Discrete-event Simulation of Operation and Maintenance of Telecommunication Equipment Using AnyLogic-based Multi-state Models

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Abstract. Telecommunication equipment is a functional subsystem of railway transport which safety and efficiency are totally dependent on the reliable operation of utilized communication devices. Preventive maintenance is one of the most popular methods of ensuring the required reliability level of technological equipment on railways. The efficiency assessment of maintenance procedures implementation is done using the approved quality indicator of preventive maintenance. Whereas the availability coefficient is used for the quality estimation of the whole exploitation process. Generally, the calculation of the mentioned measures is performed on the basis of the statistical data about occurred failures. This method is characterized by significant advantages as well as obvious disadvantages in case of the lack or constrained obtaining of empirical data. Modern computer technologies allow automating and simplifying the estimation of the target quality indicators. However, it requires the development of proper mathematical support for such analysis. In the paper, we propose a simulation model of the operational process of railway telecommunication equipment with the opportunity of the estimation of the availability coefficient and the quality indicator of preventive maintenance in automated mode. The model takes into account sudden, fictitious and latent failures, the impact of spare parts availability and erroneous actions of service staff during maintenance, as well as periodicity and length of maintenance and repair for quality measures estimation. The model is built using the discrete-event approach with AnyLogic.
Keywords. Simulation, telecommunications, quality, availability, AnyLogic.

1. Introduction

Railway telecommunication is one of the functional subsystems of the railway transport infrastructure, combining technical means and communication facilities for the transmission and (or) reception of voice and (or) non-voice data intended for the organization and execution of a sequence of operations of railway transport [1,2]. According to the interstate standard GOST 33397-2015 "Railway Telecommunications. General Safety Requirements" to the Railway Telecommunication (RT) facilities include an extensive list of devices, from switching tools and digital transport systems to power equipment for means of communication. It is evident that the functional purpose of railway telecommunications determines the high requirements to the reliability, as a critical aspect in the arrangement of an efficient and safe process of transportation on conventional lines [3], as well as on

newly developed and deployed high-speed railways [4, 5]. However, in practice, the share of operational failures in communication systems in railway transport remains significant and stands at 60% [6] At the same time, a significant amount of funds of certain groups of equipment have already fully exhausted their resources or are being operated in excess of the service life. In particular, one hundred percent wear is recorded in the fifth part of the fleet of locomotive radio stations. More than 60% of stationary and more than 65% of mobile radio stations are operated with an expired service life [6].

The organization and carrying out a set of preventive measures for maintenance is one of the main ways of maintaining the desired level of reliability of railway telecommunication funds. Moreover, controlled maintenance is a promising type of maintenance, as it is designed to minimize regulated maintenance and reduce the share of corrective maintenance [7]. The Railway Communication Directorates determine the frequency of work under controlled maintenance with account for local operating conditions, analysis of failure statistics for previous periods and quality requirements for the provided communication services. It is evident that the statistical data on failures are the most appropriate means for work planning.

However, this requires the availability of prototypes of equipment, and obtaining a relevant scope statistics may require substantially continuous operation and/or testing. Considering the influence of railway telecommunication equipment on the safety and efficiency of the transportation process, this approach can lead us to high financial costs. Thus, the application of this approach both for devices that are already in operation for a short period of time, and for newly implemented systems is difficult.

The use of simulation models of the RT facilities operation is one of the possible alternatives for solving this problem. The primary purpose of such models is the statistical or probabilistic modeling of transitions of a technical system from the initial state to the final, with consecutive simulating the railway vehicles' service. In this case, it is possible to collect statistical data on the results of modeling and further calculation of quality indicators. Based on the obtained estimates, it is possible to a conclusion about the correctness of the vehicles' service organization, in particular, about the frequency of preventive maintenance measures.

Earlier, in reference [8], we have considered a simplified model of the RT facilities operation, taking into account sudden equipment failures and performed maintenance. Computational experiments with such a model give overassessment of quality indicators, which highlighting the need for its improvement to accommodate a more significant number of factors and features of the technical operation of railway telecommunication facilities.

In particular, the reliability of the considered equipment depends on the validity of both the built-in monitoring subsystems and the diagnostic devices used at the stages of preventive maintenance and repair, which in turn causes the occurrence of latent and false device failures. Maintenance and repair operations are carried out by personnel of the structural units of the railways, which requires taking into account the influence of the human factor, as well as the degree of readiness of sets of spare parts, tools, and accessories (spare parts and accessories).

