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ANALYTICAL JUSTIFICATIONS FOR THE DEVELOPMENT OF A SIMULATION MODEL OF MAINTENANCE OF AVIATION GROUND EQUIPMENT TAKING INTO ACCOUNT THE NEED FOR SPARE PARTS AND MATERIALS

Introduction

The main directions of economic and social development in the modern world provide for an increase in the transportation of cargo and passengers by air transport. The significant growth in the volume of air transportation also predetermines the accelerated pace of development of special airport vehicles. Labor and material costs for maintaining special vehicles in technically sound condition are substantial and several times higher than the costs of their production. To reduce expenses for maintaining the fleet of aviation ground equipment in technically sound condition, it is necessary to improve the system of their maintenance, increase labor productivity, including during work in extreme conditions. Operational factors are taken into account when establishing technical requirements, selecting test modes, planning, standardizing, and organizing technical operation, storage, and transportation of aviation ground equipment, instruments, and other technical products used in airport operations. To this day, the issue of assessing the changes in the efficiency of operation of special airport vehicles has not been sufficiently developed. Due to the high rate of change in the efficiency of aviation ground equipment (AGE) depending on operating time, a significant economic effect may be lost.

Analysis of recent research and publications

The efficiency of the functioning of the system for providing the airport special transport service can be evaluated by the total costs C_Σ for the acquisition, transportation, and storage of resources, as well as from losses incurred when allocating funds to the working capital [1]. In this case, the objective function can be written as follows [2]:

$$C_\Sigma - C_{\Sigma\min} \to 0,$$

where $C_{\Sigma\min}$ – the minimum possible costs associated with providing the airport with material resources for the maintenance of AGE).

To achieve the stated goal, it is necessary that the current total costs be as low as possible:

$$C_\Sigma = C_{ac} + C_{tr} + C_{st} + C_{la} \to \min,$$

where C_{ac} – costs for the acquisition of material resources; C_{tr} – costs for the transportation of material resources; C_{st} – costs for the storage of material resources; C_{la} – losses associated with the allocation of funds tied up in material resource inventories

As practice shows [3], all cost components and the total cost depend on the inventory level P_{sp}, and therefore the objective function can be written as follows:

$$C_\Sigma(P_{sp}) = C_{ac}(P_{sp}) + C_{tr}(P_{sp}) + \\ + C_{st}(P_{sp}) + C_{la}(P_{sp}) \to \min.$$

The constraint for the objective function should be taken as follows: $P_{sp} > 0$, and the parameters that characterize the operating conditions AGE vary within the following ranges: relative humidity h – 0...100 %, air temperature t – -20...40 °C, and movement speed AGE at the airport V – 5...60 km/h [3].

The first of the specified constraints prevents the absence of resources and the associated downtime of AGE, as well as the depletion of AGE components, for example, due to untimely replacement of oils and lubricants, filtering elements, etc. Introducing such a constraint simplifies the entire model, as it eliminates the need to consider the impact of material service life

on the increased labor intensity of AGE maintenance at the airport.

The remaining constraints in our model define the variation ranges of the main factors that affect the consumption of material resources used in the operation of AGE under airport conditions.

The main parameter of our system will be time, as the consumption of material resources, as well as the accounting of these resources and the planning of their supply, is carried out over time. Over time, the operating conditions of AGE also change. These changes in the operating conditions of AGE are one of the main reasons for the variation in the intensity of operation of the corresponding equipment at the airport.

The operating conditions and operating time of AGE also determine the operating mode of their units and assemblies [4]. In turn, this affects the rate of change of the technical condition of AGE, which, in turn, influences the technical condition of AGE and the intensity of its operation, and consequently affects the rate of consumption of material resources for the operation of AGE.

The following relationship is most often observed [5]. The higher the intensity of AGE operation, the greater the amount of maintenance work required. Accordingly, the amount of maintenance work on AGE determines the need for material resources, which are primarily replaced based on operating time. The rate of consumption of material resources and the operating time determines the number of replacements of units and assemblies based on their condition. Thus, replacements based on operating time and replacements based on demand form the total consumption of material resources.

The purpose of the work

The purpose of this work is to develop a simulation model of the flow of requirements for maintenance of aviation ground equipment, which should allow us to improve the generalized model of operation of special equipment and machinery at a modern airport, regardless of the condition and volume of the fleet of this equipment and machinery.

