RT&A, No 2 (78)
Volume 19, June, 2024

STUDY OF THE FUNCTIONING OF A MULTI-COMPONENT AND MULTI-PHASE QUEUING SYSTEM UNDER THE CONDITIONS OF THE IMPLEMENTATION OF DISRUPTIVE TECHNOLOGIES IN AIR TRANSPORTATION

[1]O. Zaporozhets, [2]M. Katsman, [3]V. Matsiuk, [4]V. Myronenko

•

[1]Institute of Aviation (ILot), Warsaw, Poland
[2]The Joint-Stock Company of Railway Transport of Ukraine "Ukrzaliznytsia", Kyiv, Ukraine
[3]National University of Life and Environmental Sciences of Ukraine, Kyiv, Ukraine
[4]State University of infrastructure and technologies, Kyiv, Ukraine
[1]zaporozhets.oleksandr@gmail.com, [2]mdkatsman@gmail.com,
[3]vimatsiuk@gmail.com, [4]pupil7591@gmail.com

Abstract

The article considers multi-component and multi-stage mathematical models of queuing systems (QS) with the distribution of the incoming flow simultaneously between the system components, which consist of a certain number of service channels and waiting places in the queue. The maintenance of requirements with a lack of time to stay in the service channel and waiting is considered, while the service process in the QS of each component consists of several stages with the corresponding duration, and the full-service period is equal to the sum of such time intervals. The number of components and their parameters correspond to the similar characteristics of the production divisions of the repair enterprise. The study of the effectiveness of the operation of the repair enterprise as a multi-component and multi-stage QS consists in determining the values of the initial parameters of the QS components, taking into account the restrictions imposed on them, in order to obtain the largest values of the probabilities of servicing the requirements of the QS components and the system as a whole. The model is implemented using Any Logic University Researcher, which allows you to combine the principles of system dynamics with the paradigms of agent and discrete-event modelling. The proposed approach to the modelling of maintenance and repair processes by production divisions of the enterprise as a multi-component and multi-phase QS allows to determine the effectiveness of the functioning of such a QS and to obtain arguments for increasing the efficiency of its operation.

Keywords: aviation repair enterprise, aircraft, maintenance and repair, multi-component and multi-phase queuing system

1. Introduction

About 2% of the total worldwide fossil fuel usage corresponds to fuel consumption in aviation. Hybrid renewable integration, electrification, hydrogenation and optimizations are necessary roadmaps for the transition towards low-carbon airport transportation systems [1]. The rise of aircraft electrification with a few digital transformations in their operation and maintenance is making significant strides toward the sustainability of the aviation industry due to these absolutely new disruptive technologies and is a new challenge in air transportation development during the following decades.

As a result, aircraft emissions have caused approximately 2% of the total CO2 emissions [2]. Concept of More Electrical Aircraft (MEA) becomes much stronger [3], [4], so as the concepts of Hybrid Electrical Aircraft (HEP) and Full Electric Aircraft (FEP) in next few years will be realized in reality and the HEP and FEP will appear in operation evidently [1] − [4]. Components such as air-conditioning, cabin pressurization, de-icing, landing gear, and brake systems have traditionally been powered by pneumatic, hydraulic, or mechanical systems. Nowadays, it's becoming more common to see these components being electrically powered ″ current MEA concept [2]. The number of electrically powered components will be increased on the board of HEP and FEP aircraft, and so will the power needs and complexity of the systems. Transmitting large quantities of electrical power around an aircraft at a high voltage is required to minimize resistive losses. This transmission creates (or increases) the risk of insulation breakdown and arcing, which can cause catastrophic equipment failure ″ as electric equipment as other usual onboard equipment of the aircraft.

Also, the ground handling operations, which are used in airports for handling activities and processing passengers with the help of specially designed vehicles known as ground support equipment (GSE), will be changed from traditional energy usage on more environmentally efficient ″ electrified and hydrogenated [5].

Thus, electrical systems become decisive on board the aircraft both in terms of flight support and in carrying out maintenance services, which predetermines the need for high levels of reliability in carrying out such work. These FEA and HEA concepts will compete with sustainable aviation fuels (SAFs) implementation in the aviation sector, including biofuels [6] and hydrogen [7].

The aircraft maintenance system is designed to maintain and restore the airworthiness and serviceability of aircraft and prepare them for flight. Technical operation is carried out by operators, aviation and technical bases, maintenance and repair enterprises, repair enterprises, aviation and technical services of airports [8], [9].

One of the main factors of aircraft flight safety is the reliability of the on-board power supply system, which includes power sources, a control and protection system, switching equipment of the power distribution system, electric drives, lighting equipment, light signalling, fire extinguishing and anti-icing systems, and some other equipment. New investigations should be focused on the safety aspects of manned electric (HEP or FEP) flight based on the emerging technologies that are expected to be developed in the current decade, including their maintenance in airports and repair plants. The biggest safety concern is with the lithium-ion batteries that will power HEP or FEP aircraft. The batteries have the potential to ignite during the charging process through an uncontrollable temperature increase known as a thermal runaway.´ Also, battery energy uncertainty and battery charging safety will be the subject for flight hazards. In addition, any damage to the battery that causes the chemicals inside to be exposed to oxygen or water can lead to rapid oxidation and system failure.

Maintenance of the power supply system is carried out during capital and other repairs (or during equivalent works), inspections, modifications, upgrading, elimination of defects, which are carried out by aircraft repair enterprises both individually and collectively in the relevant workshops, production divisions, production areas, laboratories, stands, etc.

The work [10] is devoted to the creation and introduction into practice of aviation information and advisory systems for the maintenance of passenger aircraft based on modern computer technologies and mathematical methods of information processing.

In [11], the structure of the methodical apparatus for ensuring a given level of serviceability of on-board equipment products, in particular optoelectronic sighting systems of military aircraft of the Air Force of Ukraine, is proposed.

Methodical approaches to the structural and parametric determination of general requirements for ground flight maintenance facilities are considered in the paper [12], which can be used to develop a methodology for conducting tests and assessing the quality of modern air traffic control systems at all stages of the life cycle.

Based on the analysis of the existing methods of calculating the durability indicators of the radio-electronic system of the aircraft, the factors affecting its reliability were identified in [13], and measures were proposed to improve the existing scientific and methodological apparatus for calculating such indicators.

Works [14] and [15] are devoted to the analysis of the causes of failure situations at the airport. The aircraft maintenance system was analysed, it was shown that ensuring uninterrupted operation of the airport, execution of the daily flight plan in extraordinary situations is possible only by introducing into the control circuit of the aircraft ground maintenance system an intelligent decision support system for dispatchers, which will take into account the positive experience of their actions in typical, extraordinary and failure situations. This will allow, in particular, to reduce the time to get out of a malfunctioning situation and to optimize the operational planning of the ground maintenance of aircraft, considering the available equipment and special equipment.

In work [16], organizational measures are given, with the help of which it is possible to minimize the lack of transport aviation during the transportation of cargoes, including the oversized ones. Data on incidents related to aircraft ground maintenance are given, the causes of the events are indicated. The main ways of eliminating the problems of standardization of airfield technical support in the conditions of interaction with NATO and in the processes of international integration are defined.

The work [17] is devoted to the solution of the problem of minimizing the risks of import substitution in the process of factory repair of military aviation equipment in the conditions of a special period, the issue of post-repair maintenance of military aviation equipment due to the manufacture of the necessary component parts by domestic enterprises in the process of import substitution is analysed.

The work [18] presents the results of the quality of repair of aircraft equipment at aircraft repair enterprises. A significant proportion of failures detected during the operation of aviation equipment after capital (medium) repair is a consequence of manufacturing defects of components (parts) that were installed on aircraft. Technological methods for ensuring sufficient repair quality and significantly reducing the risks of production defects are proposed.

The work [19] is devoted to the problem of mathematical modeling of the processes of technical operation of military aircraft. The results of the analysis show that the most acceptable modelling method in terms of the compliance of the models with the proposed requirements is the simulation modelling method, and the more accepted model class for creating a stochastic model of aircraft maintenance and repair processes is the class of semi-Markov models.

In work [20], a three-dimensional model of an aircraft skin element with riveted seams was built using the Sold Works software, wind load simulation was carried out in the ANSYS software package, which made it possible to determine the stress-strain state of aircraft skin elements in the presence of multifocal damage to riveted seams.

Modern methods and approaches to modelling technological systems are considered in [21]. Basic definitions and concepts are given. New approaches to solving problems that arise during the development of models of mechanisms, systems and processes of machine-building production are proposed.

In work [22], it is proposed to consider the functioning of car service enterprises as an open multi-channel QS, in which random processes occur due to the combined action of random factors. As a result of the experimental study, information was obtained about the indicators characterizing maintenance and repair, as well as affecting the change in the parameters of these processes. The developed model makes it possible to consider the specifics of managing car maintenance stations.

In [23], a model for assessing the technical condition of radio-electronic elements of water transport vessels using control and diagnostic equipment as a QS with a limited number of channels and a storage of arriving customers is considered. On the basis of various optimization criteria, it is possible to establish a rational system for assessing the technical condition of such elements, to determine the feasibility of developing a certain (rational, optimal) number of different types of control and diagnostic equipment and the effectiveness of new assessment methods.

The work [24] is devoted to the development of a simulation model of the influence of an accurate assessment of the readiness factor of mobile control and diagnostic complexes on the reliability of control of radio-electronic systems of marine transport.

In work [25], a new model of the task of managing the processes of diagnosis and monitoring of automation tools is proposed for the objects of rail-water transport connection, compiled based on the results of experimental research and mathematical description using Markov chains with an informative parameter in the form of damage intensity, aimed at increasing the efficiency of forecasting the technical condition of automation equipment.

