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SIMULATION OF TRANSPORTATION LOGISTICS DURING THE PERIOD OF A SPECIAL STATE

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Introduction

The state of war in the country forced to review the logistics processes of transportation [1-6]. There are new areas in logistics that need to be explored for effective transportation planning in the face of military threats. Especially important are the directions of logistics, which are related to the transportation of weapons and military equipment (WME) to the front line and the transportation (evacuation) of the population to the rear from the front-line areas. Therefore, the topic of the proposed publication is relevant, in which optimization models are created for the rational choice of transportation routes under martial law conditions. The purpose of the research is to create models for applied information technology research of logistics processes of transporting goods and people during the period of the country's martial law. Tasks that are solved in the work:

– creation of optimization models for planning transportation of WME to the front line;

– creation of optimization models for planning the evacuation of the population to the rear.

1 Optimization model for planning transportation of weapons and military equipment to the front line

One of the urgent tasks, which is related to the implementation of effective operational and tactical actions on the battlefield, is the formation of the necessary reserves of weapons and military equipment (WME) for the front line. The front line includes actual military local zones (MLZ) in which active combat operations are conducted. It is necessary to form the necessary stocks of anti-terrorist weapons in the MLZ for conducting successful operational and tactical actions. Therefore, the task of finding relatively safe ways of supplying WME to the frontline in conditions of military threats is urgent. To solve the given problem, we will use the integer (Boolean) programming method.

Let's enter a variable x_{ijk}:

$$x_{ijk} = \begin{cases} 1, \ \textit{if the j-th way of supplting WME to i-th MLZ} \\ \textit{with k-th warehouse of logistics components} \\ \textit{(transshipment, storage, distribution, temporary stop, etc);} \\ 0, \ \textit{otherwise.} \end{cases}$$

At the same time, it is necessary to: $\sum_{j=1}^{n_i} \sum_{k=1}^{m_j} x_{ijk} = 1$, which means the mandatory choice of a specific way of supplying WME to i-th MLZ from k-th composition of logistics components, where N is the number of MLZ on the front line; m_j is the number of possible warehouses of logistics components per j-th way of supply; n_i is the number of possible ways of supplying military goods to i-th MLZ.

Let's introduce the main logistics indicators for evaluating and choosing a possible option for transporting MLZ to the front line:

1. R are the risks of supplying MLZ to the frontline, in conditions of military threats.

2. T is the time required for the supply of MLZ to the front line.

3. W are the stockpiles of weapons, which are formed on the front lines to fulfill the actual operational and tactical tasks of the military leadership.

Let's present the indicators R, T, W taking into account the variables x_{ijk}:

$$R = \sum_{i=1}^{N} \sum_{j=1}^{n_i} \sum_{k=1}^{m_j} r_{ijk} x_{ijk},$$

where r_{ijk} is the risk of delivering military cargo to i-th MLZ on j-th way of supply from k-th composition of logistics components.

$$T = \sum_{i=1}^{N} \sum_{j=1}^{n_i} \sum_{k=1}^{m_j} t_{ijk} x_{ijk},$$

where t_{ijk} is the time required for the transportation of military cargo to i-th MLZ for j-th way with k-th possible composition of logistics components.

$$W = \sum_{i=1}^{N} \sum_{j=1}^{n_i} \sum_{k=1}^{m_j} w_{ijk} x_{ijk},$$

where w_{ijk} is the number of batches of WME that can be moved by j-th possible way of delivery from k-th composition of logistics components to i-th MLZ.

We will create optimization models for solving the task of forming WME stocks on the front line for effective combat operations on the battlefield.

1. Minimization of the risks of the formation of WME stocks in the conditions of the actions of military threats:

$$\min R,\ R=\sum_{i=1}^{N}\sum_{j=1}^{n_i}\sum_{k=1}^{m_j} r_{ijk}x_{ijk},$$

while fulfilling the restrictions:

$$T \le T^*,\ T=\sum_{i=1}^{N}\sum_{j=1}^{n_i}\sum_{k=1}^{m_j} t_{ijk}x_{ijk},$$

where T^* is the permissible (planned) time of delivery of WME to the front line.

$$W \ge W^*,\ W=\sum_{i=1}^{N}\sum_{j=1}^{n_i}\sum_{k=1}^{m_j} w_{ijk}x_{ijk},$$

where W^* is a stockpile of anti-aircraft weapons, which must be formed to fulfill the actual operational and tactical tasks of the military leadership.