Patterns of Functioning of the Studied System

In the structure of the studied system for providing the airport special transport service, a number of key patterns can be identified that determine the consumption and variation in the consumption of material resources for maintenance AGE:

– changes in operating conditions over time;
– changes in the intensity of operation over time;
– the influence of operating conditions on the resource of parts that are replaced based on condition;
– changes over time in the consumption of parts replaced based on condition;

– changes over time in the amount of maintenance work by type and level;
– changes over time in the consumption of materials replaced based on operating time;
– the influence of operational intensity and the frequency of different forms of maintenance on the number of maintenance operations by type and level.

Accordingly, these patterns determine the parameters of the supply system for the airport special transport service:

– supply volumes;
– supply intervals;
– inventory volumes.

As studies [2, 3] show the patterns of the volume and frequency of resource supplies are fairly well studied. Most often, harmonic models are used to describe these patterns.

The patterns of the influence of operating conditions on the resource of parts replaced based on condition-such as the dependence of motor oil consumption on air temperature or the effect of air temperature on the resource of brake pads-are also well studied [4].

However, there remains a large number of AGE parts replaced based on condition for which the patterns of how operating conditions affect their resource are insufficiently studied. For example, it is necessary to study the pattern of the influence of seasonal conditions on the resource of engine air filters of AGE, as well as their drive belts.

In particular, the main reason for replacing an engine filter is clogging, which causes increased resistance to the air passing through it. The intensity of filter clogging is influenced by a number of factors. Among them, it is necessary to highlight those that affect dust formation in the airport area:

– the area of the airport where a specific type of AGE is operated;
– the level of air pollution in the airport area;
– the condition of the airfield territory;
– air temperature and humidity.

In the areas of the airport located farther from the runway and the main aircraft parking stands, dust formation is lower. Since this factor is difficult to quantify, it can only be considered as the proportion of engine operating time in different areas of the airport. It is obvious that the higher the proportion of engine operating time in the most dust-intensive zones of the airport, the greater the filter contamination. In the first approximation, this relationship can be described by a linear model.

Another important factor that determines the intensity of dust formation is air temperature. The higher the air temperature, the greater the amount of dust present in the air within the airport area. Here as well, in the first approximation, a linear model can be used.

A factor such as humidity is most often characterized by relative air humidity (%) or the amount of precipitation (mm) over the calendar year. In some studies, the measurement of the fraction of days with precipitation is used. The higher the humidity levels, the lower the intensity of filter contamination. As research shows, with a small margin of error, a linear relationship can also be used here.

When studying the influence of various factors on the resource of engine drive belts of AGE, it depends on the transmitted torque and their temperature. For colder regions of the Earth, a significant increase in the torque transmitted by the belt is characteristic as temperature decreases. This is due to increased viscosity of lubricants and an increase in the resistance torque of the driven shafts of the units. Additionally, changes in air temperature lead to changes in the working temperature of the belt and, consequently, the properties of its materials, which determine the resource of the drive belts. Therefore, the influence of air temperature on the failure intensity of drive belts can be described by a quadratic model. This model is adequate if the effect of temperature on the strength properties of the belt material predominates. If, however, air temperature more strongly affects the change in transmitted torque, an inverse linear model can be used.

Our studies have shown that the following patterns constitute time series:

– changes over time in the consumption of AGE parts replaced based on condition;

– changes over time in the amount of maintenance work by type and level;

– changes over time in the consumption of materials for AGE replaced based on operating time.

This is due to the patterns of change over time in AGE operating conditions, as well as changes over time in the intensity of AGE operation. Usually, these dependencies are associated with seasonal variations of influencing factors and are therefore described by harmonic models. To assess the significance of temporal changes in the studied parameters, a method that involves linearization of the harmonic model can be used.

Let us consider this using the example of material consumption over time for AGE maintenance.

The pattern of change over time in material consumption for AGE maintenance can be described by a harmonic series of the following form [5]:

$$P = P_c + \sum_{j=1}^{n} P_j \cos\left(m\left(jT_i - T_j\right)\right) + P_p,$$

where P_c – the constant component of resource consumption; j – harmonic number; n – number of harmonics; P_j – half-amplitude of the j-th harmonic variation; T_i – current time, in months; m – difference between T_i and T_{i+1}, angular degrees; T_j – initial phase of the harmonic j, months; P_p – random component.