The literature analysis [9–13, 14] shows that model development for reliability assessment of communication systems should pay special attention to the accounting for errors of the diagnostic equipment (control), which are the cause of latent and fictitious failures.

The issue of the influence of erroneous actions of personnel on reliability has been sufficiently developed and a number of studies have proved that high-quality training of the service staff and following the recommendations for operation can achieve an increase in the reliability of equipment by 3-5 times [9, 15, 16]. According to the results of factor analysis, according to the monitoring and management system of communication networks of Russian Railways JSC, it has been established that more than a third of communication device failures are caused by improper actions by maintenance staff [6]. Therefore, the need to take into account the human factor in modeling the processes of railway telecommunication facilities operation is justified.

The repair of the facilities of the railway telecommunications is carried out by the railways' structural units. Therefore, the degree of availability of the required set of spare parts used during repair work directly influences the efficiency of troubleshooting and, therefore, the quality indicators of the operation process. Many studies, with results presented in [17, 18], have proved a significant

impact of the availability of spare parts sets on the reliability of restored systems, an example of which are considered means of railway telecommunication.

Thus, the process of operation and maintenance of railway telecommunication facilities, with account for the occurrence of sudden, latent and fictitious equipment failures, as well as the impact of the availability of spare parts and the human factor during repair and preventive maintenance, is the object under investigation in this work. Analysis of indicators of the quality of operation and maintenance of RT facilities, based on the data of simulation modeling is the aim of the study.

The availability factor is the leading comprehensive indicator of the reliability of railway telecommunications [19]. The performed analysis of the literature has proved that the reliability indicators of the restored systems are widely used in solving the problem of assessing the quality of technical operation, including fiber optic communication lines [14], computer networks of a different topology [20, 21], as well as train traffic control systems [22]. In this work, the Inherent Availability A_I is proposed as an indicator of the quality of the RT equipment, while the quality of maintenance is assessed using the specific Quality Index Q_I, regulated by the Provision "Concerning the quality indicator of maintenance of communication equipment", approved by order of Russian Railways JSC dated August 20, 2014, No. CSS-767/p (further referred to as – the Provision).

The modeling, also called statistical modeling, taking into account the random properties of the model individual elements, is one of the currently demanded approaches to assess and analyze the characteristics of the functioning processes of systems for various purposes. The authors of [23, 24] emphasized the advantage of this modeling over the empirical approach for highly reliable systems when the assessment of reliability indicators is impossible with acceptable accuracy due to the infrequent occurrence of failures. As a result, statistical modeling is used not only in the analysis of the reliability characteristics of technical systems, such as vehicle fleet [24, 25] and complex repairable systems [26] but it is also a popular tool for assessing the component software reliability [27]. Not limited to the tasks of reliability analysis, simulation is a convenient and effective method for the study of traffic flows in railways networks [28, 29].

Today, the software AnyLogic [30] is available to professionals involved in the development of simulation models. The product presents a visual environment that combines "all three modern paradigms of simulation models building: system dynamics, discrete-event and agent-based modeling" [31]. In addition, the distinctive features of this product are a powerful modeling language and an intuitive graphical interface that simplifies and accelerates the development process.

Thus, the task of developing a simulation model of the operation and maintenance process using the AnyLogic tool was set to provide an opportunity to analyze the indicators of service and maintenance quality of the RT facilities. The model is designed to assess the Inherent Availability A_I and the Quality Index Q_I, with account for sudden, hidden and fictitious device failures, the effect of availability of spare parts and erroneous actions of staff in the performance of service and repair. The statistical experiments with the model let us analyzing the influence of these factors on quality indicators: A_I and Q_I, which can be used in maintenance planning as a decision-support tool. In addition to a larger number of factors in comparison with the previously considered approach in [8], the advantage of the proposed model is the calculation of the Q_I indicator in accordance with the current regulation on assessing the quality of maintenance of communication equipment on the railroad network of Russian Railways JSC. Analysis of the literature revealed the absence of possible analogs of the developed model.

2. Simulation model

The development of any simulation model begins with the formation of a conceptual description of the process under study, or otherwise, a theoretical model. For clarity, the theoretical description is supplemented by a graphical model, in a graph or state transition diagram form. For the operation process under consideration, the maintenance state diagram is shown in Figure 1 with the transitions between the following states:
 – $S0$ – operable state;
 – $S1$ – preventive maintenance;
 – $S2$ – non-operable state;

– $S3$ – latent failure;

– $S4$ – fictitious failure;

– $S5$ – maintenance of system being in latent failure.