2. Maximization of WME stocks on the front line for successful combat operations:

$$\max W,\ W=\sum_{i=1}^{N}\sum_{j=1}^{n_i}\sum_{k=1}^{m_j} w_{ijk}x_{ijk}$$

while fulfilling the restrictions:

$$R \le R^*,\ R=\sum_{i=1}^{N}\sum_{j=1}^{n_i}\sum_{k=1}^{m_j} r_{ijk}x_{ijk},$$

where R^* is the acceptable risk of the supply of WME in the conditions of the actions of military threats.

$$T \le T^*,\ T=\sum_{i=1}^{N}\sum_{j=1}^{n_i}\sum_{k=1}^{m_j} t_{ijk}x_{ijk}.$$

It is possible to formulate a multi-criteria optimization problem using indicators R, T, W.

In this case, it is necessary to form a complex indicator:

$$K=\alpha_R \overset{\vee}{R}+\alpha_T \overset{\vee}{T}+\alpha_W \overset{\vee}{W},$$

where α_R, α_T, α_W are the "weights" of indicators R, T, W, $\alpha_R+\alpha_T+\alpha_W=1$.

$\overset{\vee}{R}$ is a normalized indicator R:

$$\overset{\vee}{R} = \alpha_R \frac{R - R_{\min}}{R^* - R_{\min}},$$

where $R_{\min}$ is the minimum value of the indicator R after its optimization.

$\overset{\vee}{T}$ is the standardized indicator of delivery time:

$$\overset{\vee}{T} = \alpha_T \frac{T - T_{\min}}{T^* - T_{\min}},$$

where $T_{\min}$ is the minimum time value T after its optimization.

$\overset{\vee}{W}$ is a normalized indicator W:

$$\overset{\vee}{W} = \alpha_W \frac{W_{\max} - W}{W_{\max} - W^*},$$

where $W_{\max}$ is the maximum value of the WME stock after its optimization.

It is necessary to find:

$$\min K = \alpha_R \overset{\vee}{R} + \alpha_T \overset{\vee}{T} + \alpha_W \overset{\vee}{W} = \alpha_R \frac{R - R_{\min}}{R^* - R_{\min}} + \alpha_T \frac{T - T_{\min}}{T^* - T_{\min}} + \alpha_W \frac{W_{\max} - W}{W_{\max} - W^*} =$$

$$= \frac{\alpha_R}{R^* - R_{\min}} \sum_{i=1}^{N} \sum_{j=1}^{n_i} \sum_{k=1}^{m_j} r_{ijk} x_{ijk} + \frac{\alpha_T}{T^* - T_{\min}} \sum_{i=1}^{N} \sum_{j=1}^{n_i} \sum_{k=1}^{m_j} t_{ijk} x_{ijk} -$$

$$- \frac{\alpha_W}{W_{\max} - W^*} \sum_{i=1}^{N} \sum_{j=1}^{n_i} \sum_{k=1}^{m_j} w_{ijk} x_{ijk} - \frac{\alpha_R R_{\min}}{R^* - R_{\min}} - \frac{\alpha_T T_{\min}}{T^* - T_{\min}} + \frac{\alpha_W W_{\max}}{W_{\max} - W^*}.$$