The work [26] describes for locomotive repair workshops in the form of multi-channel QS with a limited queue. A simulation model of such a workshop as a QS object was developed, which allowed rational use of equipment, labor force, as well as distribution of repair work time.

In work [27], the issue of modelling the maintenance and repair processes of technical components of a distributed information system is considered. The model is based on a joint presentation of the serviced system and its technical operation process in the form of a closed non-homogeneous QS consisting of two types of QSs. The QS of the first type simulates the functioning processes of repair bodies to meet and serve the arriving customers.

In work [28], a study of the actions of railway transport emergency units as a process of functioning of QSs was carried out. The authors established quantitative relationships between the intensity of the influence of a railway accident dangerous factors, on one hand and, on the other hand, the time of arrival, deployment and productivity of emergency liquidation units and the effectiveness of liquidation works due to the implementation of the network-centric management principles for complex dynamic hierarchical transport systems.

In paper [29], mathematical models of QSs with the distribution of the arrival flow of customers simultaneously over several service channels are considered. The model is implemented using agent simulation in the AnyLogic University Researcher environment and the Java compiler. The use of the proposed mathematical models will make it possible to establish areas of accepted values of the probability of successful completion of assigned tasks in order to make managerial decisions regarding the rational use of forces and means for the elimination of the consequences of railway transport events.

Thus, to improve the management processes for material, human, financial and informational resources during the maintenance and repair of aircraft and other means of transport, in particular on-board power supply systems, a wide range of methods of operations research, the queuing theory and simulation modelling are currently used.

2. Methods

The on-hand practical experience of the organization of maintenance and repair of aviation equipment indicates that certain types of technical systems of aircraft that require various types of repair work, modifications, upgrade, inspections, elimination of defects, etc. are sent to specific production divisions of the repair enterprise, which, according to their purpose, carry out the necessary types of work according to the specified technologies.

To simulate the processes of maintenance and repair of aircraft, which are carried out by the production divisions of the aircraft repair enterprise, it is advisable to use multi-component and multiphase QSs, which can be of both Markov and non-Markov types, capable of serving the arriving flows of non-priority, in general, heterogeneous (mixed) customers. At the same time, the system can have an arbitrary number of common service channels of the same type, and each component can also have an arbitrary number of places in the queue.

The same service channels can have different performance depending on the types of requirements for which they are involved: when the j-component of the system receives uniform requirements with the rate λ_j determined by the overall rate λ of the source, in the general case, of mixed customers. The magnitude of the source of mixed customers entering the system has an intensity (arrival rate) of

$$\lambda = \sum_{j=1}^{L} \lambda_j, \tag{1}$$

where L is the number of components in the QS. The service process in each component of the QS consists of several stages (phases) with the corresponding duration T_i, then the full-service period T_s is equal to

$$T_s = \sum_{j=1}^{K_E} T_i \tag{2}$$

where K_E is the number of such phases.

All T_i durations have certain probability distributions with the appropriate parameters, then T_s will have a generalized Erlang distribution with the parameters of the probability distributions of order K_E.

The number of components and their parameters correspond to similar, characteristics of the repair enterprise.

The study of the operation effectiveness of the aviation repair enterprise as a multi-component QS will consist in determining the probability and time characteristics of each component and the QS as a whole. Let's consider several examples.

Example 1. Two-component QS of M/E4/2/3 type in the first component and of M/E3/1/2 in the second component with restrictions on the time spent in the service period $\beta_{1,2}$ and waiting $\gamma_{1,2}$, which is due to the force majeure circumstances in the QS operation: $\beta_{1,2}$ is the intensity of leaving the service channel due to the limitation of time spent in the system during the service period; $\gamma_{1,2}$ is the intensity of customers leaving the queue due to the time limit of their stay in the system during the service waiting period.

The graph of the states of this QS coincides with the graph of the states of the QS presented in Fig.1.

In Fig. 1 it is indicated:

$\mu_{11} = \mu^{/} + \beta_1^{/}$; $\mu_{12} = 2\mu^{/} + 2\beta_1^{/}$; $\mu_{13} = \mu_{12} + \gamma_1^{/}$; $\mu_{14} = \mu_{12} + 2\gamma_1^{/}$; $\mu_{15} = \mu_{12} + 3\gamma_1^{/}$; $\mu^{/} = 4\mu_1$; $\mu_1 = \frac{1}{\bar{t}_{s_1}}$; $\beta_1^{/} = 4\beta_1$; $\beta_1 = \frac{1}{\bar{t}_{lims_1}}$; $\gamma_1^{/} = 4\gamma_1$; $\gamma_1 = \frac{1}{\bar{t}_{limw_1}}$; $\mu_{21} = \mu^{//} + \beta_2^{//}$;$\mu^{//} = 3\mu_2$;$\mu_2 = \frac{1}{\bar{t}_{s_2}}$; $\beta_2^{//} = 3\beta_2$; $\beta_2 = \frac{1}{\bar{t}_{lims_2}}$; $\mu_{22} = \mu_{21} + \gamma_2^{//}$; $\gamma_2^{//} = 4\gamma_2$; $\gamma_2 = \frac{1}{\bar{t}_{limw_2}}$; where $\bar{t}_{lims_1}$, $\bar{t}_{lims_2}$ are the limited service time; $\bar{t}_{limw_1}$,$\bar{t}_{limw_2}$ are the limited waiting time.

The QS states of the first component are characterized by the following probabilities [30][31]:

$$P^{/}_{c^{/}} = \sum_{j=1}^{4} P^{/}_{c^{/}j}; \quad c^{/} = \overline{1,5}, \tag{3}$$

where $P_1^{/}$ is the probability of occupation of one channel (1 customer in the component); $P_2^{/}$ is the probability of occupation of 2 channels (2 customers in the component); $P_3^{/}$ is the probability of 3 customers being in the component, of which 2 are served, one is in the queue; $P_4^{/}$ is the probability of 4 customers being in the component, of them 2 are served and 2 are in the queue; $P_5^{/}$ is the probability of 5 customers being in the component, of which 2 are being served and 3 are in the queue:

$P_1^{/} = \sum_{j=1}^{4} P_{1j}^{/}$; $P_2^{/} = \sum_{j=1}^{4} P_{2j}^{/}$; $P_3^{/} = \sum_{j=1}^{4} P_{3j}^{/}$; $P_4^{/} = \sum_{j=1}^{4} P_{4j}^{/}$; $P_5^{/} = \sum_{j=1}^{4} P_{5j}^{/}$.

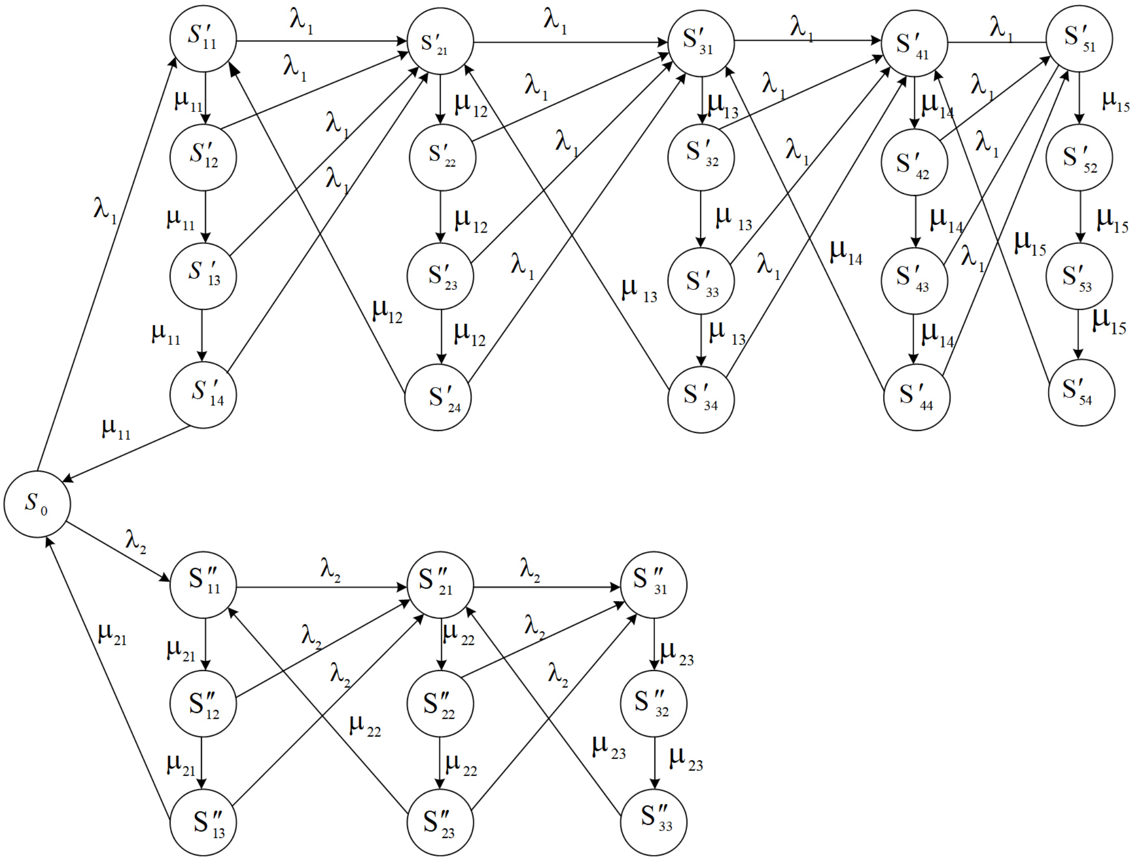

Figure 1: *State graph of QS of M/E4/2/3 type in the first component and M/E3/1/2 type in the second component with restrictions on the time spent in the service period* $\beta_{1,2}$ *and waiting* $\gamma_{1,2}$