Following the theory of reliability, the period of the normal operation of the most technical systems is characterized by a constant failure rate function [9, 32]. During this period, sudden failures prevail in the first place, due to the influence of external random factors. In this case, the dependence of the probability of failure Q on time t is determined by the exponential law in accordance with the expression:

$$Q(t) = 1 - e^{-\lambda \cdot t},\qquad(1)$$

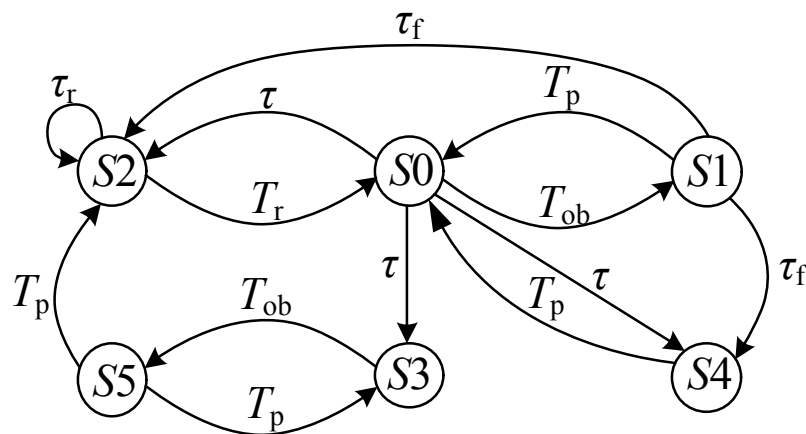where λ is the failure rate, 1/h.

Figure. 1. The state diagram of the operation and maintenance process

Consequently, the transition from an operable $S0$ to non-operable state $S2$ occurs as a result of a sudden failure according to the exponential law through a random time interval τ. After the repair, if the personnel has not made an error, the system returns to the operable state $S0$ after time T_r. If there was an error made during the repair, then the system will be in state $S2$ for a time τ_b until the next restore actions.

Transitions to state $S2$ occur randomly, while the transitions to the maintenance state $S1$ are realized at a regulated time interval corresponding to the maintenance periodicity T_{ob}. Maintenance work is carried out by the service staff of regional communication centers. Due to the human factor, an error, resulting in device failure may be accepted with probability E_{op}, which would correspond to a transition to state $S2$ after a time τ_f. After an error-free performance of maintenance operations performed during the time T_p, the equipment continues normal operation in state $S0$.

In addition to the states considered, the system can go into the latent failure $S3$ or fictitious failure $S4$ state at random time intervals τ as a result of an erroneous determination of the technical condition by the built-in control systems and failure. The probabilities of type I (a) and type II (b) are accepted as the main characteristics of control systems at work. Error a is set by the probability of false alarm, i.e. when an operable device is declared inoperative. Whereas error b is determined by the probability of skipping failure and, therefore, a non-operable device can be diagnosed as operable. Along with the built-in monitoring systems, the external diagnostic equipment used during maintenance can cause latent and fictitious failures. This type of equipment is also characterized by diagnostic errors a_2 and b_2, and built-in monitoring systems – by errors a_1 and b_1. The occurrence of one of the two considered failures is determined during the time T_p. The only and main difference consists in the fact that fictitious failure status $S4$ is diagnosed instantly, while the latent $S3$ failure can be identified during maintenance performed at T_{ob} intervals. Therefore, the model provides a separate state of system maintenance in case of latent $S5$ failure. In this case, due to erroneous actions of personnel in the process of such maintenance, the system may return to the state of latent failure $S3$.

The technical operation of railway telecommunication facilities includes the formation and maintenance of the required number of spare parts, tools, and accessories (repair parts and

accessories). The availability of spare parts in the model is proposed to consider using two parameters: the probability of lack of spare parts and accessories (P_n) and the standby time up to the delivery of spare parts (*dopvr*). These parameters affect the duration of repair time T_r. The influence of the absence of repair parts and the time of its delivery is taken into account in state $S2$ when performing the function of calculating penalty points.