The assessment of the significance of seasonal changes in resource consumption was carried out by linearizing the harmonics through a change of variables:

$$P = \sum_{j=1}^{n} P_j z_j,$$

where $z_j = \cos(m(jT_i - T_j))$.

Since we considered a calendar year, the cycle of material consumption variation was equal to 12 months. At the same time, the condition for the significance of a harmonic, checked using the correlation coefficient between consumption and the variable z_j, has the following form [5]:

$$t_r = \frac{3,6\left|r_{P/z}\right|}{\sqrt{1 - r_{P/z}^2}} \geq t_\alpha,$$

where t_α– the critical value of the Student's t-statistic for the probability α

The pattern of the influence of operational intensity and the frequency of maintenance of AGE on the number of tasks required to restore its serviceable condition by type and level has been well studied using a deterministic approach. Thus, when using the cyclic method, the number of M-1 N_1 and M-2 N_2 per cycle is calculated based on the operating time of AGE during the cycle L_K, the number of major overhauls N_K corresponding frequencies of maintenance types L_1 and L_2:

$$N_2 = (L_K/L_2) - N_K;$$
$$N_1 = (L_K/L_1) - (N_K + N_2).$$

As can be seen from these formulas, the number of maintenance operations is directly proportional to the operating time per cycle and inversely proportional to the frequency of maintenance types. Therefore, the deterministic approach is used only under the following assumptions:

– the operational intensity is assumed to be constant;

– the interval of the maintenance types is also assumed to be constant.

In reality, the intensity of operation varies significantly both across different types of AGE and throughout the calendar year. The actual frequency of maintenance types for AGE at airports also differs substantially from the so-called "normative" frequency. Therefore, the process of forming the flow of maintenance requirements for AGE is stochastic. From the analysis of the formulas presented above, we can assume that the number of maintenance types depends linearly on the intensity of operation, with the number of maintenance actions increasing more sharply as the frequency of maintenance decreases and the intensity of AGE operation rises. Our studies have shown that, when the frequency of maintenance types changes, the number of maintenance actions varies according to a hyperbolic relationship.

If we consider the generalized relationship between the number of maintenance types and the intensity of AGE operation l and the frequency L_M, then the ratio of the annual operating time of AGE to the frequency of maintenance types can be used. This relationship will be linear, and the models of the considered dependencies take the following form:

$$N_M = a_0 + a_1 l;$$
$$N_M = b_0 + b_1/L_M;$$
$$N_M = A_0 + A_1 l + A_2/L_M,$$

where $a_0, a_1, b_0, b_1, A_0, A_1, A_2$ – empirical coefficients.

The generalized model is as follows:

$$N_M = A_0 + A_1 l/L_M.$$

For a stochastic process, it is necessary not only to know the average values of the number of maintenance types over specific time periods, but also the coefficient of variation. The variation of values relative to the mean is related to the randomness of the process of AGE entering a particular maintenance type. The greater the number of maintenance actions, the smaller the random component.

As the intensity of AGE operation increases, the number of maintenance actions rises and the coefficient of variation decreases. When the frequency of maintenance types for AGE decreases, the number of actions also increases, and the coefficient of variation decreases. For example, the coefficient of variation for M-1 should be lower than that for M-2, which has a longer interval between maintenance.

To describe the considered relationship, one of three models was used in our studies: exponential, power, and logarithmic.

$$V_{N_M} = a_0 e^{-a_1 l};$$

$$V_{N_M} = a_0 l^{-a_1};$$

$$V_{N_M} = a_0 + a_1 \ln(l),$$

where a_0, a_1 – empirical coefficients.

The selection of the best model was carried out based on discriminant analysis of the experimental results. To describe the generalized form of the considered relationship, we used a power model:

$$V_{N_M} = a_0 \left(l / L_M \right)^{a_1},$$

where a_0, a_1 – empirical parameters.

To describe the generalized dependence of the coefficient of variation of the number of maintenance actions on the frequency of AGE maintenance as a fraction of annual operating time, a logarithmic model was proposed:

$$V_{N_M} = a_0 + a_1 \ln\left(\frac{L_M}{l} \right),$$

where a_0, a_1 – empirical coefficients.