Similarly, for the QS states of the second component:

$$P^{//}_{c^{//}} = \sum_{j=1}^{3} P^{//}_{c^{//}j}; \quad c^{//} = \overline{1,3}, \tag{4}$$

where $P^{//}_1$ is the probability of one customer being served in the component; $P^{//}_2$ is the probability of 2 customers being in the component, one of them is in service, the other is in the queue; $P^{//}_3$ is the probability of 3 customers being in the component, one of them is in service, two are in the queue:

$P^{//}_1 = \sum_{j=1}^{3} P^{//}_{1j};\ \ P^{//}_2 = \sum_{j=1}^{3} P^{//}_{2j};\ \ P^{//}_3 = \sum_{j=1}^{3} P^{//}_{3j}.$

The number of busy service channels in the components [30], [31]:

$$\overline{k_1} = \frac{P^{/}_1 + \sum_{c^{/}=2}^{5} P^{/}_{c^{/}}}{4}, \tag{5}$$

$$\overline{k_2} = \frac{\sum_{c^{//}=1}^{3} P^{//}_{c^{//}}}{3}. \tag{6}$$

Probability of service in the first component:

$$\mathrm{P}^{/}_{S} = 1 - P^{/}_{lS} - \sum_{c^{//}=1}^{(n+m)^{//}} P^{//}_{c^{//}} = 1 - P^{/}_{fl} - \sum_{c^{//}=1}^{(n+m)^{//}} P^{//}_{c^{//}},$$

where $P^{/}_{lS}$ is the probability of loss of a request; $P^{/}_{fl}$ is the probability of failure of serving a request.

$P^{/}_{fl} = P^{/}_{(n+m)^{/}} - \frac{P^{/}_{bo}}{4} = P^{/}_{5} - \frac{P^{/}_{bo}}{4},$

where $P^{/}_{bo} = \sum_{d=2;j=2}^{4} (d-1) P^{/}_{(b_1-1)j}, \quad b_1 = \overline{2, (n+m)^{/}}$
then $P^{/}_{20} = \sum_{i=2}^{4} (i-1) P^{/}_{1i}, \quad P^{/}_{30} = \sum_{i=2}^{4} (i-1) P^{/}_{2i}, \quad P^{/}_{40} = \sum_{i=2}^{4} (i-1) P^{/}_{3i}, \quad P^{/}_{50} = \sum_{i=2}^{4} (i-1) P^{/}_{4i}, \quad P^{/}_{b0} = \sum_{i=2}^{5} P^{/}_{io}.$ $P^{/}_{ls} = P^{/}_{fl} + P^{/}_{lv_S} + P^{/}_{lv_q}.$
where $P^{/}_{lv_S}$ is the probability of the customer leaving the system in the service channel; $P^{/}_{lv_q}$ is the probability of the customer leaving the system in the queue.

When
$P^{/}_{fl} = P^{/}_{5} - \frac{P^{/}_{b0}}{4};$
$\mathrm{P}^{/}_{lv_S} = \frac{\beta_1 \overline{k_1}}{\lambda_1};$
$\mathrm{P}^{/}_{lv_q} = \frac{\gamma_1 \overline{N^{(1)}_q}}{\lambda_1};$
where $P^{/}_{ls} = P^{/}_{5} - \frac{P^{/}_{b0}}{4} + \frac{(\beta_1 \overline{k_1} + \gamma_1 \overline{N^{(1)}_q})}{\lambda_1}.$

The expressions for the probabilities of the QS states of the first and second components are similar to the QS considered above.

The probability of customer service in the second component is

$\mathrm{P}^{//}_{S} = 1 - P^{/}_{ls} - \sum_{c^{/}=1}^{5} P^{/}_{c^{/}},$
where

$\mathrm{P}^{//}_{lS} = P^{//}_{fl} + P^{//}_{lv_S} + P^{//}_{lv_q};$
$\mathrm{P}^{//}_{fl} = P^{//}_{3} - \frac{P^{//}_{b0}}{3};$
$\mathrm{P}^{//}_{lv_S} = \frac{\beta_2 \overline{k_2}}{\lambda_2};$
$\mathrm{P}^{//}_{lv_q} = \frac{\gamma_2 \overline{N^{(2)}_q}}{\lambda_2}.$

Provided $\beta_2 = \gamma_2$, then

$\mathrm{P}^{//}_{lv_q} = \frac{\beta_2 \overline{N^{(2)}_q}}{\lambda_2}.$
$P^{/}_{bo} = \sum_{d=2;j=2}^{3} (d-1) P^{//}_{(b_2-1)j}, \quad b_2 = \overline{2, (n+m)^{//}},$

then $P^{//}_{20} = \sum_{j=2}^{3} (j-1) P^{//}_{1j}, \quad P^{//}_{30} = \sum_{j=2}^{3} (j-1) P^{//}_{2j},$
Where
$\mathrm{P}^{//}_{ls} = P^{//}_{3} - \frac{P^{//}_{b0}}{3} + \frac{(\beta_2 \overline{k_2} + \gamma_2 \overline{N^{(2)}_q})}{\gamma_2}.$

Whence the average number of requests $\overline{N^{(i)}_q}$ that are in the queue and waiting for service in the i-component:
$\overline{N^{(1)}_q} = \sum_{q^{/}=1}^{m^{/}} \frac{q^{/} P^{/}_{(n+q)^{/}}}{k_{E^{/}}} = \sum_{q^{/}=1}^{3} \frac{P^{/}_{(2+q^{/})}}{4};$
$\overline{N^{(2)}_q} = \sum_{q^{//}=1}^{m^{//}} \frac{q^{//} P^{//}_{(n+q)^{//}}}{k_{E^{//}}} = \sum_{q^{//}=1}^{2} \frac{P^{//}_{(1+q^{//})}}{3}.$

The average number of customers $\overline{N^{(i)}}$ in the i-component:

$\overline{N^{(1)}_q} = \sum_{c^{/}=1}^{(n+m))^{/}} \frac{c^{/} P^{/}_{(c)^{/}}}{k_{E^{/}}} = \sum_{c^{/}=1}^{5} \frac{c^{/} P^{/}_{(c)^{/}}}{4};$

$$\overline{N_q^{(2)}} = \sum_{c^{//}=1}^{(n+m)^{//}} \frac{c^{//}P^{/}_{(c)^{//}}}{k_{E^{//}}} = \sum_{c^{//}=1}^{3} \frac{c^{//}P^{//}_{(c)^{//}}}{3};$$

Duration of waiting time for the customer in the queue for the i-component equals:

$$\overline{W}_q^{(1)} = \frac{\overline{N}_q^{(1)}}{\lambda_1}; \quad \overline{W}_q^{(2)} = \frac{\overline{N}_q^{(2)}}{\lambda_2}.$$

Customer service time in the QS:

$$\bar{t}_{tsq} = \frac{(\lambda_1 \bar{t}_s^{(1)} + \lambda_2 \bar{t}_s^{(2)})}{(\lambda_1 + \lambda_2)};$$

$$\bar{t}_s^{(1)} = \frac{\overline{N}^{(1)}}{\lambda_1}; \quad \bar{t}_s^{(2)} = \frac{\overline{N}^{(2)}}{\lambda_2};$$

Duration of waiting for customers in QS queues: $\overline{w}_{wqs} = \frac{(\lambda_1 \overline{w}_q^{(1)} + \lambda_2 \overline{w}_q^{(2)})}{(\lambda_1 + \lambda_2)}$;

Probability of QS failure: $P_{fl}^{qs} = \frac{(\lambda_1 P_{fl_1} + \lambda_2 P_{fl_2})}{(\lambda_1 + \lambda_2)}$.

When applying the proposed mathematical models, it is advisable to consider the following:

- in multi-component QSs, the performance of any component decreases compared to a single-component system at the same rates of service stages. With the same values of the parameters of each component of the QS, the performance of multi-component and single-component systems will be the same;
- if one of the components is a QS with a queue, and the second component is a QS with failures, then the QS with a queue has a higher performance, simultaneously reducing the performance of the second component;
- with small values $(0 \leq P_S \leq 0.1)$, the impact on the system as a whole or on a separate component of the intensities of customers leaving the system during the service period and being in the queue is insignificant. When these intensities change, the P_S value will fluctuate relative to its average value.

Example 2. We will conduct a sensitivity study of the two-component QS mathematical model presented in Fig. 1. The simulation model of the two-component QS is presented in Fig. 2.

