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Original Article

THE APPROACH TO OPTIMIZATION OF THE STRUCTURE OF THE REPAIR PROCESS OF AVIATION RADIO EQUIPMENT

Maksym ZALISKYI[1✉], Viktoriia IVANNIKOVA[2☻], Oleksandr SOLOMENTSEV[3], Ivan OSTROUMOV[4], Nataliia KUZMENKO[5]

[1,3] Dept of Telecommunication and Radio Electronic Systems, National Aviation University, Kyiv, Ukraine
[2] Business School, Dublin City University, Dublin, Ireland
[4,5] Dept of Air Navigation Systems, National Aviation University, Kyiv, Ukraine

Highlights:
- the current research aims to develop a methodology for justifying the location of repair centers of air transport systems;
- the methodology gives possibility to calculate the operational costs for repair process;
- the methodology takes into account tactical and technical characteristics of equipment, reliability, and costs of operational procedures;
- clustering technique is used to find the location of repair centers;
- several scenarios for location of repair centers in Ukraine give possibility to choose the best cost-effective option.

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Abstract. The Operation System (OS) of Aviation Radio Equipment (ARE) includes such elements as equipment, organizational structure, processes, documentation, personnel, measuring equipment, consumables and information resources, and others. When considering the problems of primary design and modernization of OSs, a large number of problems arise that can be solved with the help of intelligent decision support systems. During the operation of ARE, significant material resources are consumed, the amount of which is usually random. Therefore, during design, one of the main tasks is to ensure the minimum costs. This article considers the task of cost optimization within the organizational structure of the repair process. At the same time, the article provides analytical equations that allow to calculate and estimate operational costs for a given organizational structure, tariffs for repair and delivery of equipment components, and failure flow parameters. Attention is also paid to the task of rationalizing the organizational structure of the repair process, taking into account the efficiency of the decision-making procedures depending on the failure type (simple or complex). In addition, the article considers an example of several scenarios for the possible placement of repair enterprises in the airports of Ukraine during the post-war reconstruction period.

Keywords: operational cost optimization, organizational structure, airport planning, intelligent systems, aviation radio equipment, operation, repair.

✉ Corresponding author. E-mail: *maximus2812@ukr.net*
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Notations

Abbreviations:

AI – artificial intelligence;
ARE – aviation radio equipment;
c.u. – conventional units;
FT – failure type;
OS – operation system.

Variables and functions:

$C_\Sigma(M, N|T_\Sigma)$ – total cost of delivery of the failed unit to the repair center and subsequent repair;

$C_{11}, C_{12}, C_{21}, C_{22}$ – costs associated with decision-making regarding simple or complex failure;

$C_{del\ i1}$ – the average cost of delivering one unit from the ith airport to the 1st airport;

$C_i(M|T_\Sigma)$ – the total cost for repairing the aviation equipment at the th airport;

C_{OS} – average operational cost;

$C_{rep\ com}$ – the average costs of eliminating a complex failure;

$C_{rep\ i}$ – the average repair costs of one unit arriving at the main airport from the ith airport;

$C_{rep\ rji}(M)$ – the average costs of repairing units of the rth type in the non-serviceable condition for the jth equipment in the i th airport;
$C_{rep\ sim}$ – the average costs of eliminating a simple failure;
C_T – tariff rates for the performance of certain technological procedures;
C_{td} – the tariff for delivery of one unit to the repair center [c.u./km];
$C_{tr}(M, N)$ – the tariff for performing repair procedures [c.u./h];
$E(C_\Sigma(M, N|T_\Sigma))$ – the average total cost of delivery of the failed unit to the repair center and subsequent repair;
$E(n_i)$ – the average total number of units arriving at the main airport from the ith airport (i = 1, 2, 3, 4);
$E(n_{ji})$ – the average number of units in the non-serviceable condition for the jth equipment in the ith airport;
$E(n_{rji})$ – the average number of the rth type unit in the non-serviceable condition for the jth equipment in the ith airport;
$E(t_{rji})$ – the average duration of repair of the rth type unit in the non-serviceable condition for the jth equipment in the ith airport;
K_i – the quantity of equipment types;
L – the set of limitations;
M – the number of repair centers;
N – the number of civil aviation enterprises operating ARE;
n_{ji} – the random number of units in the non-serviceable condition for the jth equipment at the ith airport;
n_{rji} – the random number of rth type units in the non-serviceable condition for the jth equipment at the ith airport;
O – the set characterizing organizational structure of OS;
$p_{11}, p_{12}, p_{21}, p_{22}$ – conditional probabilities of decision-making regarding simple or complex failure;
q_1 – the probability of simple failures;
q_2 – the probability of complex failures;
R_i – the repair parameter for the ith airport;
S – the set characterizing tactical and technical characteristics, types and number of ARE;
S_{i1} – the length of the delivery route from the ith airport (i = 1, 2, 3, 4);
T_Σ – the observation period;
t_{rji} – the duration of repair of rth type unit for the jth equipment from the ith airport;
W – the set characterizing reliability characteristics of the equipment;
$\gamma_{1,2}, \gamma_{3,4}$ – coefficients of proportionality between repair costs;
Δ – efficiency gain;
φ – the function that establishes dependence between operational costs and components of operation system;
λ – the failure rate;
$\lambda_{1...4}$ – the total rate of repair requests for the 1st option of the organizational structure;
$\lambda_{1,2}, \lambda_{3,4}$ – the total rates of repair requests for the 2nd option of the organizational structure;
λ_{com} – the rate of complex failures;
λ_{ji} – failure rate for the jth equipment in the ith airport;
λ_{K_i} – the total failure rate of equipment units for the ith airport;
λ_{rji} – failure rate of rth type units for the jth equipment in the ith airport;
λ_{sim} – the rate of simple failures;
ϑ_{ji} – the quantity of units in the jth equipment.

1. Introduction

To obtain the given level of reliability and operational efficiency of ARE in civil aviation enterprises, we can usually use the OSs (Nakagawa 2006; Solomentsev *et al.* 2019). The OS forms and implements a set of control and preventive actions for its structural components, namely: equipment, organizational structure, processes, documentation, personnel, measuring equipment, consumables and information resources, and others (Dhillon 2006; Solomentsev *et al.* 2016). The OS is not a conservative structure, it can be improved and adjusted taking into account new achievements of science and technology, intelligence information tools, positive experience of operation of electronic and related equipment, and others (Jardine, Tsang 2021; Tachinina *et al.* 2022).

In addition to tasks improvement, a class of tasks related to primary design can be distinguished (Anand, Ram 2018; André 2019). At the same time, project management technologies, intelligent decision support systems, multi-criteria optimization methods, and others can be applied (Smith 2022). Intelligent systems are usually built on the basis of AI technologies, which include statistical processing methods, a heuristic approach, machine and deep learning methods, approaches based on the use of a knowledge base, logical conclusions, fuzzy logic, and others (Poole, Mackworth 2017; Srivastava *et al.* 2014).

Optimization issues arise because significant material resources are spent during the operation of ARE, the amount of which is usually random and far exceeds the initial cost of ARE of aviation enterprises (Ren *et al.* 2017; Poberezhna 2021). Therefore, during the design process, one of the main tasks is to ensure minimum costs (Galar *et al.* 2017; Poberezhna, 2017).

Another important problem during the operation of ARE is the analysis of the processes of deterioration of the technical condition (Sugier, Anders 2010). The inevitable factors of degradation of electronic components affect the efficiency of operational processes, increasing costs and increasing the risk of dangerous situations, which in particular reduces the level of flight safety (De Jonge, Scarf 2020; Liu 2021).

The modern development of technologies and computing capacity of computer technology has caused a transition to the concepts of *Industry 4.0* (Kant, Gurung, 2023). Accordingly, there is an urgent need to collect data from the components of the OS. These data can be a source for making more effective management decisions regarding the formation and implementation of preventive actions in order to increase the efficiency of equipment operation (Duda, Gąsior, 2021; Frenz 2022).