Preliminary Selection of Factors Affecting Resource Requirements in AGE Maintenance

For the efficient organization of the supply of consumables for the airport special transport service, it is necessary not only to know the average consumption across all items in the nomenclature, but also the variation of this consumption. To this end, we consider the factors that affect both the consumption and its variation for materials replaced based on operating time as well as based on condition.

The consumption of resources replaced based on operating time depends on the replacement frequency, the number of AGE in the fleet, and the intensity of their operation. The replacement frequency depends on the sophistication of the design and the manufacturing technology of AGE. The replenishment frequency is adjusted according to the operating conditions of AGE at a specific airport. Therefore, the actual frequency may differ significantly from the normative one. The extent of this deviation depends both on the operating conditions of AGE and on the level of organization of AGE usage accounting. Resource inventories also often depend on the distance to the source of supply.

Moreover, the range of materials used is determined by the complexity of the design and the degree of standardization of AGE used at the airport.

The list of factors considered to influence the consumption of resources replaced based on operating time includes eight items. The preliminary selection of the most significant factors was carried out using expert analysis based on the a priori ranking method [5].

For the expert analysis, ten specialists in the field of AGE operation were selected, and a questionnaire was developed. The experts were asked to rank the proposed factors in descending order of significance. For each factor, the sum of ranks, the average rank, and the priorities were calculated. Factor weights were also determined, indicating the proportion of variation in resource consumption associated with each factor.

As a result, an a priori rank diagram of the factors was constructed. Factors for which the sum of ranks was below the average sum were considered the most significant. The most significant factors identified were the following:

– intensity of AGE operation;
– concentration level of similar AGE at the airport;
– climatic conditions of the airport;
– sophistication of AGE design.

The consistency of expert opinions was checked using the concordance coefficient. Since the concordance coefficient $W = 0{,}67 > 0{,}5$. It can therefore be concluded that the expert opinions are consistent. The significance of the concordance coefficient was tested using the Pearson criterion. The calculated value of

the Pearson statistic was 80.1, which exceeds the critical value of 15.5 with a probability greater than 0.95. Therefore, the concordance coefficient is significant with a probability of more than 0.95.

The variation in resource consumption was determined based on the maintenance production program at the controlled airports. It was taken into account that the greater the number of maintenance actions per unit of time, the smaller the variation in their number. Based on this pattern, in particular, a coefficient of non-uniformity of AGE arrivals in the maintenance zone was established when calculating the number of maintenance posts. In addition, the variation in demand for consumables depends on the variation in operational intensity over time – with an increase in the intensity of AGE operation, the number of maintenance requests grows [4].

The study of factors affecting the variation in resource consumption made it possible to compile the following list:

– standardization – the higher the level of standardization in the design of different types of AGE, the smaller the range of resources and the higher their consumption, which leads to a reduction in demand variation;

– operational intensity – the higher the average operational intensity of AGE, the lower the variation in resource consumption due to an increased number of maintenance actions on the equipment (the higher the variation in AGE operational intensity over time, the higher the variation in resource demand);

– climatic conditions – the operating conditions of AGE determine the normative and actual frequency of maintenance types, thereby acting the total number of maintenance types;

– fleet homogeneity by marks and models of AGE – the more homogeneous the fleet, the narrower the range of resources, the higher the consumption, and the lower the variation in consumption;

– level of AGE concentration – the greater the number of AGE in the airport special transport service, the higher the consumption and the lower the variation in resource consumption.

The conducted check using the concordance coefficient demonstrated the consistency of the experts' opinions ($W = 0,64$) at a significance level exceeding 0.95.

The following factors were recognized as the most significant:

– the intensity of AGE operation;

– the climatic conditions of the airport;

– the level of concentration of similar AGE at the airport.

The consumption of resources, which are replaced based on the condition of the AGE, is determined by the service life of the components until their limiting state and the total operational time of the AGE over the considered period.

The service life until the limiting state depends on factors such as:

– design sophistication;

– manufacturing technology;

– quality of operation;

– climatic conditions of the airport;

– quality of maintenance and repair;

– quality of material resources;

– availability of production facilities and technological equipment;

– method of inter–shift (or off–season) storage of rolling stock;

– age structure of the AGE fleet.

The total operational time of the AGE is influenced by:

– intensity of operation;

– level of fleet concentration;

– accounting for the operation of individual functional systems.

– the nomenclature of consumable materials is influenced by factors such as:

– complexity of design;

– standardization;

– homogeneity of the fleet in terms of makes and models.

