the air. The agent-based simulation model is used to calculate the delivery time and formulate rational routes for the transportation of military cargo, taking into account wartime threats.

The following mathematical and modeling methods were used: system analysis; component design; precedent approach; lexicographic ordering of options; theory of experiments, expert evaluation method, integer (Boolean) programming method; multi-criteria optimization based on linguistic variables, agent-based simulation modeling.

The proposed approach allows, in planning the objectives of a military operation, to formulate requirements for the production and supply of weapons and military equipment, and to plan weapons stocks for effective use (establishing military superiority in the air) in a military conflict zone using various types of UAVs when forming a drone swarm, which contributes to the successful execution of military operations.

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