2 Optimization models for planning evacuation transportation to the rear

The modern war led to the evacuation of the population from the front-line zone to the rear. Migration processes have arisen, for which it is necessary to create logistical evacuation chains. Therefore, the study of evacuation flows is relevant to assess the ability of the transport network to carry out the planned transportation of people to temporary places of residence (TMR). While planning evacuation processes, it is necessary to form a set of places (M), which can receive the population, with their capabilities to meet social needs. Then, it is necessary to form ways of transporting people, in conditions of risks (R) military threats, estimate the cost (W) and plan time (T) evacuation. Let’s create an optimization model, which can be used to determine rational ways of evacuating the population (F) from the front-line zone to possible places of temporary residence in the conditions of the country's martial law. Let's enter an integer (Boolean) variable x_{plk}:

$$x_{plk} = \begin{cases} \textit{1, if the transportation of people to thep-th place} \\ \textit{of residence will be carried out using the l-th transportation} \\ \textit{route with the k-th warehouse of logistics components (temporary stop,} \\ \textit{transition from one route to another, distribution of evacuation flows, etc.);} \\ \textit{0, otherwise.} \end{cases}$$

As the main logistical indicators of the evacuation process, we will consider:

1. The time required to evacuate people (T).
2. The cost of the population evacuation process (W).
3. Risks of military threats (R).
4. Number of population to be evacuated (F).

Taking into account the variables x_{plk}, the logistic indicators of population evacuation are as follows:

$$T = \sum_{p=1}^{M} \sum_{l=1}^{m_p} \sum_{k=1}^{n_l} t_{plk} x_{plk},$$

where m_p is the number of possible ways to evacuate the population to p-th place TMR; n_l is the number of possible warehouses of logistics components for their use on l-th way of transportation; t_{plk} is the time required to move people to p-th place of the TMR taking into account l-th selected evacuation route and k-th composition of logistics components.

$$W = \sum_{p=1}^{M} \sum_{l=1}^{m_p} \sum_{k=1}^{n_l} w_{plk} x_{plk},$$

where w_{plk} is the cost of transporting people to p-th possible place of TMR, taking into account the chosen one l-th way of transportation and k-th composition of logistics components.

$$R = \sum_{p=1}^{M} \sum_{l=1}^{m_p} \sum_{k=1}^{n_l} r_{plk} x_{plk},$$

where r_{plk} is the risk of transporting people, in conditions of military threats, in p-th possible place of TMR taking into account the chosen one l-th way of transportation and k-th composition of logistics components.

$$F = \sum_{p=1}^{M} \sum_{l=1}^{m_p} \sum_{k=1}^{n_l} f_{plk} x_{plk},$$

where f_{plk} is the number of the population that will be directed to p-th place of the TMR taking into account the chosen one l-th way of transportation and k-th composition of logistics components.

The following formulations of the optimization problem are possible, which are related to the evacuation of the population to the rear:

1. Minimize the time required to evacuate the population:

$$\min T, \ T = \sum_{p=1}^{M} \sum_{l=1}^{m_p} \sum_{k=1}^{n_l} t_{plk} x_{plk},$$

taking into account the limitations:

$$W \le W^*, \ W = \sum_{p=1}^{M} \sum_{l=1}^{m_p} \sum_{k=1}^{n_l} w_{plk} x_{plk},$$

$$R \le R^*, \ R = \sum_{p=1}^{M} \sum_{l=1}^{m_p} \sum_{k=1}^{n_l} r_{plk} x_{plk},$$

$$F \ge F^*, \ F = \sum_{p=1}^{M} \sum_{l=1}^{m_p} \sum_{k=1}^{n_l} f_{plk} x_{plk},$$

where W^* is the planned cost of the population evacuation process; R^* is the permissible risk of the evacuation process, which is associated with possible actions of military threats; F^* is the planned number of the population that will be evacuated from the front-line zone to the rear.

2. To maximize the number of the population that will be evacuated from the front-line zone to the rear:

$$\max F, \ F = \sum_{p=1}^{M} \sum_{l=1}^{m_p} \sum_{k=1}^{n_l} f_{plk} x_{plk},$$

taking into account the limitations:

$$T \le T^*, \ T = \sum_{p=1}^{M} \sum_{l=1}^{m_p} \sum_{k=1}^{n_l} t_{plk} x_{plk},$$

$$W \le W^*, \ W = \sum_{p=1}^{M} \sum_{l=1}^{m_p} \sum_{k=1}^{n_l} w_{plk} x_{plk},$$

$$R \le R^{*},\ R = \sum_{p=1}^{M} \sum_{l=1}^{m_p} \sum_{k=1}^{n_l} r_{plk} x_{plk},$$

where T^{*} is the planned time for population evacuation.