After processing the ranks and weights that determined the consumption of resources replaced based on condition ($W = 0,84$, the concordance coefficient is significant with a probability of 0.95), it was established that the most significant factors are:

– the level of fleet concentration;

– design perfection;

– intensity of operation;

– climatic conditions of the airport;

– quality of maintenance and repair;

– availability of production facilities and technological equipment;

– age structure of the AGE fleet;

– quality of material resources.

It was revealed that the variation in the consumption of resources replaced based on condition is associated with the variation in service life until replacement and the variation in the total operational time of the AGE over the considered period.

The service life until replacement depends on the quality of AGE supplied to the airport and is determined by the sophistication and complexity of the design, manufacturing technology, as well as operating conditions and the age structure of the equipment fleet.

The variation in the total operational time of AGE over the considered period is determined by the variation in operating intensity, the level of AGE concentration, and the organization of usage accounting (use

of AGE for purposes other than intended, and the reliability of data on actual operational time of functional systems). The variation in demand for consumables depends on the standardization of designs of different types of AGE and the homogeneity of the fleet in terms of makes and models.

As a result of the conducted a priori ranking of these factors, the concordance coefficient was $W = 0,81 > 0,5$, with the significance of the concordance coefficient exceeding 0,95.

Therefore, the most significant factors were recognized as follows:

– intensity of operation;
– level of fleet concentration;
– airport climatic conditions;
– age structure of the fleet;
– uniformity of the fleet by brands and models;
– method of inter–shift (inter–seasonal) storage of rolling stock;
– availability of production areas and technological equipment;
– quality of maintenance and repair.

Thus, as a result of the expert analysis of factors influencing the system for supplying the airport special transport service with material resources, we were able to perform a preliminary assessment of their significance. Subsequently, the results of factor selection were verified through a passive experiment under airport conditions.

The list of factors is quite extensive, and it is not feasible to study their impact on the process of material consumption for AGE maintenance within a single research project. Therefore, in our study, we considered only those factors that vary depending on the season of the year.

Patterns in the formation of maintenance demand flow

The existing methods for determining the production program for the maintenance of modern AGE do not allow for sufficiently accurate results. This is due to reasons such as:

1. Normative values of AGE maintenance intervals are typically used as initial data, whereas in practice these intervals are not always followed for various reasons.

Firstly, the maintenance frequency can be conditionally divided into three components:

$$L^{(M)} = L_C^{(M)} + L_T^{(M)} + L_P^{(M)},$$

where $L_C^{(M)}$ – trend component; $L_T^{(M)}$ – periodic component; $L_P^{(M)}$ – random component.

In calculations, it is usually assumed $L_C^{(M)} = const$, $L_T^{(M)} = 0$, $L_P^{(M)} = 0$, although regulatory documents for many types of AGE specify a random component – for example, the "Regulations on TMX-450-TLD Maintenance" [6] allow a deviation from the standard maintenance interval of $\pm$ 10 %.

Furthermore, the frequency of maintenance operations changes as the AGE ages. For instance, the interval may decrease as the total operating time of the AGE increases, or, for another type of AGE, the list of maintenance tasks may change at different operating hours while the interval remains constant. Thus, in general, changing operating conditions over time affect the rate of technical deterioration of AGE, requiring seasonal adjustments to maintenance intervals. At present, this fact has not been adequately reflected in regulatory documents.

2. Changes in the operational intensity of AGE over time lead to corresponding changes in the demand for maintenance work.

The operational intensity of AGE depends on many factors. On one hand, it is determined by the potential volume of work that needs to be performed, and on the other hand, by the ability to carry out this volume. Airports experience seasonal fluctuations in workload, which leads to variations in the potential volume of work for different types of AGE. The ability to realize this potential volume is mainly determined by the operating conditions of the AGE, including low air temperatures and seasonal changes in the condition of airport surfaces and surrounding areas.

Seasonal variations in AGE operational intensity lead to changes in the demand for various maintenance tasks. The methods currently used in airports for planning maintenance programs do not sufficiently account for this factor. As a result, there is often a shortage of maintenance stations, exceedance of the standard maintenance intervals, and a decrease in AGE reliability.

3. The conditions under which maintenance requirements arise are not always adequately considered at airports: some operations are performed based on operating hours, some based on condition, some based on time, and some on whichever comes first – operating hours or time.