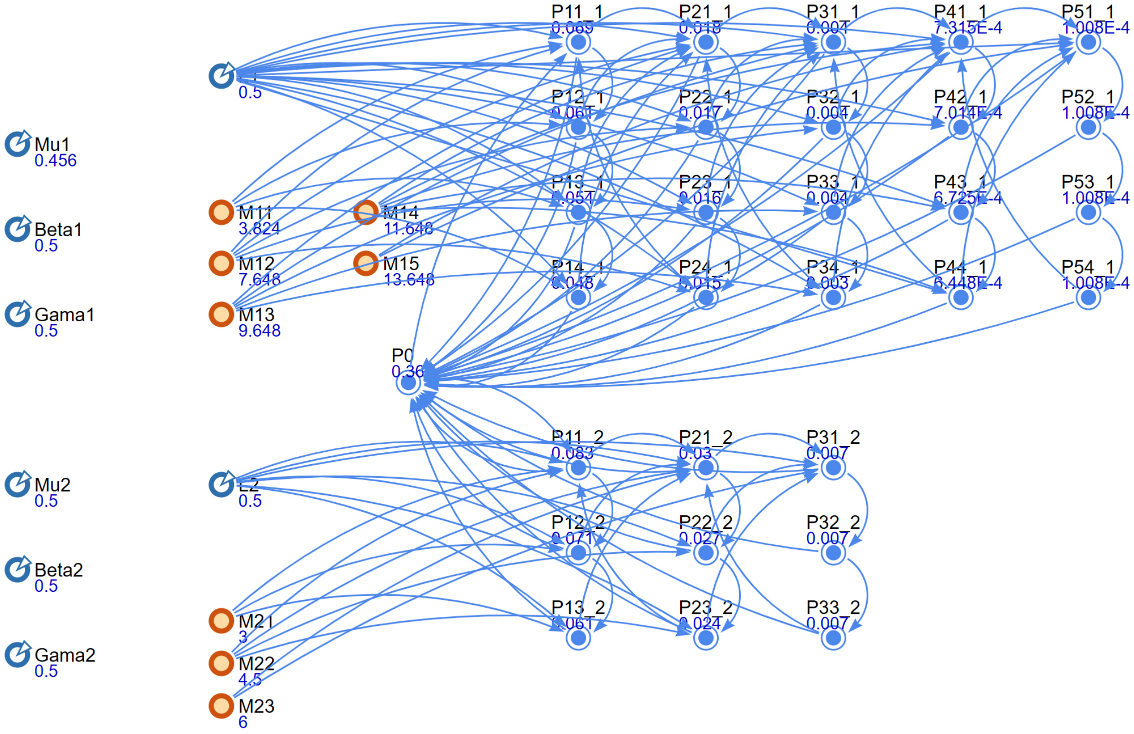

Figure 2: *Probability density of grain delivery time distribution at optimal sizes of the fleet of vehicles (trucks and ships)*

The model was implemented using System Dynamics computer simulation in the AnyLogic University Researcher environment.

3. RESULTS

The results of experiments on the sensitivity of the model are presented in Table 1 and Fig. 3 - 10.

The model was implemented using System Dynamics computer simulation in the AnyLogic University Researcher environment.

A set of dynamic variables (Dynamic Variable) P11_1−P54_1 and P11_2−P33_2 were used to establish and fix the probabilities of the QS states according to the structure of the studied QS. The usual double (Variable) type variables M11−M13 and M21−M23 were used as calculation variables of the proposed QS. The initial system parameters $\lambda_1, \lambda_2, \mu^{/}, \mu^{//}, \gamma_1^{/}, \gamma_1^{//}, {}_1^{/}, {}_1^{//}$ are described in detail above.

The probabilities of the QS states are calculated according to the general principle of solving systems of the Kolmogorov equations and the system dynamics format in the AnyLogic University Researcher environment, according to Fig. 1:

```
«P11_1 = (L1*P0 + M12*P24_1)/(L1+M11);
P12_1 = (M11*P11_1)/(L1+M11);
P13_1 = (M11*P12_1)/(L1+M11);
P14_1 = M11*P13_1/(L1+M11);
P21_1 = (L1*(P11_1+P12_1+P13_1+P14_1)+M13*P34_1)/(L1+M12);
P22_1 = M12*P21_1/(L1+M12);
P23_1 = M12*P22_1/(L1+M12);
P24_1 = M12*P23_1/(L1+M12);
P31_1 = (L1*(P21_1+P22_1+P23_1+P24_1)+M14*P44_1)/(L1+M13);
P32_1 = M13*P31_1/(L1+M13);
P33_1 = M13*P32_1/(L1+M13);
P34_1 = (M13*P33_1)/(L1+M13);
P41_1 = (L1*(P31_1+P32_1+P33_1+P34_1)+M15*P54_1)/(L1 + M14);
P42_1 = M14*P41_1/(L1+M14);
P43_1 = M14*P42_1/(L1+M14);
P44_1 = (M14*P43_1)/(L1+M14);
P51_1 = L1*(P41_1+P42_1+P43_1+P44_1)/M15;
P52_1 = P51_1;
P53_1 = P52_1;
P54_1 = P53_1;
P11_2 = (L2*P0+M22*P23_2)/(L2+M21);
P12_2 = (M21*P11_2)/(L2+M21);
P13_2 = M21*P12_2/(L2+M21);
P21_2 = (L2*(P11_2+P12_2+P13_2)+M23*P33_2)/(L2+M22);
P22_2 = M22*P21_2/(L2+M22);
P23_2 = (M22*P22_2)/(L2+M22);
P31_2 = L2*(P21_2+P22_2+P23_2)/M23;
P32_2 = P31_2;
P33_2 = P32_2;
P0 = 1-(P11_1 + P12_1 + P13_1 + P14_1 + P21_1 + P22_1 + P23_1 + P24_1 + P31_1 + P32_1 +
P33_1 + P34_1 + P41_1 + P42_1 + P43_1 + P44_1 + P51_1 + P52_1 + P53_1 + P54_1 + P11_2 +
P12_2 + P13_2 + P21_2 + P22_2 + P23_2 + P31_2 + P32_2 + P33_2);»
```

The model sensitivity experiment is implemented as a cyclical gradual change of one of the selected initial parameters by Java software code [32], [33], [34]:

```
«double step = 0.01;
Mu1 += step;
double dataVariant = Mu1;
double m_1 = 4*Mu1, b_1 = 4*Beta1, g_1 = 4*Gama1,
m_2 = 3*Mu2, b_2 = 3*Beta2, g_2 = 3*Gama2;
M11 = m_1 + b_1; M12 = 2*(m_1 + b_1); M13 = M12 + g_1;
```

```
M14 = M12 + 2*g_1; M15 = M12 + 3*g_1; M21 = m_2 + b_2;
M22 = M21 + g_2; M23 = M21 + 2*g_2;
double Pc_2 = P11_2 + P12_2 + P13_2 + P21_2 + P22_2 + P23_2 + P31_2 + P32_2 + P33_2,
Pc_1 = P11_1 + P12_1 + P13_1 + P14_1 + P21_1 + P22_1 + P23_1 + P24_1 + P31_1 + P32_1 + P33_1
+ P43_1 + P41_1 + P42_1 + P43_1 + P44_1 + P51_1 + P52_1 + P53_1 + P54_1,
P20_1 = P12_1 + 2*P13_1 + 3*P14_1, P30_1 = P22_1 + 2*P23_1 + 3*P24_1, P40_1 = P32_1 + 2*P33_1
+ 3*P43_1, P50_1 = P42_1 + 2*P43_1 + 3*P44_1,
P20_2 = P12_2 + 2*P13_2, P30_2 = P22_2 + 2*P23_2,
P1_2 = P11_2 + P12_2 + P13_2, P2_2 = P21_2 + P22_2 + P23_2, P3_2 = P31_2 + P32_2 + P33_2,
P1_1 = P11_1 + P12_1 + P13_1 + P14_1, P2_1 = P21_1 + P22_1 + P23_1 + P24_1, P3_1 = P31_1 +
P32_1 + P33_1 + P43_1,
P4_1 = P41_1 + P42_1 + P43_1 + P44_1, P5_1 = P51_1 + P52_1 + P53_1 + P54_1,
Ppok_q_1 = (Beta1 / L1) * ((1*P3_1 + 2*P4_1 + 3*P5_1)/4),
Ppok_serv_1 = (Beta1 / L1) *((P1_1 + 2*(P2_1 + P3_1 + P4_1 + P5_1))/4),
Pfalue_1 = P5_1 - ((P20_1 + P30_1 + P40_1 + P50_1)/4),
Pvrtat_1 = Pfalue_1 + Ppok_serv_1 + Ppok_q_1,
Pser_1 = 1 - Pvrtat_1 - (Pc_2),
Ppok_q_2 = (Beta2 / L2) * ((1*P2_2 + 2*P3_2)/3),
Ppok_serv_2 = (Beta2 / L2) * (Pc_2 /3),
Pfalue_2 = P3_2 - ((P20_2 + P30_2) / 3),
Pvrtat_2 = Pfalue_2 + Ppok_serv_2 + Ppok_q_2,
Pser_2 = 1- Pvrtat_2 - Pc_1;
dataset_Pserv_1.add(dataVariant, Pser_1);
dataset_Pserv_2.add(dataVariant, Pser_2);»
```

The generalized characteristics of the QS of the system components are the service probabilities $P_s^{/}$ and $P_s^{//}$.

These characteristics include the initial parameters and some other parameters of the QS components, the calculation formulas of which are presented above.

The initial parameters of the experiments and the results of their implementation are presented in Table 1.

Graphs of dependences of service probabilities $P_s^{/}$ and $P_s^{//}$ on the initial parameters of the model are presented in fig. 3-10.

In the calculation example, the boundary value of the service probabilities of QS components $P_{b.v_s} = 0.6$ is set, i.e. $P_s^{/}$ and $P_s^{//}$ must not be less than 0.6 at the same time, provided that the components serve requirements with the same priorities.