3. Minimize the risks of population evacuation:

$$\min R,\ R = \sum_{p=1}^{M} \sum_{l=1}^{m_p} \sum_{k=1}^{n_l} r_{plk} x_{plk},$$

taking into account the limitations:

$$T \le T^{*},\ T = \sum_{p=1}^{M} \sum_{l=1}^{m_p} \sum_{k=1}^{n_l} t_{plk} x_{plk},$$

$$W \le W^{*},\ W = \sum_{p=1}^{M} \sum_{l=1}^{m_p} \sum_{k=1}^{n_l} w_{plk} x_{plk},$$

$$F \ge F^{*},\ F = \sum_{p=1}^{M} \sum_{l=1}^{m_p} \sum_{k=1}^{n_l} f_{plk} x_{plk}.$$

A multi-criteria formulation of the population evacuation optimization problem is possible. To do this, we will introduce a complex criterion in the form of an additive composition of logistic indicators T, W, R, F:

$$Q = \alpha_T \overset{\vee}{T} + \alpha_W \overset{\vee}{W} + \alpha_R \overset{\vee}{R} + \alpha_F \overset{\vee}{F},$$

where α_T, α_W, α_R, α_F are the «weights» of indicators T, W, R, F $\alpha_T + \alpha_W + \alpha_R + \alpha_F = 1$; $\overset{\vee}{T}$, $\overset{\vee}{W}$, $\overset{\vee}{R}$, $\overset{\vee}{F}$ are the normalized values of indicators T, W, R, F:

$$\overset{\vee}{T} = \frac{T - T_{\min}}{T^{*} - T_{\min}},$$

$$\overset{\vee}{W} = \frac{W - W_{\min}}{W^{*} - W_{\min}},$$

$$\overset{\vee}{R} = \frac{R - R_{\min}}{R^{*} - R_{\min}},$$

$$\overset{\vee}{F} = \frac{F_{\max} - F}{F_{\max} - F^{*}}.$$

It is necessary to minimize the complex criterion Q:

$$\min Q,\ Q=\alpha_T \overset{\vee}{T}+\alpha_W \overset{\vee}{W}+\alpha_R \overset{\vee}{R}+\alpha_F \overset{\vee}{F}=\frac{\alpha_T}{T^*-T_{\min}}\sum_{p=1}^{M}\sum_{l=1}^{m_p}\sum_{k=1}^{n_l} t_{plk}x_{plk}+$$

$$+\frac{\alpha_W}{W^*-W_{\min}}\sum_{p=1}^{M}\sum_{l=1}^{m_p}\sum_{k=1}^{n_l} w_{plk}x_{plk}+\frac{\alpha_R}{R^*-R_{\min}}\sum_{p=1}^{M}\sum_{l=1}^{m_p}\sum_{k=1}^{n_l} r_{plk}x_{plk}-$$

$$-\frac{\alpha_F}{F_{\max}-F^*}\sum_{p=1}^{M}\sum_{l=1}^{m_p}\sum_{k=1}^{n_l} f_{plk}x_{plk}-\frac{\alpha_T T_{\min}}{T^*-T_{\min}}-$$

$$-\frac{\alpha_W W_{\min}}{W^*-W_{\min}}-\frac{\alpha_R R_{\min}}{R^*-R_{\min}}+\frac{\alpha_F F_{\max}}{F_{\max}-F^*},$$

where $T_{\min}$, $W_{\min}$, $R_{\min}$, $F_{\max}$ are the extreme values of indicators after their optimization.

3 Optimization models for taking preventive measures against the influence of military threats during the transportation of goods and people

The outdated transport infrastructure has a large number of vulnerabilities that affect the disruption of the transportation of goods and people, especially during the period of martial law, under the conditions of military threats.