A requirement for a specific maintenance task is generated when the normative operating hours are reached or exceeded. For certain operations or types of maintenance, the interval until the next maintenance is limited by time. Another variant is that if the

established operating hours are reached first, maintenance is carried out based on usage; if the operational intensity is insufficient, maintenance is carried out based on time. Typical operations performed at set time intervals include coolant replacement.

4. Traditionally, AGE maintenance is organized as a two-tier system, including Maintenance Level 1

(M-1) and Maintenance Level 2 (M-2), along with daily and seasonal maintenance. However, for many types of AGE today, a greater number of maintenance levels is provided. For example, M-1 may have two sets of operations performed during even and odd maintenance intervals, while M-2 may include four different sets, differing both in the list of operations and in labor intensity.

5. For new types of AGE, there is a consistent trend toward longer intervals between all forms of maintenance. This creates challenges in calculating the monthly and annual production schedules for the airport special transport service.

6. As AGE ages, their operational intensity decreases.

Thus, there is a challenge in forecasting the maintenance production schedule for a modern AGE fleet. Therefore, when modeling the maintenance program for AGE, the following patterns must be taken into account:

– the pattern of the influence of operating conditions on the utilization rate of AGE.

– the influence of operating conditions on the periodic component of the utilization rate of AGE, j_1.

– the influence of operating conditions on the random component of the utilization rate of AGE, s_1.

– the pattern of formation of the requirement flow, taking into account different conditions under which maintenance requirements arise (based on L_M, based on τ_M)

– the influence of $(L_M/l)/t_M$ on the pattern of $N_M = f(T)$

– the influence of (L_M/l) on the intensity of change in the number of AGE maintenance types.

– the influence of φ_1 on the intensity of change in the number of AGE maintenance types.

– the influence of σ_1 on the intensity of change in the number of AGE maintenance types.

Simulation model of maintenance demand flow

The model we used is based on a methodological approach that involves recording the operating hours of each AGE at the beginning of the forecast period, as well as the type of the last completed maintenance form and the operating hours at which it was performed. It then forecasts daily increments in operating hours for each AGE unit, checks whether the threshold for the next maintenance form has been reached, and counts the projected maintenance actions.

Such a simulation model is employed to study systems when it is impossible to obtain the desired result using an analytical model. Since the patterns that generate maintenance demand are stochastic, the system under study is also stochastic. Therefore, a deterministic approach can only determine the average number of maintenance forms over a sufficiently long period

but does not allow for assessment of the variation in the number of maintenance actions. Solving this problem is only possible using the Monte Carlo method to simulate the patterns of AGE operating hours and the actual intervals of maintenance forms.

To create the simulation model, it is first necessary to determine the list of initial data and the method of their representation. As initial data, we decided to use the following indicators:

– operating hours of each AGE at the beginning of the forecast period;

– operating hours of each AGE at the time of the last maintenance;

– identifier of the type and form of the last maintenance;

– actual maintenance intervals by type and form;

– actual operational intensities of AGE.

As experience shows, the formation of initial data is a complex task, since the indicators under consideration are random variables. It is necessary to select methods for representing each indicator.

1. The operating hours of each AGE at the beginning of the forecast period can be represented in two ways.

The first method is to represent the operating hours of AGE as an array of numbers for L_i. The advantage of this method is its simplicity, while the drawbacks are: high labor intensity for manual input if the AGE fleet is large, and the inability to obtain accurate data if the forecast period has not yet begun.

The second method is to specify the distribution of operating hours: the type of distribution law and its parameters. The advantage of this method is the relatively low labor required to input initial data, while the disadvantage is low accuracy for a small AGE fleet. Additionally, this method requires further study to forecast the age structure of the AGE fleet using a distribution specified in a table.

2. The operating hours of each AGE at the time of its last maintenance can also be represented in two ways.

The first method is by using the actual values for each AGE at the airport under consideration, presented as an array of numbers L_{pi}. The advantage of this method for specifying initial data is its simplicity and accuracy, while the disadvantages are the high labor intensity of manual input for a large AGE fleet.

The second method is to specify this indicator using a distribution defined by the type of distribution law and its parameters. The advantage of this method is low labor intensity, while the disadvantages are low accuracy for small AGE fleets and for high maintenance interval values.