During the design, there are tasks related to the determination of quantitative and qualitative indicators characterizing all elements of the OS (Modarres, Groth 2023). The main process in the OS is the process of equipment use for its functional purpose (Gertsbakh 2000). Other processes are aimed at ensuring this process, which are auxiliary. These processes include maintenance and repair, resource extension, monitoring and control, environmental protection, labor protection, provision of security and fire alarms, professional skills development, and others (Karakoc *et al.* 2024; Raza, Ulansky 2021).

From the point of view of system and process approaches, each component of the OS should be characterized by input, output, auxiliary resources and management actions (Gąsiorkiewicz 2020). The chain of management actions can be considered as a feedback loop to increase the efficiency and improve the OS elements based on the processing of collected statistical data (Ayers 2000; Gonçalves Machado *et al.* 2019).

The process of use for the functional purpose is accompanied by the occurrence of failure, damages and misfunctions (McPherson 2019; Okoro *et al.* 2022). To eliminate their consequences, a repair process is carried out, the purpose of which is to restore the functionality of the equipment. The repair process is implemented in the relevant OS subsystem. For this subsystem, the tasks of organizational structure building of this system, determining the control and measuring equipment, technical personnel, preparing regulatory documentation must be solved (Rausand *et al.* 2021; Solomentsev *et al.* 2024).

Failures can be caused by internal and external factors (Bourassa *et al.* 2016; Freisinger, McCarthy 2024). The internal ones include failures of radio components, structural connections, wires, generating devices due to aging processes, instability of power sources, and others. The external factors of failure can be attributed to the environment, in particular humidity, pressure, temperature, weather conditions, the presence of dust, as well as electromagnetic compatibility, disturbances and noises that are both natural and organized in nature. Separately, it is also possible to highlight the human factor, which is accompanied by the formation of incorrect decisions and appropriate actions (Mygal 2024).

The process of eliminating failures and their consequences can be carried out in 2 ways (Chen *et al.* 2019):

- on the basis of preventive actions;
- by restoring the serviceability.

Preventive actions can be formed within the framework of the implementation of the basic ideas of predictive and prescriptive maintenance (Ucar *et al.* 2024; Yıldız, Soylu 2023). In accordance with this, the technical condition of the equipment is monitored and information on changes in the determining parameters is measured. The use of advanced data processing tools, in particular based on AI, makes it possible to perform a forecast of the remaining useful life of the equipment before the predicted failure occurs (Zhao *et al.* 2022). Usually, this approach assumes the presence of preventive and operational tolerances in the monitoring and data processing system, the crossing of which is controlled or predicted in the future by the value of the determining parameter (Grall *et al.* 2002). The obtained processing results are the basis for preventive actions, which are aimed at eliminating the negative causes of possible failure and bringing the equipment to normal operational conditions.

The serviceability recovery eliminates the consequences of failure (Boylan, Syntetos, 2010). This process includes procedures for: (1) searching for the failed equipment element; (2) repair; (3) checking the serviceability of equipment after repair (Rahito *et al.* 2019). In this case, the failure has already occurred and it was not possible to eliminate it preventively. When considering repair processes, it should be noted a large number of random factors that should be taken into account. Among these factors are random failure processes in randomly selected equipment blocks, the human factor, errors of control and measuring equipment, and others (Goncharenko 2017). All this leads to the need to consider repair processes and other related operational processes from the point of view of the tolls of probability theory and mathematical statistics.

From an analytical point of view, the task of optimizing the organizational structure of ARE OS is a quite difficult one, in particular, due to the large number of parameters describing OS.

Indeed, the concept of equipment operation includes such life cycle processes as transportation, storage, commissioning, maintenance, and repair. These processes are implemented in the relevant technological systems or subsystems of OS. This means that in each case there is a certain vector of parameters for the description of the technological system, which includes the parameters of organizational, technological, personnel, and other descriptions of OS. During optimization of the OS organizational structure, it is necessary to take into account the models of other descriptions of the OS components. Otherwise, the found organizational solutions may not be very effective. In the literature devoted to the theory and practice of the operation of multi-energetic systems, the task of analysing the efficiency of the organizational structure of the ARE repair subsystem was practically not considered. At the same time, it is usually understood that the task of finding the optimal organizational structure of the ARE repair subsystem is reduced to the analysis of the efficiency of one or another variant of this subsystem building.

Let's perform the formulation of the problem in generalized functionals. We will assume that the average operational cost C_{OS} is a generalized indicator of efficiency. These costs depend on the following constituent elements:

- organizational structure of OS O;
- tariff rates for the performance of individual technological procedures C_T;

- tactical and technical characteristics, types, and number of ARE S;
- reliability characteristics of the equipment W.

At the same time, the OS functions within certain limitations imposed by the set L. Taking this into account, the average operational costs can be represented as a function:

$$C_{OS} = \varphi\left(O\left(S\right), C_T, W|L\right). \quad (1)$$

The main task is to determine such an organizational structure that will ensure minimum costs, i.e.:

$$C_{OS\,\min} = \inf \varphi\left(O\left(S\right), C_T, W|L\right). \quad (2)$$

Therefore, the purpose of this article is to optimize costs within the organizational structure of the repair process. At the same time, the main attention will be paid to analytical equations that allow to calculate and estimate operational costs for a given organizational structure, tariffs for repair and delivery of equipment components, failure flow parameters, and the type of failure (simple or complex).

The specified problem, which is solved in this article, is directly related to the tasks of transport sciences:

- optimization of the technological loading of resources used for the repair of ARE for the flight support;
- timely and high-quality repair of ARE for the flight support in repair centers directly affects the stability of the functioning of the transport system, in particular the safety of aircraft flights;
- the article is aimed at solving tasks related to the transport economy, in particular, building the organizational structure of repair centers for the civil aviation airports.

The article's findings give the ability to develop the optimal structure of repair centers for ARE in Ukraine for the period of post-war reconstruction. The main theoretical contribution of the article is associated with new methods synthesis and analysis in the theory and practice of equipment operation. The proposed approaches are not limited to ARE and can be extended to other elements of the transport sector.

The article is organized as follows:

- the Section 1 – is introduction;
- the Section 2 describes the general methodology of organizational structure optimization for the repair process taking into account geographical location of airports, tariffs for repair, tariffs for delivery of equipment components, and failure flow parameters;
- the Section 3 considers the possibility of operational costs minimization based on improvement of decision-making on the complexity of failure;
- the Section 4 shows the numerical examples and discussions.
- the main results are concluded in the Section 5.

2. Method of organizational structure optimization for the repair process

We will assume that there is one central body at the state level, located, for example, in the capital, which manages the operation processes of ARE and performs repair procedures with equipment units that cannot be repaired by personnel in civil aviation enterprises. Let's suppose that the efficiency of the repair subsystem can be estimated using the average total cost E (C_Σ (M, $N|T_\Sigma$)) of delivery of the failed unit to the repair center and subsequent repair during the observation period T_Σ. In this case, M is the number of repair centers, N is the number of civil aviation enterprises operating ARE.

In case of using Ukraine as a case study, from a geographical point of view, the central repair center in Kyiv is located in the northern part of the country, so it can be intuitively concluded that the delivery of equipment units with failures from the southern and other regions will be quite expensive and long-lasting.

Taking this into account, the essence of the proposed method of improving the organizational structure of the repair process is associated with the necessity to create several repair centers to reduce the total costs C_Σ (M, $N|T_\Sigma$) of repairing equipment operated in N enterprises. Accounting the large number of parameters that affect the value of the C_Σ (M, $N|T_\Sigma$) indicator, we will perform the calculations for 2 examples of organizational structure.

The 1st option of the organizational structure involves one repair center. Let there be a total of 4 airports and corresponding enterprises N = 4, and the repair center is located at the 1st airport M = 1.

The 2nd option of the organizational structure involves 2 repair centers. Let these centers for 4 airports N = 4 be located in the 1st and 4th airports M = 2.

The location of airports and repair centers for 2 options of the organizational structure are shown in Figures 1 and 2.