Incidents caused by malfunctions and/or inoperability of the RT facilities are classified as failures and technological disruptions. The Provision mentioned above provides for three categories of failures and two categories of technological disruptions, which corresponds to a certain number of penalty points Q_{I0}. The average network repair time t_{av}, regulated by the Provision, is allocated to eliminate the incident. If the actual restore time t_{ac} exceeded the average network repair time, then the final score point Q is calculated by the formula:

$$Q = Q_{I0} + 0.5 \cdot Q_{I0} (t_{ac} \cdot t_{av}) / t_{av}, \tag{2}$$

If the restoration of the operable condition of telecommunication facilities was carried out within a time not exceeding the average network repair time t_{av}, then the final score for incident Q is equal to Q_{I0}.

Thus, the final scores for all incidents that have arisen are summarized at the end of each month, and the specific indicator of the technical maintenance quality Q_I is calculated per every 100 technical units (TU) of serviced equipment according to the formula:

$$Q_I = \frac{\sum Q}{T_0 / 100} = \frac{\sum Q}{T_0} \cdot 100, \tag{3}$$

where Q_I is the index of the technical maintenance quality of communication facilities in penalty points; $\sum Q$ is the total number of penalty points for all incidents per month; T_0 is technical equipment with telecommunication devices, TU.

The telecommunication facilities equipment capability T_0 on railway sections is measured in technical units (TU), which are calculated in accordance with the current methodology for determining the volume of work for the regional communication centers [33].

Further, the Quality Index Q_I obtained in penalty points (p/p) is interpreted under the respective quality category: "Excellent" – from 0 to 14.5 p/p, "Good" – between 14.5 p/p and the planned value of p/p (Q_p), "Satisfactory" – over Q_p and up to 80 p/p and "Poor" – over 80 p/p. The planned value of penalty points Q_p is set monthly by the Railway Communication Directorate. The ability to change Q_p is introduced to control the quality of maintenance. The value Q_p should gradually decrease, thereby stimulating an increase in the quality of the RT facilities service.

Consequently, the Quality Index Q_I serves as an assessment of the efficiency of measures to maintain the equipment of the RT equipment in the operable state, i.e., quality of maintenance. Whereas, an assessment of how well the operation of telecommunication facilities is generally organized can be given with the help of a complex reliability indicator – Inherent Availability A_I. This indicator is the ratio of the operable time to the sum of the periods when the system was operable and intervals during repairs.

For the model under consideration, the Inherent Availability A_I is calculated as follows:

$$A_I = \frac{TS_0 + TS_4}{TS_0 + TS_2 + TS_3 + TS_4}, \tag{4}$$

where TS_0 is the total time spent in the operable state $S0$; TS_2 is the total accumulated downtime due to the transition of a device to state $S2$ and the implementation of restoring repair; TS_3, TS_4 is the total time spent in the latent failure and fictitious failure states, respectively.

Thus, performing stochastic simulation of the analyzed process with the state diagram in Figure 1 through the repeated implementation of runs of the model, it becomes possible to collect statistical data in each state S_i, $i = [0, 5]$. Based on the obtained data, the assessment of the Inherent Availability A_I is calculated as an average value.

The AnyLogic simulation environment was chosen to implement the simulation model. The model in AnyLogic comprises a set of objects (tools), which joint use enables setting the logic of various processes. Discrete-event modeling instruments are used to describe the process of the railway

telecommunication facilities operation in Figure 1. The "Statechart" and the "Event" objects refer to these instruments in AnyLogic version 7.

A "Statechart" is a direct graph of a finite-state machine with the ability to specify the conditions under which a transition will occur, as well as the set of actions, caused by the change of states. Transitions between states can occur as a result of the expiration of the assigned timeout, performing of a given condition, or at the receipt of a message.

"Event" serves as a tool for modeling the time intervals of events occurrence, which functioning is implemented in three different modes: by timeout, when the condition is fulfilled, with a given intensity. In this work, there was adopted the operating mode with a given intensity.

Such tools as "Database", "Dataset", and "Collection" were used to store and process data obtained during the simulation.

A "Collection" is a set of the same type of data, which size, unlike an array, can dynamically change during the simulation. To save the values of the target parameters at the simultaneous changing of other parameters, for example, simulation time, the "Dataset" tool, a two-dimensional array of finite size, can be used during the simulation. At the end of the experiment, the results (model output parameters: the average value of A_I and Q_I) are recorded in the built-in database.

The state diagram in the developed model repeats the graph in Figure 1, in which the simulation of transition is implemented randomly and is defined using properties and additional Java code in each state. As an example, we will consider the algorithm for executing the code of operable condition S_0, which is launched before the running of each new model. For visual clarity, the operation algorithm is presented in the form of pseudocode 1.