3. The identifier of the type and form of the last maintenance is necessary to determine the type of the next maintenance. When creating the simulation model,

the most convenient method of identification was chosen: assigning a sequential number to each type and form of maintenance. Considering the variety of maintenance system structures in modern AGE from different manufacturers, it is necessary to establish rules for designating maintenance types and forms.

With a multi-level maintenance system structure, the identification process becomes fairly complex.

4. The actual intervals of maintenance forms can differ significantly from the normative ones. It has been established that the actual maintenance intervals can be modeled using normal or log-normal distributions. Therefore, to obtain values of this variable in the model, corresponding random number generators were used. The initial data for generation are the average maintenance interval and the coefficient of variation.

5. The actual operational intensities for each AGE unit were generated at each modeling step. Based on the average operational intensity, the periodic component was calculated using a polyharmonic model. The random component was generated using a random number generator. The initial data for modeling actual operational intensities included the parameters of the harmonic model for calculating the periodic component and the parameters of the distribution law for the random component. The parameters of the harmonic model were calculated in advance based on actual data on AGE operational intensity.

The operation of the model involves the implementation of the following steps.

1. Input of initial data:
– simulation start time;
– simulation end time;
– time increment step;
– number of AGE units in the fleet;
– average annual operating hours of AGE;
– normative maintenance intervals by levels;
– operating hours of each AGE after the last maintenance;
– time elapsed since the last maintenance for each AGE unit;
– number of maintenance levels;
– level number of the next maintenance for each AGE unit;
– numerical values of the parameters of the mathematical model describing the effect of time on operational intensity;
– numerical values of the parameters of the operational intensity distribution (random component);
– numerical values of the parameters of the distribution of actual maintenance intervals.

2. Opening a cycle T_c with the parameter: simulation start time T_s; simulation end time T_e; time increment step ΔT.

3. Opening a cycle A with the following parameters: initial value $A = 0$; step $A = 1$; cycle end condition $- A = A_C$.

4. Generation of operational intensity for AGE l.

5. Calculation of AGE operating hours over the time period ΔT: $\Delta L = l \cdot \Delta T$.

6. Calculation of AGE operating hours since the last maintenance: $L = L + \Delta L$.

7. Generation of actual maintenance intervals L_M.

8. Checking the condition of whether the AGE has reached the operating hours for the next maintenance: $L < L_M$. If the total operating hours have reached the threshold requiring maintenance, the process moves to step 10; otherwise, it proceeds to step 9.

9. Checking the condition of whether the time for the next maintenance has been reached: $T < T_M$. If the time for the next maintenance has not been reached, the process moves to step 14; otherwise, it proceeds to step 10.

10. The execution of the next maintenance for the given AGE unit is recorded, along with the corresponding time and operating hours at which the maintenance action is performed.

11. The operating hours after the next maintenance are reset to zero, the count of maintenance actions at this level is increased by one, and the level number of the next maintenance is also increased by one.

12. The end of the maintenance cycle is checked. If the current maintenance level number exceeds the number of maintenance levels in the cycle, the process moves to step 13; otherwise, it proceeds to step 14.

13. The current number of the next maintenance level is set to one.

14. The end of cycle A is checked. If the current AGE number has not reached its maximum value, the process returns to step 3; otherwise, it proceeds to step 15.

15. The end of cycle T is checked. If the current time has not reached the end of the simulated period, the process returns to step 2; otherwise, it proceeds to step 16.

16. The modelling results are outputted: the number of maintenance actions at each level per unit of time, and the actual operating hours at maintenance. The process then proceeds to the termination of the model.

Conclusions

As a result of the theoretical studies conducted, the following outcomes were obtained.

An objective function for the research was developed, which provides for the minimization of total costs dependent on the inventory levels of materials for maintenance.

The structure of the studied system was established, comprising six levels of elements and the relationships between them. The input to the system is time, and the output is the total costs associated with the acquisition, delivery, and storage of maintenance materials.

The patterns of interaction between the elements of the studied system were examined, and hypotheses regarding the mathematical models of these patterns were proposed.

Factors influencing the demand for materials for AGE maintenance were considered, and a preliminary assessment was performed based on expert analysis.

The patterns forming the flow of maintenance demands were analyzed. It was shown that modeling this flow requires the use of a simulation model, and an algorithm for such a model was also developed.

All of this formed the theoretical basis for developing a simulation model for the operation of special equipment and machinery in modern airports.