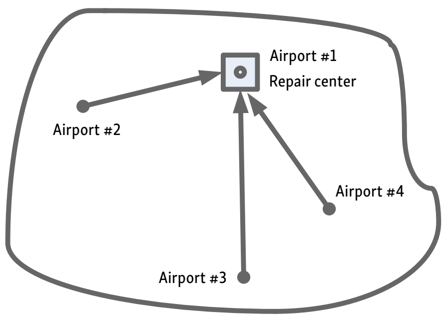

Figure 1. The example of organizational structure with one repair center (source: own elaboration of the authors)

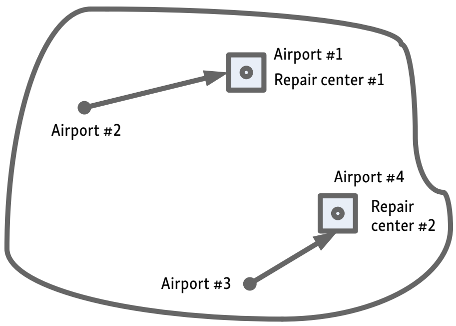

Figure 2. The example of organizational structure with 2 repair centers (source: own elaboration of the authors)

We will assume that K_i types of equipment are operated in the ith airport. In the event of equipment failure, the unit with the failure is searched for and replaced with a serviceable one from the number of unit spare parts.

To restore the fund of spare parts, the unit that failed is delivered to the repair center, where procedures are performed to restore serviceability or replace it with a serviceable unit. After that, the unit is returned to the operating company. At the same time, the efficiency indicator in the form of total costs C_Σ (M, $N|T_\Sigma$) will take into account the costs of units delivery, repair costs, and reliability properties of the equipment. In the general case, the value of C_Σ (M, $N|T_\Sigma$) is random due to the stochasticity of the failure flow of ARE and because the repair cost is also random depending on the type of equipment and the particular failed unit.

Consider the ith airport. Let the jth equipment contain ϑ_{ji} units, where $j \in [1, K_i]$. We denote $C_{del\ i1}$ as the average cost of delivering one unit from the ith airport to the 1st airport, where the repair center is located, n_{ji} as the random number of units in the non-serviceable condition for the jth equipment at the ith airport, and n_{rji} as the random number of rth type units in the non-serviceable condition for the jth equipment at the ith airport. Let's include the parameter $C_{rep\ rji}(M)$ – the average costs of repairing units of the rth type in the non-serviceable condition for the jth equipment in the ith airport, provided that the number of repair centers is equal to M. Taking into account the introduced variables, the total costs of repair of the jth equipment from the ith airport during the observation period will be a random variable equal to:

$$C_{ji}(M|T_\Sigma) = 2 \cdot C_{del\ i1} \cdot n_{ji} + \sum_{r=1}^{\vartheta_{ji}} C_{rep\ rji}(M) \cdot n_{rji}. \tag{3}$$

We define the parameter $C_{del\,i1}$ using a variable related to the distance of the ith airport from the repair center:

$$C_{del\ i1} = C_{td} \cdot S_{i1}. \tag{4}$$

The parameter $C_{rep\ rji}(M)$ will be determined with the help of variables that will contain the costs of creating a repair base for the maintenance of aviation equipment from 4 airports:

$$C_{rep\ rji}(M) = C_{tr}(M, N) \cdot t_{rji}. \tag{5}$$

On the one hand, the parameter $C_{tr}(M, N)$ will be determined by the cost of control and measuring devices in the repair center, and on the other hand, will depend on the average number of repair requests.

Taking into account Equations (3)–(5), we will determine the total costs for repairing the aviation equipment at the i th airport:

$$C_i(M|T_\Sigma) = 2 \cdot C_{td} \cdot S_{i1} \cdot \sum_{j=1}^{K_i} n_{ji} + \sum_{j=1}^{K_i} \sum_{r=1}^{\vartheta_{ji}} C_{tr}(M,N) \cdot t_{rji} \cdot n_{rji}. \tag{6}$$

For the 1st option of the organizational structure, there will be no delivery costs from the 1st airport. Then the equation for total costs will take the following form:

$$C_\Sigma(M, N|T_\Sigma) = 2 \cdot C_{td} \cdot \sum_{i=2}^{4} \left(S_{i1} \cdot \sum_{j=1}^{K_i} n_{ji} \right) + \sum_{i=1}^{4} \sum_{j=1}^{K_i} \sum_{r=1}^{\vartheta_{ji}} \left(C_{tr}(M, N) \cdot t_{rji} \cdot n_{rji} \right). \tag{7}$$

The average value of the costs C_Σ (M, $N|T_\Sigma$) can be determined by averaging with respect to the random variables presented in the Equation (7), so:

$$E\left(C_\Sigma(M, N|T_\Sigma)\right) = 2 \cdot C_{td} \cdot \sum_{i=2}^{4} \left(S_{i1} \cdot \sum_{j=1}^{K_i} E(n_{ji}) \right) + C_{tr}(M, N) \cdot \sum_{i=1}^{4} \sum_{j=1}^{K_i} \sum_{r=1}^{\vartheta_{ji}} \left(E(t_{rji}) \cdot E(n_{rji}) \right). \tag{8}$$

For an assumption about the simplest flow of failures, let us denote: λ_{ji} is failure rate for the jth equipment in the ith airport, λ_{rji} is failure rate of rth type units for the jth equipment in the ith airport. Then we will get during the observation period:

$$E(n_{ji}) = \lambda_{ji} \cdot T_\Sigma;$$
$$E(n_{rji}) = \lambda_{rji} \cdot T_\Sigma;$$
$$\lambda_{ji} = \sum_{r=1}^{\vartheta_{ji}} \lambda_{rji}. \tag{9}$$

Taking Equation (7) into account, we present Equation (6) as:

$$E\left(C_\Sigma(M=1, N=4\,|T_\Sigma)\right) = 2 \cdot C_{td} \cdot T_\Sigma \cdot \sum_{i=2}^{4} \left(S_{i1} \cdot \sum_{j=1}^{K_i} \lambda_{ji} \right) + C_{tr}(M=1,\ N=4) \cdot T_\Sigma \times \sum_{i=1}^{4} \sum_{j=1}^{K_i} \sum_{r=1}^{\vartheta_{ji}} \left(E(t_{rji}) \cdot \lambda_{rji} \right). \tag{10}$$

Similar equations can be obtained for the 2nd option of the organizational structure. At the same time, the equation for the efficiency indicator will take the form:

$$E\left(C_\Sigma(M=2, N=4\,|T_\Sigma)\right) = 2 \cdot C_{td} \cdot T_\Sigma \left(S_{21} \cdot \sum_{j=1}^{K_2} \lambda_{j2} + S_{34} \cdot \sum_{j=1}^{K_3} \lambda_{j3} \right) + C_{tr}(M=1, \text{Airport}\ \#1) \cdot T_\Sigma \times \sum_{i=1}^{2} \sum_{j=1}^{K_i} \sum_{r=1}^{\vartheta_{ji}} \left(E(t_{rji}) \cdot \lambda_{rji} \right) + C_{tr}(M=1,\ \text{Airport}\ \#4) \cdot T_\Sigma \times \sum_{i=3}^{4} \sum_{j=1}^{K_i} \sum_{r=1}^{\vartheta_{ji}} \left(E(t_{rji}) \cdot \lambda_{rji} \right). \tag{11}$$

We consider that the tariffs for performing repair procedures $C_{tr}\left(M=1, \text{Airport}\,\#1\right)$ and $C_{tr}\left(M=1, \text{Airport}\,\#4\right)$ in Equation (11) differ in values, since the total flows of faulty units, which are repaired at the 1st and 4th airports are also different. Let's define these parameters through $C_{tr}\left(M=1, N=4\right)$, which corresponds to the 1st option of the organizational structure. Let λ_{K_i} be the total failure rate of equipment units for the ith airport, i.e.:

$$\lambda_{K_i}=\sum_{j=1}^{K_i}\lambda_{ji}. \quad (12)$$

For the 1st option of the organizational structure, the total rate of repair requests is:

$$\lambda_{1\ldots4}=\sum_{i=1}^{4}\lambda_{K_i}. \quad (13)$$

For the 2nd option of the organizational structure, the total rate of repair requests is:

$$\lambda_{1,2}=\lambda_{K_1}+\lambda_{K_2};$$
$$\lambda_{3,4}=\lambda_{K_3}+\lambda_{K_4}. \quad (14)$$