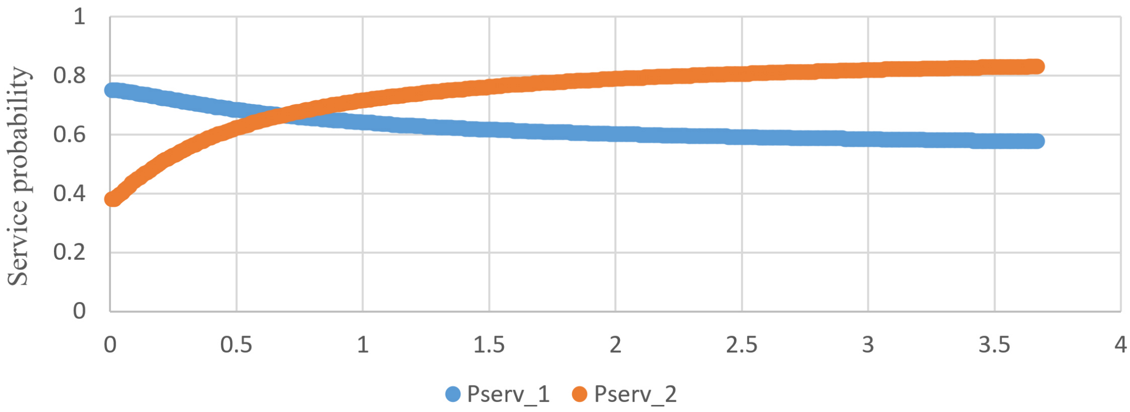

Figure 3: *Graph of the dependence of the probabilities* $P_s^{/}$ *and* $P_s^{//}$ *on the parameter* $\mu^{/}$

From the graphs of the dependences of the probabilities $P_s^{/}$ and $P_s^{//}$ on the parameter $\mu^{/}$

Table 1: *The results of sensitivity experiments for the mathematical model of the QS components functioning*

Numbers of graphs of depend-es	Initial parameters of the model		Results of sensitivity experiments		
	constant	variables $[range]$	Ranges of changes in probabil-es	Values of service probabil-es	Values of variable param-s

3	$\lambda_1 = \lambda_2 =$
	$\mu^{//} = \gamma_1^{/} =$
	$\gamma_2^{//} = \beta_1^{/} =$
	$\beta_2^{//} = 0.5$
		$\mu^{/}$
		[0.01...2.5]
			$P_S^{/}$
			[0.59...0.75]
			$P_S^{//}$
			[0.38...0.8]
				$P_S^{/} = 0.15$
				$P_S^{//} = 0.8$
				$P_S^{/} = P_S^{//}$
				=0.69
					$\mu^{/} = 0.01$
					$\mu^{/} = 2.5$
					$\mu^{/} = 0.69$

4	$\lambda_1 = \lambda_2 =$
	$\mu^{/} = \mu^{//} =$
	$\gamma_1^{/} = \gamma_2^{//}$
	$= \beta_2^{//} = 0.5$
		$\beta_1^{/}$
		[0.01...2.5]
			$P_S^{/}$
			[0.49...0.98]
			$P_S^{//}$
			[0.3...0.8]
				$P_S^{/} = 0.98$
				$P_S^{//} = 0.8$
				$P_S^{/} = P_S^{//}$
				=0.65
					$\beta_1^{/} = 0.01$
					$\beta_1^{/} = 2.5$
					$\beta_1^{/} = 0.62$

5	$\lambda_1 = \lambda_2 =$
	$\mu^{//} = \gamma_2^{//} =$
	$\beta_1^{/} =$
	$= \beta_2^{//} = 0.5$
		$\gamma_1^{/}$
		[0.01...2.5]
			$P_S^{/}$
			[0.679...0.683]
			$P_S^{//}$
			[0.618...0.626]
				$P_S^{/} = 0.58$
				$P_S^{//}$
				=0.626
					$\gamma_1^{/} = 2.5$
					$\gamma_2^{/} = 2.5$

6	$\lambda_1 = \lambda_2 =$
	$\gamma_1^{/} =$
	$= \gamma_2^{//} = \beta_1^{/} =$
	$= \beta_2^{//} = 0.5$
		$\beta_1^{/}$
		[0.01...2.5]
			$P_S^{/}$
			[0.4350.902]
			$P_S^{//}$
			[0.5970.593]
				$P_S^{/} = 0.902$
				$P_S^{//} = 0.622$
				$P_S^{/} = P_S^{//}$
				=0.62
					$\beta_2^{/} = 2.5$
					$\beta_2^{/} = 0.47$
					$\beta_2^{/} = 0.34$

7	$\lambda_1 = \lambda_2 =$
	$\mu^{//} =$
	$= \gamma_1^{//} = \gamma_2^{/}$
	$= \beta_1^{/} = 0.5$
		$\beta_2^{//}$
		[0.01...2.5]
			$P_S^{/}$
			[0.4350.902]
			$P_S^{//}$
			[0.8770.434]
				$P_S^{/} = 0.902$
				$P_S^{//} = 0.877$
				$P_S^{/} = P_S^{//}$
				=0.651
					$\beta_2^{/} = 2.5$
					$\beta_2^{/} = 0.01$
					$\beta_2^{/} = 0.41$

8	$\lambda_1 = \lambda_2 =$
	$\mu^{//} =$
	$= \gamma_1^{//} = \beta_1^{/}$
	$= 0.5$
		$\gamma_2^{//}$
		[0.01...2.5]
			$P_S^{/}$
			[0.6260.73]
			$P_S^{//}$
			[0.5580.652]
				$P_S^{/} = 0.73$
				$P_S^{//} = 0.652$
					$\gamma_1^{/} = 2.5$
					$\gamma_2^{/} = 2.5$

9	$\lambda_2 = \mu^{//} =$
	$\gamma_1^{/} = \gamma_2^{//} =$
	$\beta_1^{/} = \beta_2^{//} =$
	$= 0.5$
		$\lambda_1^{/}$
		[0.01...2.5]
			$P_S^{/}$
			[0.499...0.952
			...0.879]
			$P_S^{//}$
			[0.884...0.8]
				$P_S^{/} = 0.499$
				$P_S^{/} = 0.952$
				$P_S^{/} = 0.873$
				$P_S^{//} = 0.884$
				$P_S^{//} = 0.01$
				$P_S^{/} = P_S^{//} =$
				$= 0.657$
					$\lambda_1^{/} = 0.4$
					$\lambda_1^{/} = 1.65$
					$\lambda_1^{/} = 2.5$
					$\lambda_1^{/} = 0.01$
					$\lambda_1^{/} = 2.5$
					$\lambda_1^{/} = 0.45$

10	$\lambda_1 = \mu^{//} =$
	$\gamma_1^{/} = \gamma_2^{//} =$
	$\beta_1^{/} = \beta_2^{//} =$
	$= 0.5$
		$\lambda_2^{/}$
		[0.01...2.5]
			$P_S^{/}$
			[1.0...0.047]
			$P_S^{//}$
			[0.50...0.68
			...0.049]
				$P_S^{/} = 1.0$
				$P_S^{/} = 0.047$
				$P_S^{/} = 0.50$
				$P_S^{//} = 0.68$
				$P_S^{//} = 0.049$
				$P_S^{/} = P_S^{//} =$
				$= 0.64$
					$\lambda_1^{/} = 0.01$
					$\lambda_1^{/} = 2.5$
					$\lambda_1^{/} = 0.06$
					$\lambda_1^{/} = 0.9$
					$\lambda_1^{/} = 2.5$
					$\lambda_1^{/} = 0.57$

presented in Fig. 3, it can be seen that when $\mu^{/} = 0.01$, then $P_s^{/} = 0.75$, $P_s^{//} = 0.378$, while at

$\mu^{/} = 2.5$ the probabilities are $P_s^{//} = 0.8$ and $P_s^{/} = 0.53$, i.e. do not satisfy the boundary condition. At $\mu^{/} = 0.69$ the probabilities are $P_s^{/} = P_s^{//} = 0.66$, which satisfies the boundary condition.

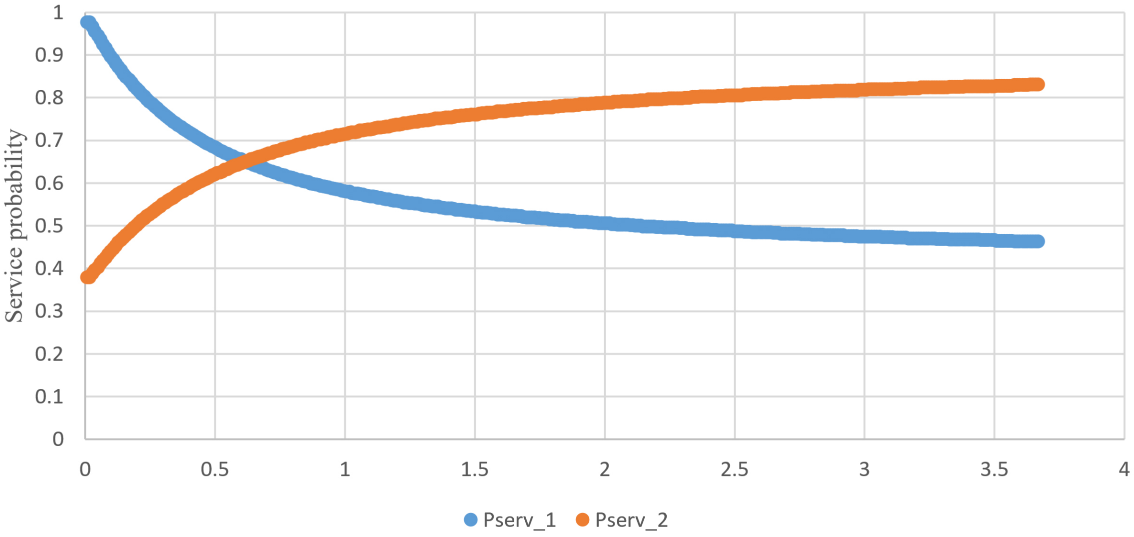

Figure 4: *Graphs of the dependence of the probabilities* $P_s^{/}, P_s^{//}$ *on the parameter* $\beta_1^{/}$

From Fig. 4, which shows the graphs of the dependences of the probabilities $P_s^{/}, P_s^{//}$ on the parameter $\beta_1^{/}$, it is possible to investigate that with $\beta_1^{/} = 0.01$ the probabilities $P_s^{/} = 0.98$ and $P_s^{//} = 0.378$ with $\beta_1^{/} = 2.5$ probabilities $P_s^{/} = 0.48$ and $P_s^{//} = 0.8$, i.e. do not satisfy the boundary condition. At $\beta_1^{/} = 0.62$ probabilities $P_s^{/} = P_s^{//} = 0.65$, which is a satisfactory result.