Pseudocode 1. The algorithm of the operable state S_0
1.   Generate a random number $\xi \leftarrow U(0,1)$
2.   **if**: the probability of transition from $S0$ to $S2 \geq \xi$
3.   **then**: Generate τ
4. $TS_0 = TS_0 + \tau$
5.   Enable transition to $S2$
6.   **else if**: the probability of transition from $S0$ to $S4 \geq \xi$
7.   **then**: Generate τ
8. $TS_0 = TS_0 + \tau$
9.   Enable transition to $S4$
10.   **else if**: the probability of transition from $S0$ to $S3 \geq \xi$
11.   **then**: Generate τ
12. $TS_0 = TS_0 + \tau$
13.   Enable transition to $S3$
14.   **else**: $TS_0 = TS_0 + T_{ob}$
15.   Generate $T_p \leftarrow N(sig*T_{p0}, T_{p0})$
16.   Enable transition to $S1$
17.   **end procedure**

At the initial moment or at the returning to state $S0$, the generating of a random variable ξ according to a uniform law in the interval from 0 to 1 is performed in the first place. Further, the obtained number is sequentially compared with the probabilities of transition from state $S0$ to possible states $S2$, $S3$, and $S4$. When one of the conditions is met, τ value, corresponding to the time interval in hours, through which the transition occurs, is generated. Further, the current value of τ is stored in the variable TS_0, and transition corresponding to the fulfilled condition is enabled.

The initialization of the time interval τ for the exponential law by the inverse transformation method [34] is performed by the formula:

$$\tau = -\frac{1}{\lambda}\ln(\xi), \tag{5}$$

where λ is the failure rate specified in the simulation, 1/h; ξ is a random number with uniform distribution law in the interval [0, 1].

The exit from state $S0$ occurs by timeout after time interval τ or after a user-defined frequency of maintenance interval T_{ob}, if none of the pseudocode 1 conditions are met, the transition to the maintenance state $S1$ is enabled. Wherein, in order to take into account the fact that the time for performing preventive maintenance can actually vary, the variable T_p in Pseudocode 1 is initialized by a random number with a normal distribution, given standard deviation sig and the mathematical expectation T_{p0}.

Special attention in the simulation model structure should be given to the function that evaluates the proposed indicator Q_I of the maintenance quality. This element of the model, with the block diagram shown in Figure 2, is realized in accordance with the Provision "Concerning the quality indicator of maintenance of communication equipment", already mentioned above. The actions described in the algorithm are performed at every transition of the system into non-operable state $S2$.

Since by the Provision, the possible incidents with the telecommunication equipment are divided into three categories of failures and two categories of technological disruptions, we perform the random generating of an incident type in block 1 in Figure 2. For this, a random number ξ with a uniform distribution law is generated in the interval from 0 to 1, and then sequentially compared with empirical data of a particular incident occurrence. In the current implementation of the model, values are set for each type of incident based on statistics on failures and disturbances, occurred during the period 2014–2016 in the communication sector of one of the West Siberian railway sections: 1st category failure constitutes 0.03; 2nd category – 0.01; 3rd category – 0.7 and 1st and 2nd category technological disruptions – 0.13 each. As we have considered collectively exhaustive events, then the type of incident will be determined after the verification of the previously generated random number ξ for all possible conditions. For this incident will be performed the follow-up actions after block 2. So, for example, in the case of the 1st category failure, the Provision requires the accrual of 80 or 40 penalty points Q_{I0} and the average network repair time t_{av} for 4 or 0.5 hours. Therefore, in block 3, the number of points Q_{I0} and time for solving the incident t_{av} is randomly selected with a probability of 0.5.

The actual incident solving time t_{ac} is determined similarly to the inspection time during maintenance T_p. It is set by a random number with a normal distribution with the same standard deviation sig, but the mathematical expectation is initialized by the value $vrRI$ (block 4). This input parameter is set by the user and characterizes the average repair time in case of the 1st category failure.

In the absence of the necessary set of spare parts, in block 5 in Figure 2, the value of the waiting time up to the delivery of spare parts t_{sp} is generated in accordance with the normal distribution, with the standard deviation sig and the mathematical expectation $dopvrI_0$. Further, the actual incident solving time t_{ac} is updated in accordance with the necessary waiting t_{sp}.