The following main existing vulnerabilities can be identified:

– physical and moral aging of components of the transport network (bridges, intersections, viaducts, highways, etc.);

– bottlenecks that lead to the accumulation of goods and people (transport queues, temporary stops, redistribution according to transportation directions, etc.);

– places where climatic phenomena occur more often (flooding, mud avalanches, soil disturbances, etc.).

During the period of martial law, the country may become vulnerable due to possible actions of military threats (arrivals of missiles, drone attacks, bombings, etc.), which leads to disruptions in transportation, occurrence of emergency situations, disasters with loss of life.

Therefore, the topic of the proposed research is relevant, in which the influence of military threats on the vulnerability of the transport infrastructure, which is used for transportation to the front and to the rear in the period of the country's martial law, is simulated.

The purpose of the research is to create models for assessing the impact of military threats on the vulnerability of transport infrastructure (TI), for the formation of preventive actions aimed at reducing the risks of the impact of threats on planned transportation both to the front and to the rear.

To research the influence of military threats on IT, we will form a chain of sequence of actions in the form of: modeling the emergence of a military threat $\rightarrow$ excitation of possible vulnerabilities $\rightarrow$ modeling of the scale of TI violations in the form of damages (material and human) $\rightarrow$ formation of a set of preventive actions to reduce or neutralize the effects of military threats.

A set of preventive actions (M) depends on: the scale of violations; losses (P), which arise; from military threats (V); set of vulnerabilities that are excited (W). To assess the effect of military threats, we will form a set of indicators:

1. The risks of military threats – R;
2. Expenses for the elimination of possible losses from the action of military threats – Z;
3. The time required to carry out preventive measures to minimize or neutralize the actions of military threats – T.

We will use integer (Boolean) programming to simulate the impact of military threats on IT. Let's enter a Boolean variable x_{epk}:

$$x_{epk} = \begin{cases} 1, \textit{if the occurrence of the e-th threat triggers the p-th set} \\ \textit{of TI vulnerabilities, for which it is necessary to form the k-th set} \\ \textit{of preventive actions;} \\ 0, \textit{otherwise.} \end{cases}$$

Then, taking into account the variables x_{epk} indicators R, Z, T have the form:

$$R = \sum_{e=1}^{v} \sum_{p=1}^{m_e} \sum_{k=1}^{n_p} r_{epk}\, x_{epk},$$

where V is the number of possible threats; r_{epk} is the risk of e-th military threat, which excites p-th composition of vulnerabilities that lead to use k-th composition of necessary preventive actions; n_p is a set of preventive actions for neutralization p-th composition of vulnerabilities; m_e is a set of possible compositions of vulnerabilities that can be excited upon occurrence threats.

$$Z = \sum_{e=1}^{v} \sum_{p=1}^{m_e} \sum_{k=1}^{n_p} z_{epk} x_{epk},$$

where z_{epk} are the costs of carrying out k-th component of preventive actions to eliminate possible damages that occur during excitation p-th composition of vulnerabilities from the action of e-th threats.

$$T = \sum_{e=1}^{v} \sum_{p=1}^{m_e} \sum_{k=1}^{n_p} t_{epk} x_{epk},$$

where t_{epk} is the time required for implementation k-th composition of preventive measures necessary to eliminate possible damages that occur during excitation p-th composition of e-th threats.

In the conditions of the state of war in the country, it is extremely necessary to minimize the time (T) to carry out preventive actions regarding the possible influence of military threats on transportation both to the front and to the rear. Therefore, it is necessary:

$$\min T, \ T = \sum_{e=1}^{v} \sum_{p=1}^{m_e} \sum_{k=1}^{n_p} t_{epk} x_{epk},$$

taking into account the limitations:

$$Z \leq Z^*, \ \ Z = \sum_{e=1}^{v} \sum_{p=1}^{m_e} \sum_{k=1}^{n_p} t_{epk} x_{epk} \ .$$

Acceptable risks to prevent military threats:

$$R \geq R^*, \ R = \sum_{e=1}^{v} \sum_{p=1}^{m_e} \sum_{k=1}^{n_p} t_{epk} x_{epk},$$

where R^* is the assessment by experts of risks for the emergence of military threats to IT.