Let the repair centers have control and measuring equipment of the same value, so we will get it:

$$C_{tr}\left(M=1, \text{Airport}\,\#1\right)=C_{tr}\left(M=1, N=4\right)\cdot\gamma_{1,2};$$
$$C_{tr}\left(M=1, \text{Airport}\,\#4\right)=C_{tr}\left(M=1, N=4\right)\cdot\gamma_{3,4}, \quad (15)$$

where:

$$\gamma_{1,2}=\frac{\lambda_{1\ldots4}}{\lambda_{1,2}}=\frac{\sum_{i=1}^{4}\lambda_{K_i}}{\lambda_{K_1}+\lambda_{K_2}};$$

$$\gamma_{3,4}=\frac{\lambda_{1\ldots4}}{\lambda_{3,4}}=\frac{\sum_{i=1}^{4}\lambda_{K_i}}{\lambda_{K_3}+\lambda_{K_4}}.$$

Since the coefficients $\lambda_{1,2}$ and $\lambda_{3,4}$ are greater than 1, the tariffs for repair procedure for the 2nd option will be higher than for the 1st option of organizational structure.

Thus, with the help of the obtained Equations (3)–(15), it is possible to perform an analysis of the efficiency of the organizational structure of the subsystem of the repair of ARE in the presence of one or more repair centers. Let's perform the following analysis for the considered 2 options. For this purpose, let's compare Equations (10) and (11). To simplify the mathematical calculations, we introduce the repair parameter for the ith airport:

$$R_i=\sum_{j=1}^{K_i}\sum_{r=1}^{\vartheta_{ji}}\left(E\left(t_{rji}\right)\cdot\lambda_{rji}\right). \quad (16)$$

Taking into account Equations (15) and (16), Equation (10) for $E\left(C_\Sigma\left(M=1, N=4\,|\,T_\Sigma\right)\right)$ will have the form:

$$E\left(C_\Sigma\left(M=1, N=4\,|T_\Sigma\right)\right)=$$
$$2\cdot C_{td}\cdot T_\Sigma\cdot\left(S_{21}\cdot\lambda_{K_2}+S_{31}\cdot\lambda_{K_3}+S_{41}\cdot\lambda_{K_4}\right)+$$
$$C_{tr}\left(M=1,\ N=4\right)\cdot T_\Sigma\times$$
$$\left(R_1+R_2+R_3+R_4\right). \quad (17)$$

Equation (11) for $E\left(C_\Sigma\left(M=2, N=4\,|\,T_\Sigma\right)\right)$ will have the form:

$$E\left(C_\Sigma\left(M=2, N=4\,|T_\Sigma\right)\right)=$$
$$2\cdot C_{td}\cdot T_\Sigma\cdot\left(S_{21}\cdot\lambda_{K_2}+S_{34}\cdot\lambda_{K_3}\right)+$$
$$C_{tr}\left(M=1,\ \text{Airport}\,\#1\right)\cdot T_\Sigma\times$$
$$\left(\gamma_{1,2}\cdot R_1+\gamma_{1,2}\cdot R_2+\gamma_{3,4}\cdot R_3+\gamma_{3,4}\cdot R_4\right), \quad (18)$$

where: S_{34} – is length of delivery route from 3rd to 4th airport.

By subtracting Equation (18) from Equation (17), we get the value:

$$\Delta=E\left(C_\Sigma\left(M=1, N=4\,|T_\Sigma\right)\right)-$$
$$E\left(C_\Sigma\left(M=2, N=4\,|T_\Sigma\right)\right)=$$
$$2\cdot C_{td}\cdot T_\Sigma\cdot\lambda_{K_3}\cdot\left(S_{31}-S_{34}\right)+$$
$$2\cdot C_{td}\cdot T_\Sigma\cdot\lambda_{K_4}\cdot S_{41}+$$
$$C_{tr}\cdot T_\Sigma\cdot\left(1-\gamma_{1,2}\right)\cdot\left(R_1+R_2\right)+$$
$$C_{tr}\cdot T_\Sigma\cdot\left(1-\gamma_{3,4}\right)\cdot\left(R_3+R_4\right). \quad (19)$$

It can be proved that:

$$1-\gamma_{1,2}=-\frac{\lambda_{K_3}+\lambda_{K_4}}{\lambda_{K_1}+\lambda_{K_2}}=\frac{1}{1-\gamma_{3,4}}. \quad (20)$$

Then,

$$\Delta=2\cdot C_{td}\cdot T_\Sigma\cdot\lambda_{K_3}\cdot\left(S_{31}-S_{34}\right)+$$
$$2\cdot C_{td}\cdot T_\Sigma\cdot\lambda_{K_4}\cdot S_{41}+$$
$$C_{tr}\cdot T_\Sigma\cdot\left(1-\gamma_{1,2}\right)\cdot\left(R_1+R_2\right)+$$
$$C_{tr}\cdot T_\Sigma\cdot\frac{R_3+R_4}{1-\gamma_{1,2}}. \quad (21)$$

Let's make a number of assumptions. Let the flows of repair requests in both repair centers be approximately the same, then $1-\gamma_{1,2}\approx-1$. Let's the average duration of repair of the rth type units for the jth equipment in the ith airport be a constant value equal to one hour, i.e. $E\left(t_{rji}\right)=1$. Then the repair parameter – Equation (16) – will be equal to:

$$R_i=\sum_{j=1}^{K_i}\lambda_{ji}. \quad (22)$$

From this we get a simplified Equation (18) of the form:

$$\Delta=2\cdot C_{td}\cdot T_\Sigma\cdot\lambda_{K_3}\cdot\left(S_{31}-S_{34}\right)+$$
$$2\cdot C_{td}\cdot T_\Sigma\cdot\lambda_{K_4}\cdot S_{41}-$$
$$C_{tr}\cdot T_\Sigma\cdot\left(\lambda_{K_1}+\lambda_{K_2}+\lambda_{K_3}+\lambda_{K_4}\right). \quad (23)$$

If we divide Equation (23) by $T_\Sigma\cdot\lambda_K$ and take into account the assumption made regarding the approximate equality of the flow of repair requests, we get:

$$\frac{\Delta}{T_\Sigma\cdot\lambda_{K_i}}\cong 2\cdot C_{td}\cdot\left(S_{31}-S_{34}+S_{41}\right)-4\cdot C_{tr}. \quad (24)$$

Let's make an approximate estimate of value – Equation (24). Let we have the following initial data: S_{31} =

150 km, S_{34} = 100 km, S_{41} = 160 km, C_{td} = 0.03 c.u./km, C_{tr} = 2 c.u./h. Then:

$$\frac{\Delta}{T_{\Sigma}\cdot\lambda_{K_i}} \cong 2\cdot 0.03\cdot\left(150-100+160\right)-4\cdot 2=4.6\,.$$

Thus, the difference in total costs is a positive value, which means that the 2nd option of the organizational structure of the repair process is more effective one. For arbitrary cases of initial data, Equation (19) should be applied without unnecessary assumptions and restrictions.

So, using the calculations for 4 airports, we can get the equations for arbitrary number of airports.

3. Decision-making support for the ARE repair process

Let's consider the issue of rationalization of ARE OS due to the use of decision-making schemes regarding the complexity of the repair procedure. At the same time, we assume that the cause of the loss of operational efficiency of the equipment can be either a simple failure that can be eliminated directly at the airport where the equipment is operated, or a complex failure that can be eliminated at a special repair center.

Logically, the cost of the repair procedure during simple failures is much less than the cost of the repair procedure during complex failures. It is intuitively clear that if we apply decision-making schemes regarding the nature of failures, we can save resources in cases where, during simple failures, the equipment does not need to be taken to a special repair center. Mistakes are possible during decision-making, so the positive effect of the proposed rationalization will be smaller.