Therefore, if the actual time t_{ac} exceeds the average network time t_{av}, then the score Q in block 6 will be calculated with account for the delay in restoring to working condition according to the formula (2). Next, in block 7, the Quality Index Q_I expressed in penalty points is calculated in accordance with the expression (3).

Thus, simulating the communication device operation process in accordance with the states graph in Figure 1, it is possible to generate statistics on the time spent in each state S_i, $i = [0, 5]$ and evaluate the proposed indicator of the quality of operation, the Inherent Availability A_I, using the formula (4). Whereas the assessment of the maintenance quality indicator Q_I is performed using the developed custom function at each transition to the non-operable state $S2$. The simulation process is fulfilled by the AnyLogic tools and the simulation of the analyzed process starts automatically from the operable state $S0$ after the launch of the model. Further, the transitions between the states are realized randomly according to the given conditions. A single run of the model is performed during the simulation time $vrpr$, at which the simulation process begins anew with the state $S0$. In this case, the calculation of estimates of the model output parameters, A_I and Q_I, is implemented once a month according to the simulation time. Therefore, if $vrpr$ is 100 years, then the model will generate 1200 estimates. To obtain the average values of estimates, the experiment with the model involves kp runs followed by averaging all 1200 ratings by all runs. The required number of kp runs can be calculated in accordance with the recommendations given in [35]. In the particular case, with the confidence interval of 5%, each experiment with the model requires 2000 runs.
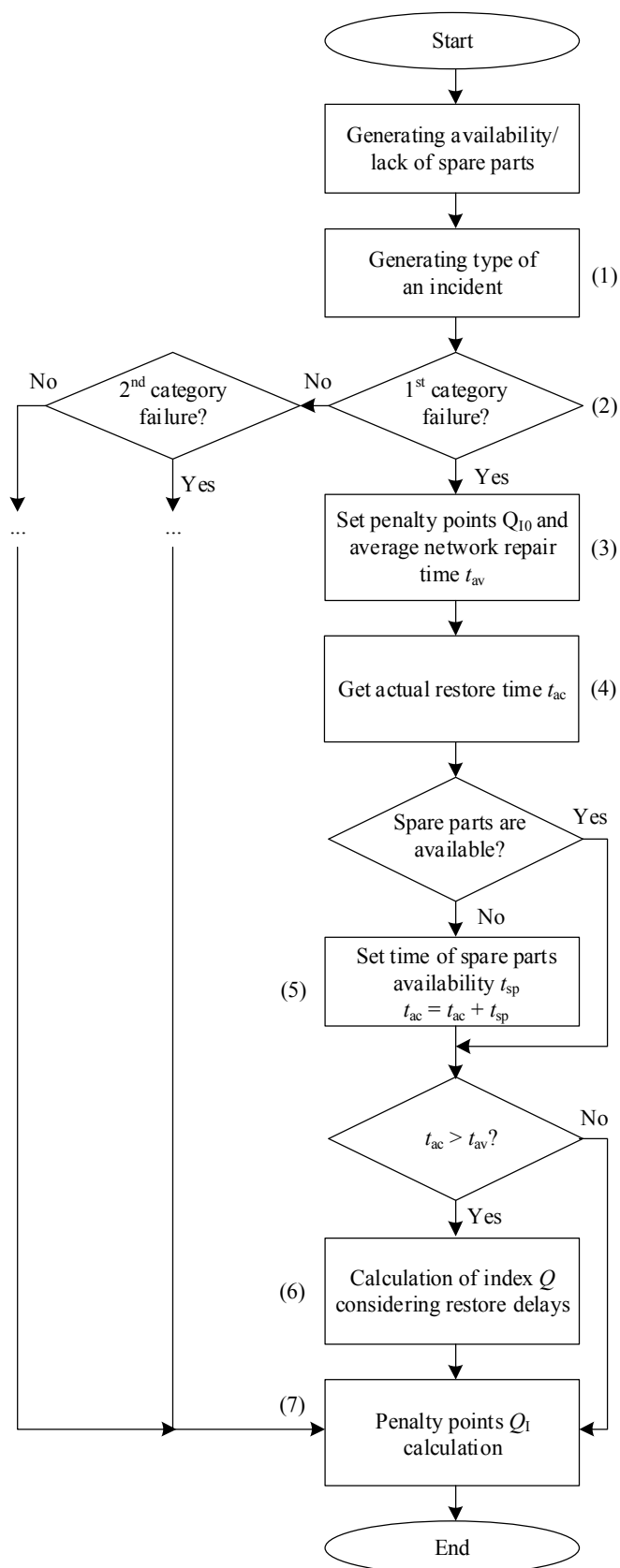
Figure 2. The block diagram of the algorithm of maintenance quality estimation function