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Тамаргазін О. А., Приймак Л. Б., Кабика С. М.
АНАЛІТИЧНІ ОБГРУНТУВАННЯ ПОБУДУВАННЯ ІМІТАЦІЙНОЇ МОДЕЛІ ТЕХНІЧНОГО ОБСЛУГОВУВАННЯ АВІАЦІЙНОЇ НАЗЕМНОЇ ТЕХНІКИ З ОБЛІКОМ ПОТРЕБИ У ЗАПАСНИХ ЧАСТИНАХ І МАТЕРІАЛАХ

У статті розглянуто питання вдосконалення системи технічного обслуговування сучасної спеціальної техніки в аеропорту за рахунок оптимізації процесів, пов'язаних із забезпеченням її експлуатації запасними частинами та матеріалами. Було показано, що ефективність діяльності сучасного аеропорту багато в чому визначається якістю управління його діяльністю на всіх рівнях, у тому числі на рівні організації використання за призначенням спеціальної техніки та обладнання. Якість цих процесів істотно залежить від наявності коректного, відповідного стану та тенденцій розвитку конкретного аеропорту, а також методичного забезпечення, зокрема процесів, пов'язаних з технічним обслуговуванням авіаційної наземної техніки. Проведені дослідження лежать у рамках вирішення глобального завдання управління ризиками в авіаційній галузі. З цією метою було запропоновано модель функціонування системи забезпечення запасними частинами та матеріалами служби спецтранспорту аеропорту. Також запропоновано цільову функцію та проаналізовано найбільш суттєві обмеження при досягненні поставленої цілі. Зокрема, вивчені основні закономірності, які формують витрату та варіацію витрати матеріальних ресурсів використовуваних під час технічного обслуговування авіаційної наземної технік: зміна за часом умов експлуатації; зміна за часом інтенсивності експлуатації; вплив умов експлуатації на ресурси деталей, які замінюються за станом; зміна часу витрати деталей, які замінюються за станом; зміна за часом кількості робіт з технічного обслуговування за видами та ступенем; зміна часу витрати матеріалів, які замінюються за напрацюванням; вплив інтенсивності експлуатації та періодичності різних форм технічного обслуговування на кількість обслуговування за видами та ступенями. Розроблена імітаційна модель потоку вимог на технічне обслуговування авіаційної наземної техніки яка дозволила вдосконалити узагальнену модель експлуатації спеціальної техніки та обладнання в сучасному аеропорту незалежно від стану та обсягу парку цієї техніки та обладнання.

Ключові слова: аеропорт; спецтехніка; обслуговування; ресурси; стохастичність

Tamargazin O., Pryimak L., Kabyka S.
ANALYTICAL JUSTIFICATIONS FOR THE DEVELOPMENT OF A SIMULATION MODEL OF MAINTENANCE OF AVIATION GROUND EQUIPMENT TAKING INTO ACCOUNT THE NEED FOR SPARE PARTS AND MATERIALS

The article considers the issues of improving the maintenance system of modern special equipment at airports through the optimization of processes related to ensuring its operation with spare parts and materials. It was shown that the efficiency of a modern airport's operations largely depends on the quality of management at all levels, including the organization of the proper use of special equipment and machinery. The quality of these processes significantly depends on the availability of accurate information corresponding to the condition and development trends of a specific airport,

as well as methodological support, in particular for processes related to the maintenance of aviation ground equipment. The conducted research considers the framework of addressing the global challenge of risk management in the aviation industry. For this purpose, a model of the functioning of the airport special transport service's spare parts and materials supply system was proposed. Additionally, an objective function was introduced, and the most significant constraints in achieving the set goal were analyzed. In particular, the main patterns that determine the consumption and variation in the consumption of material resources used during the maintenance of aviation ground equipment were studied: changes over time in operating conditions; changes over time in the intensity of operation; the influence of operating conditions on the resource of parts replaced based on condition; changes over time in the consumption of parts replaced based on condition; changes over time in the amount of maintenance work by type and level; changes over time in the consumption of materials replaced based on operating time; and the influence of operational intensity and the frequency of different forms of maintenance on the number of maintenance operations by type and level. The developed simulation model of maintenance demand for aviation ground equipment allowed for the improvement of a generalized model for the operation of special equipment and machinery at a modern airport, regardless of the condition and size of the equipment fleet.

Keywords: airport; special equipment; maintenance; resources; stochasticity.