Figure 3 schematically shows the following points:

- the objective state of faulty equipment in which a simple or complex failure occurred;
- the rate of these 2 types of failures λ_{sim} and λ_{com}. The sum of these intensities is equal to the intensity of equipment failures, i.e.:

$$\lambda=\lambda_{sim}+\lambda_{com}. \tag{25}$$

In the general failure flow, equipment with probability q_1 has simple failures and with probability q_2 – complex failures. In this case:

$$q_1=\frac{\lambda_{sim}}{\lambda_{sim}+\lambda_{com}};\quad q_2=\frac{\lambda_{com}}{\lambda_{sim}+\lambda_{com}}; \tag{26}$$

- decisions are made regarding the type of failure (simple or complex). Let's denote the conditional probabilities of making a decision as follows: p_{11} is the conditional probability of making a decision regarding a simple failure in the case when a simple failure objectively occurred; p_{12} is a conditional probability of making a decision regarding a complex failure in the case when a simple failure objectively occurred; p_{21} is conditional probability of making a decision on a simple failure in the case when a complex failure objectively occurred; p_{22} is the conditional probability of making a decision regarding a complex failure in the event that a complex failure objectively occurred. For these probabilities, the normalization condition is fulfilled, i.e.:

$$p_{11}+p_{12}=1;\quad p_{21}+p_{22}=1; \tag{27}$$

- costs associated with making relevant decisions are C_{11}, C_{12}, C_{21}, and C_{22}.

To check the efficiency of taking into account the type of failure, we will use the 1st option of the organizational structure of the repair process (Figure 1). As an efficiency indicator, we will use the average total repair costs without classification and with FT classification, i.e. $E\left(C_{\Sigma}\left(M,N\,|\,T_{\Sigma},\text{with } FT\right)\right)$ and $E\left(C_{\Sigma}\left(M,N\,|\,T_{\Sigma},\text{ without } FT\right)\right)$.

As a basic analytical equation, we will use the average total costs for the repair as follow:

$$E\left(C_{\Sigma}\left(M=1,N=4\,|T_{\Sigma}\right)\right)= 2\cdot C_{del\,21}\cdot E\left(n_2\right)+2\cdot C_{del\,31}\cdot E\left(n_3\right)+ 2\cdot C_{del\,41}\cdot E\left(n_4\right)+C_{rep1}\cdot E\left(n_1\right)+ C_{rep2}\cdot E\left(n_2\right)+C_{rep3}\cdot E\left(n_3\right)+C_{rep4}\cdot E\left(n_4\right). \tag{28}$$

For simplification, we will assume that all repair costs $C_{rep\ i}$ are the same in magnitude, then Equation (28) will take the following form:

$$E\left(C_{\Sigma}\left(M=1,N=4\,|T_{\Sigma}\right)\right)= 2\cdot\sum_{i=2}^{4}C_{del\ i1}\cdot E\left(n_i\right)+C_{rep\,i}\cdot\sum_{i=1}^{4}E\left(n_i\right). \tag{29}$$

We believe that the 1st airport can repair units that had simple and complex failures. In all other airports, it is possible to restore operational capacity only after simple failures. Let $C_{rep\ sim}$ and $C_{rep\ com}$ be the average costs of eliminating a simple and complex failures, respectively.

Let's consider the option without failure classification. In all airports, except the 1st one, costs are formed as follows. If, objectively, a simple failure occurred at the ith airport, then the unit is delivered to the 1st airport, where a simple repair with the cost of $C_{rep\ sim}$ is performed. After repair, the unit returns to the ith airport, that is, we have average costs for one unit at the level of $2\cdot C_{del\ i1}+C_{rep\ sim}$. If, objectively, a complex failure occurred at the ith airport, then the unit is delivered to the 1st airport, where a com-

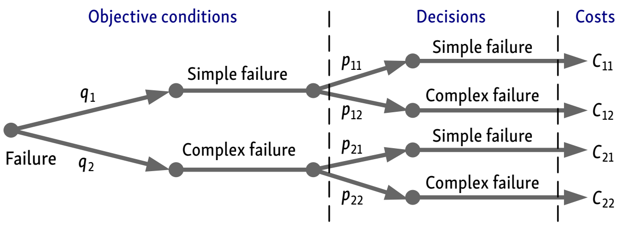

Figure 3. Scheme of cost formation in the OS with classification of equipment FTs (source: own elaboration of the authors)

plex repair is performed with the cost of $C_{rep\ com}$, and the average costs will be equal to $2 \cdot C_{del\ i1} + C_{rep\ com}$. If we consider the Airport #1, then the cost formation scheme will be the same only without the cost of delivery. Then, the average total repair costs without failure classification will be as follows:

$$E\left(C_\Sigma\left(M=1, N=4 \mid T_\Sigma, \text{ without } FT\right)\right) = \\ E\left(n_1\right) \cdot q_1 \cdot C_{rep\ sim} + E\left(n_1\right) \cdot q_2 \cdot C_{rep\ com} + \\ E\left(n_2\right) \cdot q_1 \cdot \left(2 \cdot C_{del\,21} + C_{rep\ sim}\right) + \\ E\left(n_2\right) \cdot q_2 \cdot \left(2 \cdot C_{del\,21} + C_{rep\ com}\right) + \\ E\left(n_3\right) \cdot q_1 \cdot \left(2 \cdot C_{del\,31} + C_{rep\ sim}\right) + \\ E\left(n_3\right) \cdot q_2 \cdot \left(2 \cdot C_{del\,31} + C_{rep\ com}\right) + \\ E\left(n_4\right) \cdot q_1 \cdot \left(2 \cdot C_{del\,41} + C_{rep\ sim}\right) + \\ E\left(n_4\right) \cdot q_2 \cdot \left(2 \cdot C_{del\,41} + C_{rep\ com}\right). \quad (30)$$

After mathematical transformations, we get:

$$E\left(C_\Sigma\left(M=1, N=4 \mid T_\Sigma, \text{ without } FT\right)\right) = \\ \left(q_1 \cdot C_{rep\ sim} + q_2 \cdot C_{rep\ com}\right) \cdot \sum_{i=1}^{4} E\left(n_i\right) + \\ 2 \cdot q_1 \cdot \sum_{i=2}^{4} \left(C_{del\ i1} \cdot E\left(n_i\right)\right) + \\ 2 \cdot q_2 \cdot \sum_{i=2}^{4} \left(C_{del\ i1} \cdot E\left(n_i\right)\right) = \\ \left(q_1 \cdot C_{rep\ sim} + q_2 \cdot C_{rep\ com}\right) \cdot \sum_{i=1}^{4} E\left(n_i\right) + \\ 2 \cdot \sum_{i=2}^{4} \left(C_{del\ i1} \cdot E\left(n_i\right)\right). \quad (31)$$

Let's consider the option with the classification of failures. 1st, we will determine the costs at the Airport #1. If objectively there was a simple failure, then we believe that in cases of correct and false classification, repair procedure with the cost $C_{rep\ sim}$ is still performed. The same situation occurs in the case of a complex failure. The costs associated with making these decisions will be equal to:

$$C_{11} = C_{12} = C_{rep\ sim}; \\ C_{21} = C_{22} = C_{rep\ com}. \quad (32)$$

In the case of the *i*th airport, we consider that in the case of a correct simple failure classification, the unit is repaired at the *i*th airport and the costs are $C_{rep\ sim}$. In other cases, the unit is delivered to the 1st airport, where repairs are carried out according to the actual condition of the unit. The costs associated with making these decisions will be equal to:

$$C_{11} = C_{rep\ sim} \\ C_{12} = 2 \cdot C_{del\ i1} + C_{rep\ sim}; \\ C_{21} = C_{22} = 2 \cdot C_{del\ i1} + C_{rep\ com}. \quad (33)$$