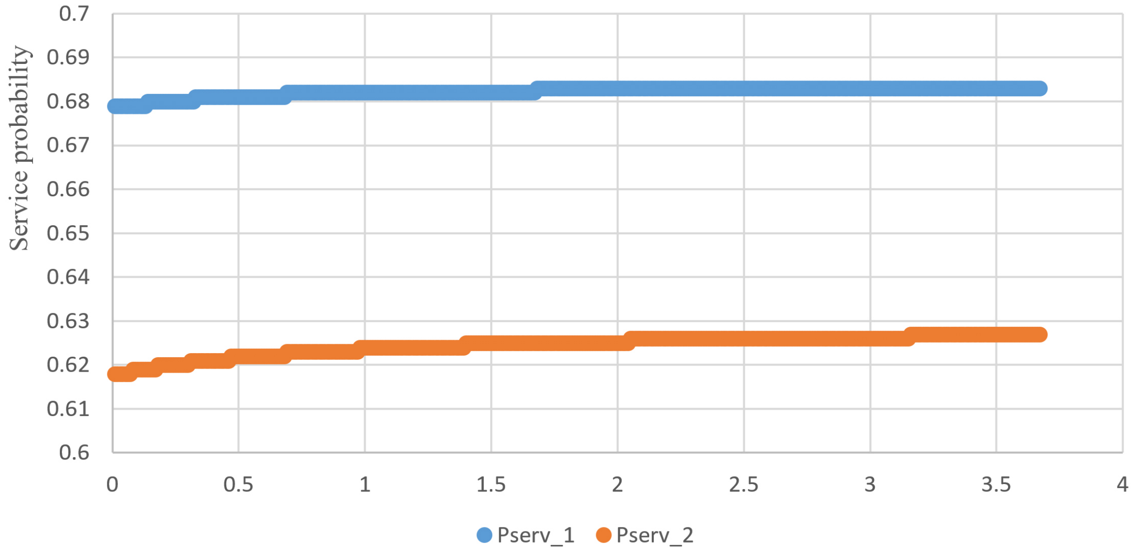

Figure 5: *Graphs of the dependence of the probabilities* $P_s^{/}, P_s^{//}$ *on the parameter* $\gamma_1^{/}$

From those presented in fig. 5 graphs of the dependence of the probabilities $P_s^{/}, P_s^{//}$ on the parameter $-\gamma_1^{/}$, it is possible to investigate that at $\gamma_1^{/} = 2.5$ the probabilities $P_s^{/} = 0.68$ and $P_s^{//} = 0.626$, which satisfies the boundary condition.

In Fig. 6 are presented the graphs of dependences of the probabilities $P_s^{/}, P_s^{//}$ on the parameter $\mu^{//}$, from which it can be seen that at $\mu^{//} = 2.5$ the probabilities $P_s^{/} = 0.902$ and $P_s^{//} = 0.593$. This option does not meet the boundary condition. At $\mu^{//} = 0.47$ $P_s^{/} = 0.668$ and $P_s^{//} =' = 0.626$ at $\mu^{//} = 0.34_s^{/} = P_s^{//} = 0.62$. These options meet the boundary condition. The option with

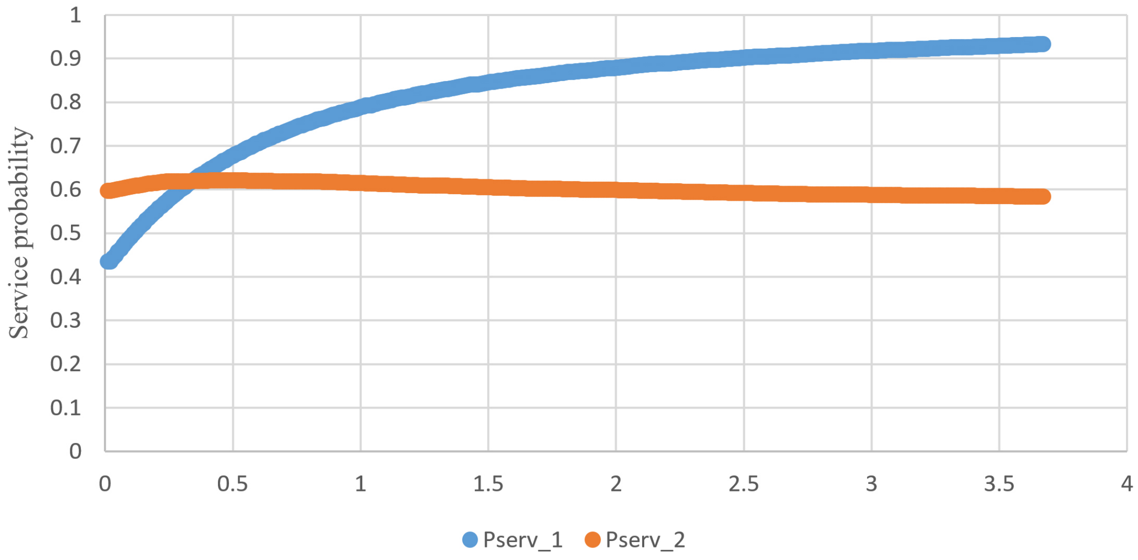

Figure 6: *Graphs of the dependence of the probabilities* $P_s^{/}, P_s^{//}$ *on the parameter* $\mu^{//}$

$\mu^{//} = 0.47$ may be preferable, because with $\mu^{//} = 0.47$ at $t_{(s_2)} = 2.18$, and with $\mu^{//} = 0.34$ at $t_{(s_2)} = 2.94$.

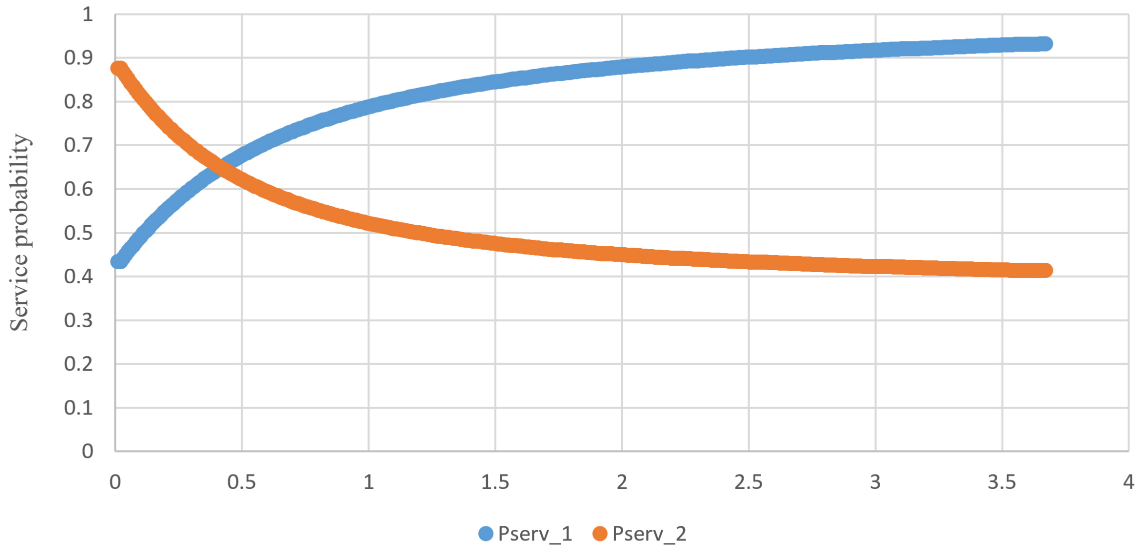

Figure 7: *Graphs of the dependence of the probabilities* $P_s^{/}, P_s^{//}$ *on the parameter* $\beta_2^{//}$

From the graphs of the dependences of the probabilities $P_s^{/}, P_s^{//}$ on the parameter $\beta_2^{//}$, presented in Fig. 7, it can be seen that at $\beta_2^{//} = 0.41$, $P_s^{/} = P_s^{//} = 0.651$. This option meets the boundary condition. Options at $\beta_2^{//} = 2.5$, $P_s^{/} = 0.902$ and $P_s^{//} = 0.593$ and at $\beta_2^{//} = 0.01$, $P_s^{//} = 0.432$ and $P_s^{//} = 0.877$ do not meet the boundary condition.

$\mu^{//} = 0.34$ at $t_{(s_2)} = 2.94$.

From Fig. 8, which shows graphs of the dependence of the probabilities $P_s^{/}, P_s^{//}$ on the parameter $\gamma_2^{//}$, it can be determined that with $\gamma_2^{//} = 2.5$, $P_s^{/} = 0.78$ and $P_s^{//} = 0.652$, which corresponds to the boundary condition.

From those presented in Fig. 9 graphs of the dependence of the probabilities $P_s^{/}, P_s^{//}$ on the parameter λ_1, the following conclusions can be drawn: at $\lambda_1 = 0.45, P_s^{/}, P_s^{//} = 0.652$, which satisfies the boundary condition.