3. Model Experiments

To demonstrate the work of the developed simulation model, the number of computational experiments were carried out, during which there were obtained graphs of estimates of the Inherent Availability A_I (Figure 3, a) and linearly approximated graphs of estimates of the Quality Index Q_I (Figure 3, b) as a function of time. The purpose of the experiment – is to evaluate the influence of the devices' failure rate on the A_I and Q_I indicators. Whereby, the A_I coefficient characterizes the quality of the operation of communication equipment in general, while Q_I is used for estimating the quality of ongoing measures for the maintenance of devices. This way, six experiments were performed for the following failure rates λ: 5, 6, 7, 8, 9 and $10 \cdot 10^{-5}$ 1/h. The values of the input parameters remained constant during the experiment are given in Table 1.

The set of curves of the Inherent Availability A_I as a function of time for various values of failure rate, presented in Figure 3, a, is an example of implementing the A_I functions obtained experimentally using the developed model.

Table 1. Input values of the constant parameters of the model

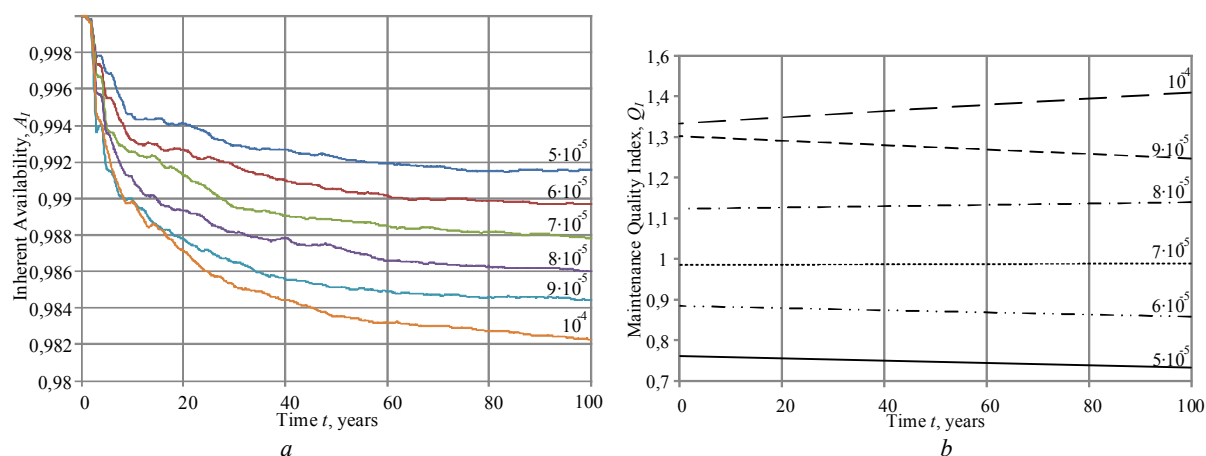| Parameter	Value
The mathematical expectation of the waiting time until the delivery of spare parts at:	
failures, $dopvrI_0 - dopvrIII_0$	24
technological disturbances, $doptnI_0$, $doptnII_0$, hours	12
The probability of the lack of spare parts $QZIP$	0.1
Technical equipment with telecommunication devices T_0, TU	600
Maintenance interval T_{ob}, h	8640
The mathematical expectation of inspection time T_{p0}, hours	3
The mathematical expectation of the repair time:	
the failure of the 1st category, $vrRI$	10
the failure of the 2nd category, $vrRII$	5
the failure of the 3rd category, $vrRIII$	2.5
technological disruptions of the 1st and 2nd categories, $vrRtnI$ and $vrRtnII$, hours	1.25
The probability of the service staff errors, E_{op}	0.126
The probability of type I errors of built-in diagnostic tools, a_1	0.01
The probability of type I errors of external diagnostic tools, a_2	0.005
The probability of type II errors of built-in diagnostic tools, b_1	0.02
The probability of type II errors of external diagnostic tools, b_2	0.05
Number of runs, kp	2000
The time of one run $vrpr$, years	100

Figure. 3. Experimental graph of the dependence of the Inherent Availability A_I estimates (*a*) and of the Quality Index Q_I (*b*), as a function of time t and failure rate λ

As we can observe, the obtained experimental curves decrease nonlinearly, starting from the maximum possible value set to unity, which is consistent with the assumption accepted in the model that the operation of the railway telecommunication facilities begins strictly at the operable state $S0$. This assumption is based on the functional purpose of the RT facilities and their impact on the safety of the transportation process; therefore, the early life period for such devices should not be considered.