Then the average total repair costs with the classification of failures will be as follows:

$$E\left(C_\Sigma\left(M=1, N=4 \mid T_\Sigma, \text{ with } FT\right)\right) = \\ E\left(n_1\right) \cdot q_1 \cdot p_{11} \cdot C_{rep\ sim} + E\left(n_1\right) \cdot q_1 \cdot p_{12} \cdot C_{rep\ sim} + \\ E\left(n_1\right) \cdot q_2 \cdot p_{21} \cdot C_{rep\ com} + E\left(n_1\right) \cdot q_2 \cdot p_{22} \cdot C_{rep\ com} + \\ E\left(n_2\right) \cdot q_1 \cdot p_{11} \cdot C_{rep\ sim} + \\ E\left(n_2\right) \cdot q_1 \cdot p_{12} \cdot \left(2 \cdot C_{del\,21} + C_{rep\ sim}\right) + \\ E\left(n_2\right) \cdot q_2 \cdot \left(p_{21} + p_{22}\right) \cdot \left(2 \cdot C_{del\,21} + C_{rep\ com}\right) + \\ E\left(n_3\right) \cdot q_1 \cdot p_{11} \cdot C_{rep\ sim} + \\ E\left(n_3\right) \cdot q_1 \cdot p_{12} \cdot \left(2 \cdot C_{del\,31} + C_{rep\ sim}\right) + \\ E\left(n_3\right) \cdot q_2 \cdot \left(p_{21} + p_{22}\right) \cdot \left(2 \cdot C_{del\,31} + C_{rep\ com}\right) + \\ E\left(n_4\right) \cdot q_1 \cdot p_{11} \cdot C_{rep\ sim} + \\ E\left(n_4\right) \cdot q_1 \cdot p_{12} \cdot \left(2 \cdot C_{del\,41} + C_{rep\ sim}\right) + \\ E\left(n_4\right) \cdot q_2 \cdot \left(p_{21} + p_{22}\right) \cdot \left(2 \cdot C_{del\,41} + C_{rep\ com}\right). \quad (34)$$

After mathematical transformations, we get the following:

$$E\left(C_\Sigma\left(M=1, N=4 \mid T_\Sigma, \text{ with } FT\right)\right) = \\ \left(q_1 \cdot C_{rep\ sim} + q_2 \cdot C_{rep\ com}\right) \sum_{i=1}^{4} E\left(n_i\right) + \\ 2 \cdot \left(q_1 \cdot p_{12} + q_2\right) \cdot \sum_{i=2}^{4} \left(C_{del\ i1} E\left(n_i\right)\right). \quad (35)$$

Let's compare the efficiency of 2 options for organizing repair procedure with and without classification of FTs. To do this, we will define the difference:

$$\Delta = E\left(C_\Sigma\left(M=1, N=4 \mid T_\Sigma \text{ without } FT\right)\right) - \\ E\left(C_\Sigma\left(M=1, N=4 \mid T_\Sigma \text{ with } FT\right)\right) = \\ 2 \cdot \left(1 - q_1 \cdot p_{12} - q_2\right) \cdot \sum_{i=2}^{4} \left(C_{del\ i1} \cdot E\left(n_i\right)\right). \quad (36)$$

According to the Equation (36), we have Δ > 0 and, in principle, the option of organizing repair procedure with the classification of FTs is more effective than the option without classification.

If only complex failures occur, then q_2 = 1 and, accordingly, q_1 = 0 and Δ = 0. That is, the efficiency of the compared options is the same. If only simple failures occur, then q_1 = 1 and, accordingly, q_2 = 0. If we make the assumption that there are no errors during classification, then we get p_{12} = 0 and:

$$\Delta = \sum_{i=2}^{4} \left(C_{del\ i1} \cdot E\left(n_i\right)\right).$$

Thus, on a specific example with a given number of airports, the efficiency of the use of decision-making schemes regarding the types of failures in the ARE OS is proven.

4. Results and discussions

In this section, we will consider examples of the application of the proposed methods for the infrastructure organization of ARE repair centers in Ukraine. At the same time, options for the structure of repair centers for Ukrainian airports before the start of the war (January 2022) and during the post-war reconstruction period will be considered and compared. We will assume that due to the military actions, a certain part of airports was damaged, for the restoration of which significant financial resources are needed.

In general, as of the beginning of the war, 17 international airports were functioning in Ukraine, the network of which is shown in Figure 4. Let us assume that after the end of the war, 5 airports lost their functionality. Let's these airports be Mariupol, Mykolaiv, Kherson, Kharkiv, Zaporizhzhia. These airports are shown in red dots on Figure 5.

Figures 4 and 5 contain the following designations of airports: Boryspil (UKBB), Cherkasy (UKKE), Chernivtsi (UKLN), Dnipro (UKDD), Kharkiv (UKHH), Ivano-Frankivsk (UKLI), Kherson (UKOH), Kryvyi Rih (UKDR), Lviv (UKLL), Mariupol (UKCM), Zaporizhzhia (UKDE), Mykolaiv (UKON), Odesa (UKOO), Rivne (UKLR), Uzhhorod (UKLU), Vinnytsia (UKWW), Kyiv (UKKK).

Distances in kilometers between the correspondent airports are marked on the edges of the graph (Figures 4 and 5). For a more thorough analysis and further calculations, the distances between airports are also given in Table 1.

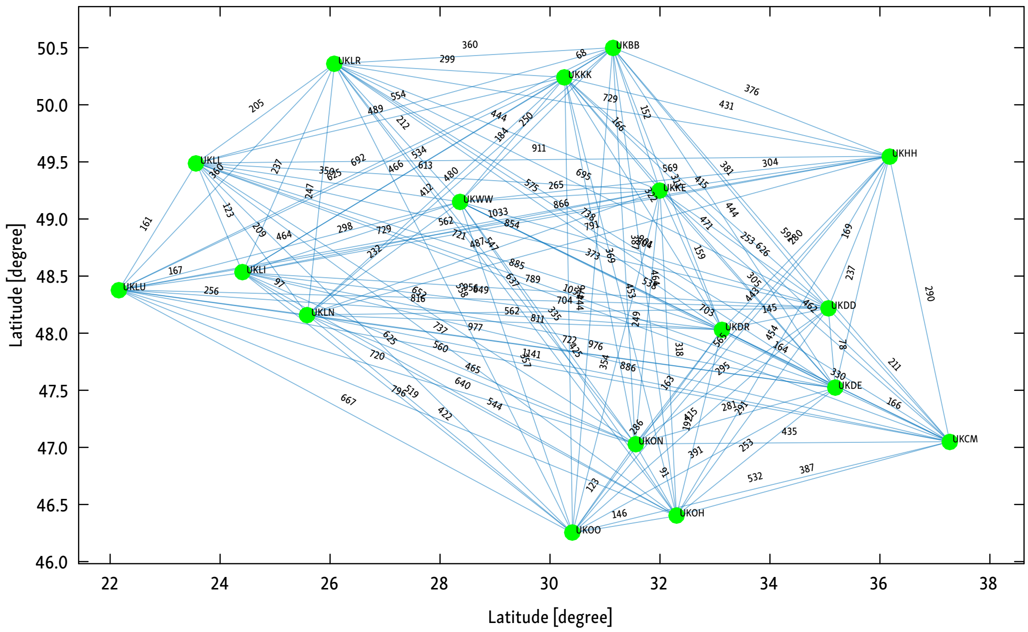

Figure 4. Chart of Ukrainian airports before January 2022 (source: own elaboration of the authors)