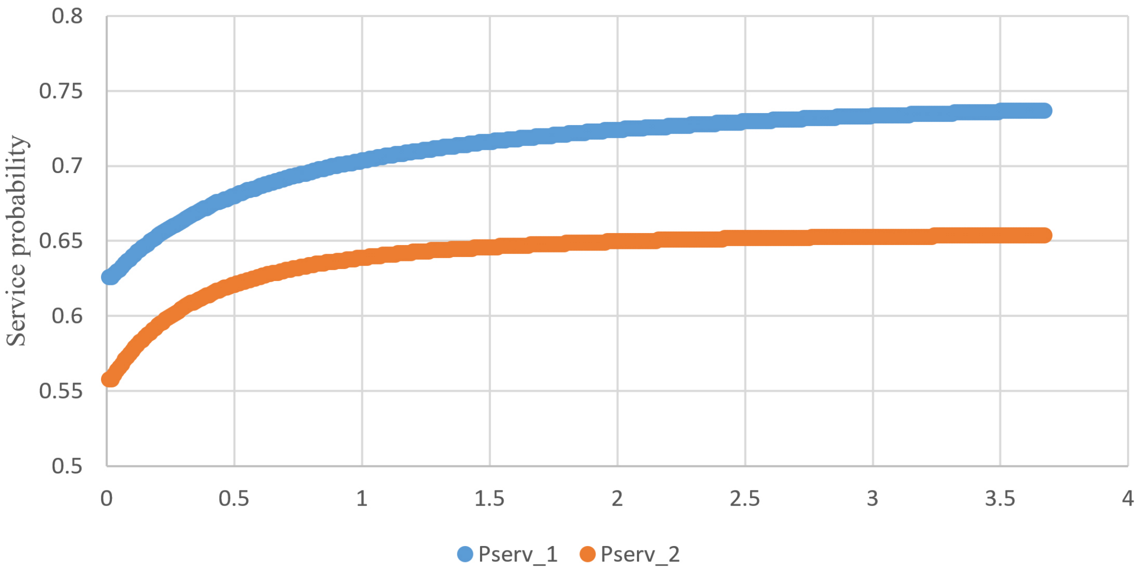

Figure 8: *Graphs of the dependence of the probabilities* $P_s^{/}, P_s^{//}$ *on the parameter* $\gamma_2^{//}$

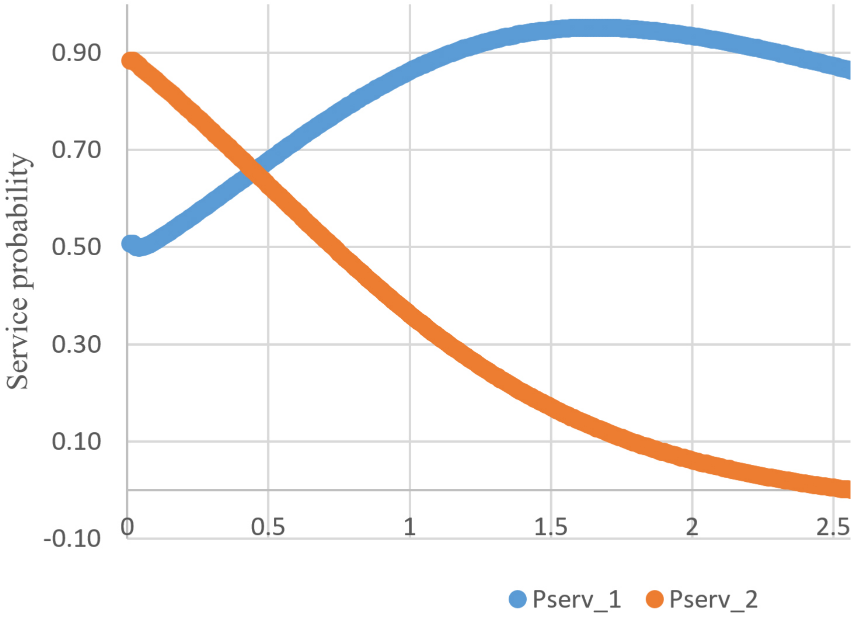

Figure 9: *Graphs of the dependence of the probabilities* $P_s^{/}, P_s^{//}$ *on the parameter* λ_1

Other options do not meet the boundary condition

at $\lambda_1 = 0.45, P_s^{/} = 0.506$ and $P_s^{//} = 0.884$, as at $\lambda_1 = 0.04 P_s^{/} = 0.499$ and $P_s^{//} = 0.87$; at $\lambda_1 = 1.65, P_s^{/} = 0.952$ and $P_s^{//} = 0.13$; at $\lambda_1 = 2.5, P_s^{/} = 0.873$ and $P_s^{//} = 0.01$.

From those presented in Fig. 10 graphs of the dependence of the probabilities $P_s^{/}, P_s^{//}$ on the parameter λ_2 it can be seen that the boundary condition is met by the variant with $\lambda_2 = 0.57, P_s^{/} = P_s^{//} = 0.64$. Other options do not meet the boundary condition, namely: at $\lambda_2 = 0.01, P_s^{/} = 1.0$ and $P_s^{//} = 0.51$, at $\lambda_2 = 0.06 P_s^{/} = 0.977$ and $P_s^{//} = 0.50$; at $\lambda_2 = 0.9, P_s^{/} = 0.432$ and $P_s^{//} = 0.68$; at $\lambda_2 = 2.5, P_s^{/} = 0.47$ and $P_s^{//} = 0.49$. We summarize the obtained results in the Table 2 and determine P_s of the two-component QS from the formula:

$P_s = 1 - (1 - P_s^{/})(1 - P_s^{//})$.

From the Table 2, it can be seen that the determined results of the initial parameters, which

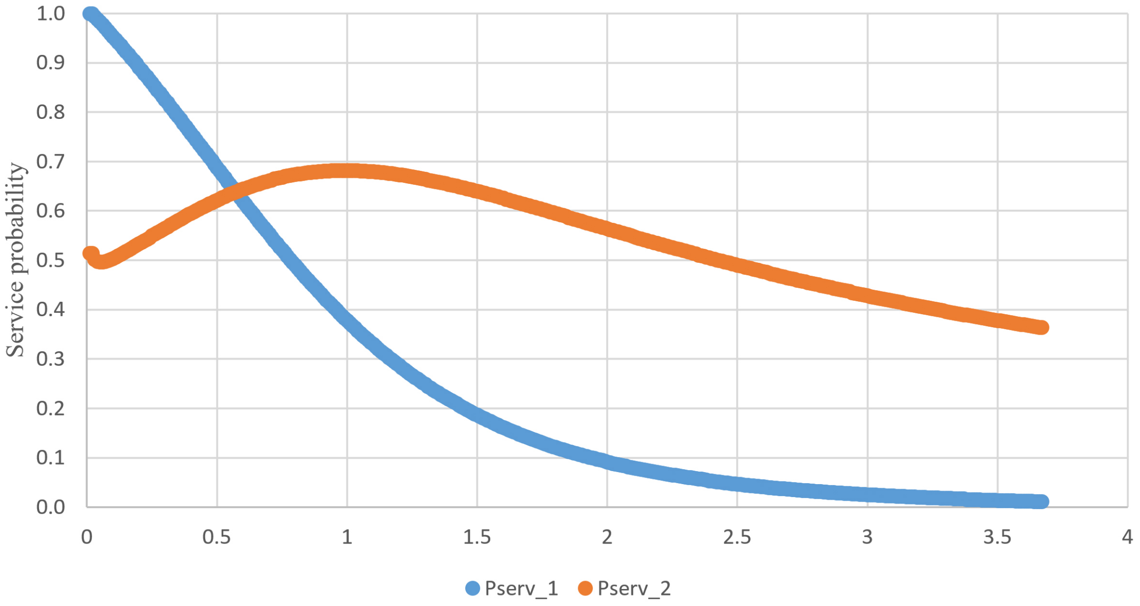

Figure 10: *Graphs of the dependence of the probabilities* $P_s^{/}$, $P_s^{//}$ *on the parameter*λ_1

Table 2: *Results of the sensitivity experiments analysis*

Probabilities	λ_1	λ_2	λ_1	λ_2	$\mu^{/}$	$\gamma_1^{/}$	$\beta_1^{/}$	$\mu^{//}$	$\gamma_2^{//}$	$\beta_2^{//}$
of service	0.45	0.55	0.43	0.57	0.69	2.5	0.62	0.34	2.5	0.41
$P_s^{/}$	0.66	0.65	0.65	0.64	0.63	0.62	0.62	0.62	0.73	0.65
$P_s^{//}$	0.66	0.63	0.67	0.64	0.63	0.63	0.62	0.62	0.65	0.65
P_s	0.88	0.87	0.87	0.87	0.86	0.88	0.86	0.86	0.91	0.88

correspond to the boundary condition, make it possible to obtain the most acceptable values of the probability values $P_s^{/}, P_s^{//}$ and P_s. In turn, the above-mentioned initial parameters reflect and quantitatively characterize both the external conditions of the system's functioning (λ) and its internal capabilities and limitations (μ, β, γ) in response to changes in external conditions, including force majeure circumstances.

4. Conclusions

The new energy planning and management requirements should support innovation in aircraft designs and their operation and maintenance. They must allow for the smooth integration of new technologies into the air operations domain. Therefore, the term 'energy' should be used together with the term 'fuel' ('energy/fuel', for example), wherever appropriate, to accommodate operations with aircraft that use other energy sources than conventional hydrocarbon-based fuel. Also, the development of new production standards and safety and certification rules by regulators often lag behind technological development, bringing product development to a halt, including new onboard electrical equipment and technologies. Therefore, it is appropriate to include in the service system the possibility of the occurrence of force majeure circumstances and to consider the system with their impact on the results. The proposed theoretical approach consists in the fact that in a multi-component queueing system (QS), the value of the probability of serving a customer in a certain QS component can be determined taking into account that the second component contains the sum of all probabilities of the "enlarged" states of other components of the QS.