In conditions of limited capabilities of the country, it is necessary to minimize costs Z to carry out preventive measures against possible actions of military threats.

In this case, it is necessary:

$$\min Z, \ Z = \sum_{e=1}^{v} \sum_{p=1}^{m_e} \sum_{k=1}^{n_p} z_{epk} x_{epk},$$

taking into account the limitations:

$$T \leq T^*, \ T = \sum_{e=1}^{v} \sum_{p=1}^{m_e} \sum_{k=1}^{n_p} t_{epk} x_{epk},$$

where T^* is the planned time of the risks of preventing military threats for the implementation of preventive measures against the possible impact of military threats.

$$R \geq R^*, \ R = \sum_{e=1}^{v} \sum_{p=1}^{m_e} \sum_{k=1}^{n_p} t_{epk} x_{epk} \ .$$

A multi-criteria formulation of the task of planning preventive actions to the influence of possible military threats is possible.

Let's introduce a complex indicator Q:

$$Q = \alpha_R \cdot \check{R} + \alpha_z \cdot \check{Z} + \alpha_T \cdot \check{T},$$

where α_R, α_z, α_T are the «weights» of indicators R, Z, T; $\check{R}$, $\check{Z}$, $\check{T}$ are the values of indicators R, Z, T:

$$\check{R} = \frac{R - R^*}{R_{\max} - R^*},$$

where $R_{\max}$ is the experts' pessimistic assessment of the risk of military threats affecting IT.

$$\check{Z} = \frac{Z - Z_{\min}}{Z^* - Z_{\min}},$$

$$\check{T} = \frac{T - T_{\min}}{T^* - T_{\min}}.$$

It is necessary to minimize the complex indicator (Q) to find a compromise solution among indicators R, Z, T:

$$\min\ Q, Q = \alpha_R \cdot \check{R} + \alpha_z \cdot \check{Z} + \alpha_T \cdot \check{T} =$$

$$= \frac{\alpha_R}{R_{\max} - R^*} \sum_{e=1}^{v} \sum_{p=1}^{m_e} \sum_{k=1}^{n_p} r_{epk} x_{epk} + \frac{\alpha_z}{Z^* - Z_{\min}} \sum_{e=1}^{v} \sum_{p=1}^{m_e} \sum_{k=1}^{n_p} t_{epk} x_{epk} +$$

$$+ \frac{\alpha_T}{T^* - T_{\min}} \sum_{e=1}^{v} \sum_{p=1}^{m_e} \sum_{k=1}^{n_p} t_{epk} x_{epk} - \frac{\alpha_R \cdot R^*}{R_{\max} - R^*} - \frac{\alpha_z \cdot Z_{\min}}{Z^* - Z_{\min}} - \frac{\alpha_T \cdot T_{\min}}{T^* - T_{\min}}.$$

Conclusions

In the work, research of the logistics processes of transportation during the period of the country's martial law was carried out. Current areas of research related to the transportation of military cargo to the front line, as well as the evacuation of the population from the front-line zone to the rear, are separated. The main logistic indicators that must be used to evaluate transportation processes under the conditions of military threats have been formed (transportation time, transportation risks, transportation cost, the number of the population being evacuated). Optimization models have been created for choosing rational routes of transportation to the front line and to the rear. Local optimization of logistics indicators was carried out, taking into account limitations on the permissible time and risk of transportation. Multi-criteria models were created for finding compromise solutions for transportation logistics.

Used mathematical methods and models: system analysis, methods of transport logistics, integer (Boolean) optimization, multi-criteria optimization, methods of expert evaluation.

The scientific novelty of the research is related to the creation of a complex of original optimization models, which can be used to analyze and plan the logistics of transporting weapons and military equipment to the front and evacuating the population to the rear.

The proposed approach is the basis for the creation of applied information technology for the planning of transportation logistics both to the front and to the rear, taking into account possible military threats, during the period of the country’s martial law.

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