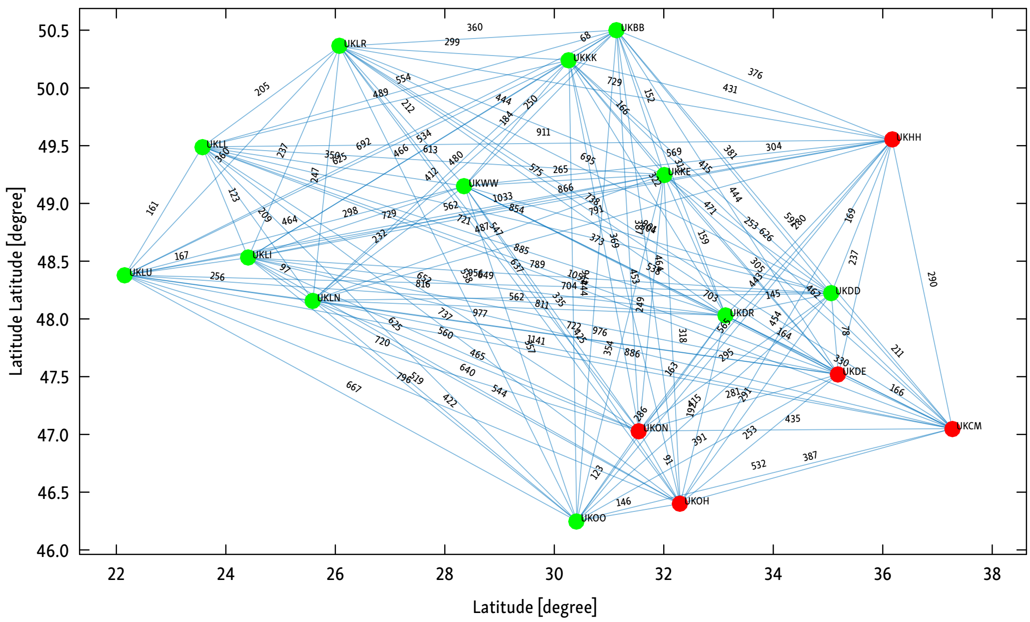

Figure 5. Chart of Ukrainian airports during the post-war reconstruction period (accepted scenario) (source: own elaboration of the authors)

Table 1. The distances between Ukrainian airports (source: own elaboration of the authors)

	UKBB	UKKE	UKLN	UKDD	UKDD	UKLI	UKOH	UKDR	UKLL	UKCM	UKDE	UKON	UKOO	UKLR	UKLU	UKWW	UKKK
UKBB	0	152	480	381	704	534	464	311	554	591	444	387	476	360	692	250	68
UKKE	152	0	487	253	704	562	318	159	613	462	305	249	354	444	729	265	166
UKLN	480	487	0	704	791	97	544	562	209	886	722	465	422	247	256	232	412
UKDD	381	253	704	0	169	789	291	145	854	211	78	295	415	695	956	504	415
UKDD	704	304	791	169	0	866	454	280	911	290	237	443	565	729	1033	569	431
UKLI	534	562	97	789	866	0	640	649	123	976	811	560	519	237	167	298	466
UKOH	464	318	544	291	454	640	0	464	737	387	253	91	146	637	796	425	453
UKDR	311	159	562	145	280	649	192	0	721	330	164	163	286	575	816	373	322
UKLL	554	613	209	854	911	123	737	721	0	1051	885	652	625	205	161	350	489
UKCM	591	462	886	211	290	976	387	330	1051	0	166	435	532	901	1141	703	626
UKDE	444	305	722	78	237	811	253	164	885	166	0	281	391	738	977	538	471
UKON	387	249	465	295	443	560	91	163	652	435	281	0	123	547	720	335	369
UKOO	476	354	422	415	565	519	146	286	625	532	391	123	0	558	667	357	444
UKLR	360	444	247	695	729	237	637	575	205	901	738	547	558	0	360	212	299
UKLU	692	729	256	956	1033	167	796	816	161	1141	977	720	667	360	0	464	625
UKWW	250	265	232	504	569	298	425	373	350	703	538	335	357	212	464	0	184
UKKK	68	166	412	415	431	466	453	322	489	626	471	369	444	299	625	184	0

During calculation and simulation for efficiency analysis, a number of assumptions were made:

- each airport meets the requirements set for international airports. Therefore, we believe that each of them has 10 types of ARE, sufficient to perform the functions of flight support;
- each type of ARE has a number of units that is generated using a random number generator with a uniform distribution in the range from 5 to 10;
- failure rates for each ARE unit are generated using a random number generator with a uniform distribution in the range from 0.0001 to 0.0003 1/h;
- the repair duration of each unit is a normally distributed random variable with a mean of 5 h and a standard deviation of 1 h;
- the tariff for delivery of one unit to the repair center is C_{td} = 0.02 c.u./km;
- the tariff for one unit repair is C_{tr} (M, N) = 5 c.u./h.

To determine the possible options for the organization of the ARE repair centers infrastructure, one of the AI methods, namely the method of *k* -means clustering was used. This method is non-parametric, which means that it does not require knowledge about the parameters of the training sample and their distributions. For the method, it is enough to specify only the number of clusters. In this article, we considered infrastructure options with one, 2, and 3 repair centers within the country. In the case of one repair center, its location will be determined by averaging the geographic coordinates of all airports. At the same time, the center will be selected based on the criterion of the minimum distance to the airport.

In the case of 2 and 3 repair centers, their location was chosen based on the criterion of the minimum distance to the formed centroids. At the same time, the final coordinates of the centroids according to the *k*-means clustering method are determined iteratively until they stop changing at the next iteration.

The formation of clusters for the case of 17 airports (pre-war period) and 12 airports (post-war period) is shown in Figures 6 and 7.

For the case of 2 clusters and 17 airports, the nearest airports to the centroids are the airports in Kryvyi Rih and Ivano-Frankivsk. For the case of 3 clusters and 17 airports, the nearest airports to the centroids are the airports in Dnipro, Cherkasy, and Ivano-Frankivsk.

For the case of 2 clusters and 12 airports, the nearest airports to the centroids are the airports in Cherkasy and Ivano-Frankivsk. For the case of 3 clusters and 12 airports, the nearest airports to the centroids are the airports in Kyiv, Kryvyi Rih, and Ivano-Frankivsk.

Based on this, we can form 8 research scenarios with the aim of obtaining quantitative evaluations of efficiency in the form of average total repair costs:

- scenario 1 – repair center in Kyiv (pre-war period, 17 airports);
- scenario 2 – repair center in Boryspil (pre-war period, 17 airports);
- scenario 3 – repair centers in Kryvyi Rih and Ivano-Frankivsk (pre-war period, 17 airports);
- scenario 4 – repair centers in Dnipro, Cherkasy and Ivano-Frankivsk (pre-war period, 17 airports);
- scenario 5 – repair center in Vinnytsia (post-war period, 12 airports);
- scenario 6 – repair center in Kyiv (post-war period, 12 airports);
- scenario 7 – repair centers in Cherkasy and Ivano-Frankivsk (post-war period, 12 airports);
- scenario 8 – repair centers in Kyiv, Kryvyi Rih and Ivano-Frankivsk (post-war period, 12 airports).

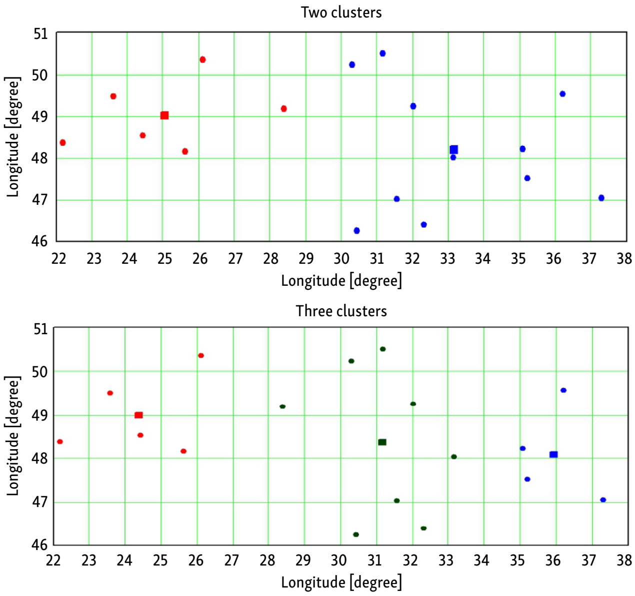

Figure 6. Clusters formation for airports location before January 2022 (source: own elaboration of the authors)