Based on this theoretical provision, the modelling of vehicle maintenance and repair processes, using the example of an aviation repair enterprise, allows to determine the necessary initial parameters of the system components as interacting QSs and to obtain the largest values of the probabilities of servicing the arriving customers in these components and the system as a whole, which provide an acceptable level of its reliability.

When studying real production, logistics, and other systems for which the mathematical apparatus of queueing theory is adequate, the necessary initial mathematical parameters of the system components must be expressed through physical parameters (flows of vehicles or other objects requiring maintenance, performance of equipment for various types of work, production tasks, time constraints, etc.), which will make it possible to optimize specific technologies and enterprises.

When modelling QS processes, non-standard system dynamics solutions were proposed in the AnyLogic University Researcher environment, which allowed to:

- solve a multi-rank system of Kolmogorov equations;
- implement multi-iterative sensitivity experiments with the initial parameters of the QS;
- obtain experimental dependences of the influence of all key parameters on QS indicators, in particular, service probabilities.

The described mathematical apparatus and modelling tools have shown their relevance to real processes and can be applied to improve the performance of multi-component and multi-phase queueing systems, which reflect the technological processes occurring in real production, transport-logistics and other systems intended for operation, maintenance and repair of technical equipment of various nature.

New hazards concerning the operation and maintenance of the new onboard electric equipment and systems should be investigated to complete the safety analysis of new clean aviation increasing their sustainability in the future. They will connect with normal flight operation of the new aircraft (their separate systems and equipment), so as with their production, maintenance, and repair. However, the proposed mathematical apparatus must cover new links and allow safe and sustainable solutions.

References

[1] Update on uk sustainable aviation fuel potential | sustainable aviation URL `https://www.sustainableaviation.co.uk/news/update-on-uk-sustainable-aviation-fuel-potential/`

[2] Zaporozhets O, Isaienko V and Synylo K 2020 *Energy* **211** 118814 ISSN 0360-5442

[3] Wheeler P and Bozhko S 2014 *IEEE Electrification Magazine* **2**(4) 6–12 ISSN 23255889

[4] Baharozu E, Soykan G and Ozerdem M B 2017 *Energy* **140** 1368–1377 ISSN 0360-5442

[5] Alruwaili M and Cipcigan L 2022 *Electric Power Systems Research* **211** 108242 ISSN 0378-7796

[6] Yilmaz N and Atmanli A 2017 *Energy* **140** 1378–1386 ISSN 0360-5442

[7] Dincer I and Acar C 2016 *International Journal of Sustainable Aviation* **2**(1) 74 ISSN 2050-0467

[8] Aviation rules of ukraine maintenance of the identity of aircraft and aviation products, components and possession and praise of the organization and personnel received before the cessation of these commands.´ | order of the state aviation service of ukraine dated march 6, 2019 no. 256 URL `https://avia.gov.ua/wp-content/uploads/2019/08/Release-to-service-of-the-Ukrainian-registered-aircraft.pdf`

[9] Rules for engineering and aviation security of the sovereign aviation of ukraine. order of the ministry of defense of ukraine dated 07/05/2016 no. 343. registered with the ministry of justice of ukraine on september 08, 2016. for no. 1101/29231 from changes introduced by order of the Ministry of Defense of Ukraine No. 223 dated 08/03/2021 URL `https://zakon.rada.gov.ua/laws/show/z1101-16#Text`

[10] Tamargazin OA M O 2013 *Scientific technologies* (1) 33–36 ISSN 2075-0781 URL `http://www.irbis-nbuv.gov.ua/cgi-bin/irbis_nbuv/cgiirbis_64.exe?I21DBN=LINK&P21DBN=UJRN&Z21ID=&S21REF=10&S21CNR=20&S21STN=1&S21FMT=ASP_meta&C21COM=S&2_S21P03=FILA=&2_S21STR=Nt_2013_1_9`

[11] Khromchenko VA Voznyuk MM P V 2022 *Collection of scientific works of the State Research Institute of Aviation* (18(25)) 110–116 ISSN 2786-4839 URL `https://znp.dndia.org.ua/index.php/znp/article/view/43`

[12] Zhdanyuk MM Cherednik MM M S M Y S S 2021 *Collection of scientific works of the State Research Institute of Testing and Certification of Weapons and Military Equipment* **10**(4) 45–55 ISSN 2706-7386 URL `https://dndivsovt.com/index.php/journal/article/view/129`

[13] S V Gaevsky S M Balakireva D V K V O Y A 2020 *Control systems, navigation and communication* **1**(59) 15–20 ISSN 2073-7394 URL `https://journals.nupp.edu.ua/sunz/article/view/1774`

[14] Medinsky D 2021 *Technical Sciences* **1**(59) 113–122 ISSN 2073-7394 URL `chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.tech.vernadskyjournals.in.ua/journals/2021/1_2021/part_2/21.pdf`

[15] Shevchuk D M D 2020 *Technical Sciences* **70**(31) 254–260 ISSN 2073-7394 URL `chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.tech.vernadskyjournals.in.ua/journals/2020/5_2020/43.pdf`

[16] SM Novichonok OM Babich I T 2020 *Armor systems and military equipment* (2(62)) 24–34 ISSN 1997-9568 URL `https://journal-hnups.com.ua/index.php/soivt/article/view/328`

[17] Ye Ilenko M Sushak P S 2020 *Armor systems and military equipment* (3(65)) 43–49 ISSN 2073-7378 URL `https://journal-hnups.com.ua/index.php/zhups/article/view/350`

[18] M Sushak M Derevianko S F 2022 *Collection of scientific works of the State Research Institute of Aviation* (18(25)) 187–196 ISSN 2786-4839 URL `https://znp.dndia.org.ua/index.php/znp/article/view/55`

[19] V Grishin O S 2022 *Collection of scientific works of the State Research Institute of Aviation* (18(25)) 134–140 ISSN 2786-4839 URL `https://znp.dndia.org.ua/index.php/znp/article/view/47`

[20] Tsybulnyk S and Okhota B 2018 *Bulletin of the Kyiv Polytechnic Institute. Instrumentation series* **0**(55(1)) 93–100 ISSN 2663-3450 URL `http://visnykpb.kpi.ua/article/view/135844`

[21] Matviychuk VA Veselovska NR S S 2018 *Vinnytsia National Agrarian University* **0**(1) 93–100 ISSN 978-966-949-855-7 URL `http://repository.vsau.org/getfile.php/29057.pdf`

[22] Olexander Subochev Yuliya Poloz V M O S 2019 *Foreign interdepartmental scientific and technical collection Design and operation of agricultural machines´* **49**(49) 221–232 ISSN 2414-3820 URL `chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://zbirniksgm.kntu.kr.ua/pdf/49/29.pdf`

[23] Pavlenko MA Rublyova RI T A 2020 *Collection of scientific works ›“* 89–92 URL `https://ojs.ukrlogos.in.ua/index.php/logos/article/view/4630`

[24] Bogomiya VI Belobrova TA D S 2019 *Scientific technologies* (1) 82–87 ISSN 2075-0781 URL `http://www.irbis-nbuv.gov.ua/cgi-bin/irbis_nbuv/cgiirbis_64.exe?I21DBN=LINK&P21DBN=UJRN&Z21ID=&S21REF=10&S21CNR=20&S21STN=1&S21FMT=ASP_meta&C21COM=S&2_S21P03=FILA=&2_S21STR=Nt_2019_1_13`

[25] OO E 2020 *Technical Sciences* (70) 195–201 ISSN 2075-0781

[26] Bondar BE Ochkasov AB B E G T O M 2018 *Technical Sciences* (31(70)) 195–201 ISSN - URL `http://eadnurt.diit.edu.ua>bistream.pdf`

[27] Guzenko VL Mironov EA S O 2014 *Technical Sciences* (6(22)) 195–201 ISSN 2075-0781 URL `http://iea.gostimjo.ru>_66_11.pdf`

[28] MD Katsman OI Zaporozhets V V O 2021 *Kiev FOP: Luk™yanenko V.V.* (1) 380 ISSN 978-617-7609-61-1 URL -

[29] Katsman M D, Myronenko V K, Matsiuk V I and Lapin P V 2021 *Reliability: Theory and Applications* **16**(1) 71–80 ISSN 19322321 URL `http://www.gnedenko.net/Journal/2021/012021/RTA_1_2021-06.pdf`

[30] Katsman M D, Matsiuk V I and Myronenko V K 2023 *Reliability: Theory Applications* **June 2**(73) 167–179 URL `https://doi.org/10.24412/1932-2321-2023-273-167-179`

[31] Katsman M D, Matsiuk V I and Myronenko V K 2023 *Reliability: Theory and Applications* **18**(3) 751–767 ISSN 19322321

[32] Matsiuk V, Ilchenko N, Pryimuk O, Kochubei D and Prokhorchenko A 2022 *AIP Conference Proceedings* **2557**(1) ISSN 15517616 URL `/aip/acp/article/2557/1/080003/2829501/Risk-assessment-of-transport-processes-by-agent`

[33] Matsiuk V, Myronenko V, Horoshko V, Prokhorchenko A, Hrushevska T, Shcherbyna R, Matsiuk N, Khokhlacheva J, Biziuk I and Tymchenko N 2019 *Eastern-European Journal of Enterprise Technologies* URL `http://www.scopus.com/inward/record.url?eid=2-s2.0-85065018277&partnerID=MN8TOARS`

[34] Prokhorchenko A, Parkhomenko L, Kyman A, Matsiuk V and Stepanova J 2019 Improvement of the technology of accelerated passage of low-capacity car traffic on the basis of scheduling of grouped trains of operational purpose vol 149 pp 86–94 ISSN 18770509 URL `http://www.scopus.com/inward/record.url?eid=2-s2.0-85063811295&partnerID=MN8TOARS`