In addition to that, here is clearly demonstrated the influence of the failure rate λ on the value of the Inherent Availability A_I and, as a result, on the quality of the organization of operation of the RT facilities. If we assign the minimum acceptable level of availability factor, for example, 0.99, then in the case under consideration, only for the failure rate $\lambda = 5 \cdot 10^{-5}$ 1/h, the estimation of the A_I factor along the entire time axis will meet the specified requirements. Therefore, we can confirm the quality operation of the equipment with the parameters from Table 1 and the rate $\lambda = 5 \cdot 10^{-5}$ 1/h.

Analyzing the experimental dependency graph of the Quality Index Q_I (see Figure. 3, b), we can note a regular increase of the average value of this indicator with an increase of the failure rate for values of 5, 6, 7, 8, 9, and 10 $\cdot$ 10^{-5} 1/h with average points 16.7; 13.3; 14.5; 12.8 and 7.5%, respectively.

Figure 4 shows a graph of the average value of the Quality Index Q_I, as well as its maximum and minimum values for the corresponding period of time at the failure rate $\lambda = 5 \cdot 10^{-5}$ 1/h. According to the Provision "Concerning the quality indicator of maintenance of communications equipment", we can conclude that with the given model parameters, the highest quality category "Excellent" is achieved, as the maximum value at all points does not exceed the threshold of 14.5 penalty points.
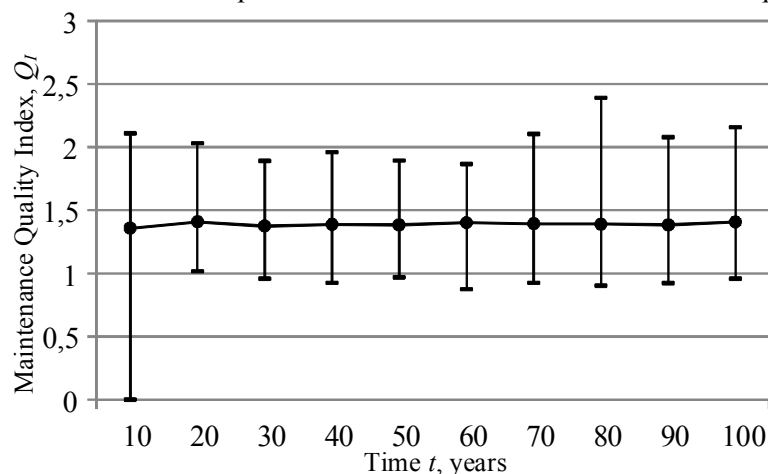

Figure. 4. Variation of the average value of Q_I and its maximum and minimum values for the failure rate $\lambda = 5 \cdot 10^{-5}$ 1/h

4. Conclusion

Analysis of the operation quality of equipment involved in the organization of responsible technological processes in industry and transport remains a crucial task. The use of modern software tools, allowing to automate the calculation of quality indicators, has an indisputable advantage, which consists in the prompt obtaining of the computer modeling results in comparison with field tests and (or) experimental data of operation. However, this requires the development of adequate mathematical models, which accuracy is comparable with the results of calculations based on real experimental data.

This work presents a simulation model of the operation process of railway telecommunication devices, designed to assess the maintenance quality of communication facilities with the Quality Index Q_I and to get estimates of the Inherent Availability A_I, as an indicator of the quality of the operation process in general. The principle of the discrete-event simulation was adopted as the model basis, facilitating its implementation in the AnyLogic environment with the application of built-in tools. The developed model takes into account the occurrence of sudden, latent and fictitious device failures, the impact of the availability of spare parts, erroneous actions of the maintenance personnel, as well as the frequency and duration of maintenance and repair.

Using the proposed model, it becomes possible to conduct a computer experiment to analyze the influence of input parameters on the A_I factor and Q_I indicator of preventive maintenance. Thus, the developed model can serve as a decision-making support tool, for example, for improving the maintenance of the system, already in used and (or) newly deployed telecommunication equipment.

In the future, we plan to improve the developed model to take into account the gradual failures of the components of railway telecommunication equipment, as well as to enhance the frequency of maintenance that changes during operation.

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