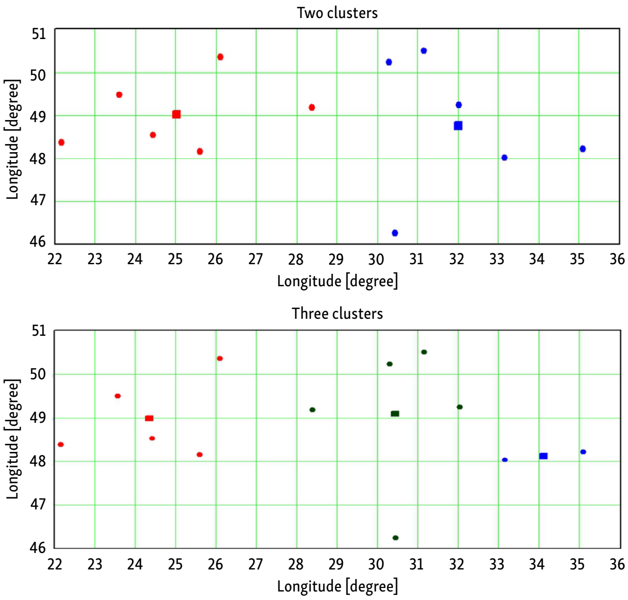

Figure 7. Clusters formation for airports location during the post-war reconstruction period (accepted scenario) (source: own elaboration of the authors)

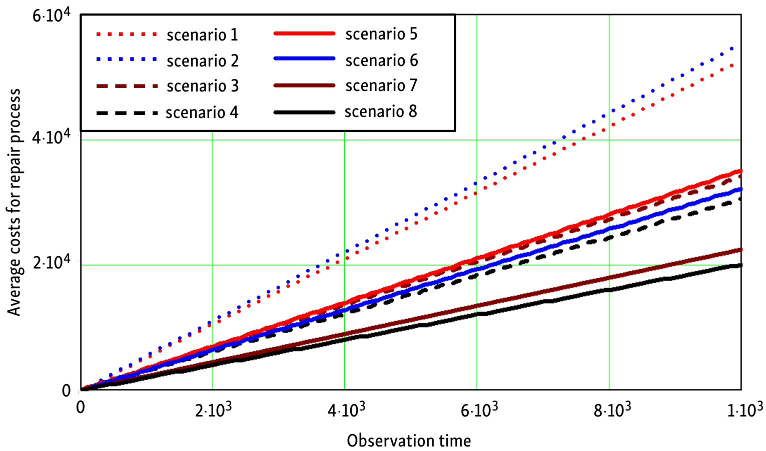

Figure 8. Efficiency analysis for different scenarios of repair centers location (source: own elaboration of the authors)

During the simulation, it was assumed that the equipment operated continuously throughout the observation period. The observation interval was limited to one year.

A more detailed analysis should take into account not only repair costs but also the organization of the repair center, namely: measuring equipment, stands, personnel, etc. In this simulation, the task was to check the appropriateness of increasing the number of repair centers according to the criterion of minimum operational costs.

The simulation results for the specified scenarios are shown in Figure 8.

According to Figure 8, the introduction of additional repair centers increases the efficiency of ARE OS from the point of view of minimizing operational costs. At the same time, the profit from using 2 repair centers for 17 airports compared to the one center's best location is 35.4%. The profit of using 3 repair centers for 17 airports compared to the one center's best location is 42.1%. The difference between 2 and 3 repair centers is insignificant and equals to 6.7%. This value is relatively small compared to the cost of organizing a 3d repair center, so the use of 2 repair centers is more attractive at this stage of the analysis.

The profit of using 2 repair centers for 12 airports compared to one center's best location is 29.5%. The profit of using 3 repair centers for 12 airports compared to one center's best location is 35.6%. As it can be seen, the difference between 2 and 3 repair centers is insignificant and equals to 6.1%. In the period of post-war reconstruction of Ukraine, the use of 2 repair centers looks also more attractive.

Performing a general analysis of the proposed approaches, it should be noted the use of the clustering method as an element of AI. Using the clustering method, it was possible to form a number of alternative options for the placement of nodal repair centers. In the future, it is possible to form other options for the placement of centers, if we take into account the cost of delivery and repair operations of ARE, the cost of deploying a repair center with justification for the types of necessary equipment, the number of workplaces, personnel, and others.

It should be noted that the development and modernization of sub-systems for the repair of ARE are carried out in management decision support systems. These systems monitor the condition of the repair process components and, if necessary, make adjustments to certain components.

It is advisable to periodically analyse the parameters in the equations given in the article using appropriate methods of examination of this subject area. At the same time, it is necessary to collect statistical data on fluctuations in the cost of deliveries of equipment elements, changes in tariffs for repair procedures, changes in the amount of equipment at airports and its failure and damage statistics. This approach makes it possible to develop and optimize the infrastructure of repair centers for the aviation industry within any state. In addition, these approaches can be extended to other types of transport.

In general, the results of the research can be used in project organizations, state regulatory bodies for civil aviation activities, individual airports and their associations, where ARE is operated. The prospects of using the obtained results should be associated with the wide application of AI methods and technologies, the principles of adaptability, systematicity and functional integrity for the effective solution of ARE repair issues.

5. Conclusions

The article is devoted to the development of methods for optimizing the organizational structure of the process of ARE repair.

The optimization problem is solved from the point of view of 2 directions. The 1st direction was related to the evaluation of the efficiency of the organizational structure of ARE OS during the repair process, taking into account the costs of delivering units with failures to the repair center and the costs of the repair procedure. The 2nd direction was related to the rationalization of the organizational structure of ARE OS, taking into account the efficiency of decision-making procedures regarding the implementation of a certain type of repair procedure, depending on the type of failure (simple or complex). In the event of a simple failure, repair procedures can be performed by the personnel of the airport where the equipment is located. In case of complex failures, it is advisable to carry out repairs in specialized repair centers. Analytical equations were obtained during the research, and made it possible to substantiate the possibility of further reduction of operational costs.

The use of the given approach to improving ARE OS can be used during solving applied problems with a random number of airports, their random geographical location, different types of equipment in each of them, different reliability properties, and different types of observed failures.

In general, the scientific novelty of the obtained results is related to taking into account a large number of parameters that characterize the process of repairing ARE. It is especially necessary to emphasize that possible errors in the classification of failures are taken into account when dividing them into simple and complex. It should also be noted that the clustering method was used when determining the geographic location of repair centers. This approach corresponds to the elements of AI.

The article presents a comparative analysis of 8 scenarios for the organization of the infrastructure of repair centers in Ukraine for the pre-war period and the period of post-war reconstruction (4 scenarios each). The coordinates of the repair centers were obtained based on averaging the data on the longitude and latitude of the airports in Ukraine (in the case of only one repair center usage) and using k-means clustering technique for corresponding data (in the case of *k* repair centers usage). An approximate assessment showed that it is enough to have 2 repair centers for the period of post-war reconstruction of Ukraine to ensure minimal operational costs and acceptable initial investment for the deployment of these centers. Analysis of performed calculations and simulation of various scenarios shows that the use of 2 repair centers allows to reduce operating costs for repairs in the range of 21 to 43 percent. Using a 3rd repair center increases efficiency by up to 8%.

The obtained results are of great practical importance, when in the period of the post-war reconstruction of the aviation industry of Ukraine there will be significant restrictions on expendable resources and it will be necessary to search for rational options for the organizational infrastructure of repair centers for elements, blocks and components of ARE.

Further scientific research will be aimed at:

- developing an optimal structure for the placement of repair centers for civil aviation equipment during the post-war reconstruction of Ukraine;
- justification of the structure, personnel, equipment of the repair center;
- analysis of the efficiency of the use of mobile repair teams in the event of failure of ARE;
- substantiation of the management decision support system and creation of datahubs in which information on all processes implemented in ARE OSs is collected and systematized.

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Author contributions

Conceptualization and methodology: *Maksym Zaliskyi*, *Oleksandr Solomentsev* and *Ivan Ostroumov*.

Investigation: *Viktoriia Ivannikova* and *Nataliia Kuzmenko*.

Resources: *Viktoriia Ivannikova*, *Oleksandr Solomentsev* and *Nataliia Kuzmenko*.

Data curation: *Oleksandr Solomentsev*.

Writing (original draft preparation): *Maksym Zaliskyi* and *Oleksandr Solomentsev*.

Writing (review and editing): *Maksym Zaliskyi*.

Visualization: *Ivan Ostroumov* and *Nataliia Kuzmenko*.

Validation: *Maksym Zaliskyi*.

Supervision: *Viktoriia Ivannikova* and *Oleksandr Solomentsev*.

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Disclosure statement

The authors declare no conflict of interest.

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