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THE USE OF SIMULATION EXPERIMENTAL RESEARCH IN DIFFERENT AREAS CONCERNING RAILWAY TRAFFIC CONTROL ISSUES

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Abstract – The article presents examples of transport applications in which simulation experimental research is of great importance and particularly useful. The first part presents examples of important railway transport areas where computer simulations have been used. In the second part of the study, more reference is made to the study of the exploitation process of railway traffic control devices using a so-called simulation experiment. As railway control systems are complex systems, it is practically impossible to carry out direct studies or carry out diagnostics without disconnecting a component from the complete system. This is when simulation research becomes helpful. In the simulation of the exploitation process, the initially known theoretical cumulative distribution functions of times between failures and times of repair of the objects distinguished in the model of the railway control system and the distributions of the number of their failures were assumed. The exploitation and reliability parameters of these objects were then determined based on real data, using statistical analysis and on the basis of simulations of future exploitation states of this system. A parametric and non-parametric verification of empirical distributions of reliability parameters determined for selected system components was also carried out.

Key words – railway traffic control devices, exploitation process, simulation experimental research, simulation model, distributions of times between failures and times of repair

JEL Classification – C65, C91, L92, R41, R42

INTRODUCTION

Different tools are used to study railway transport processes depending on the problem being analysed, e.g. stochastic methods, dynamic programming, mass service theory, etc.

Experimental research, including computer simulation, is now widely used in the analysis of rail transport systems and the processes occurring within them. The literature analysis of simulation studies of train movements on the railway network using computer software considers the following relevant transport threads:

in works [1-2], the Java Modelling Tools application JSIMgraph was used for simulation studies of train traffic fluidity on the railway network. Various situations that can cause disruptions to railway traffic were modelled and the effects of such events were predicted;

the DOSIMIS 3 package ([1], [3]) was used to control the transport events in the production process and operation strategy , discrete simulation capabilities were used;

simulation of movement processes using automatic set route was carried out in the work [4] using various models, including: the track layout in the Track Editor module, the railway signalling system (signals, switches), the European Rail Traffic Management System - ERTMS/European Train Control System – ETCS (balises, Radio Block Centre) in ERSA software with Traffic Simulator and Operational Simulator modules. The RailML language, a specialised language for railway applications, was used to model the positioning of trains and to take into account the timetable;

the RailML programming language was also used in works [5] and [6] to describe important dependency data in railway transport, important from the point of view of traffic safety, with reference in [6] to railway station systems, while in [5] to line interlockings. RailML Editor software was used to create useful definitions of selected dependency aspects for the aforementioned systems, etc.

1. Experimental research applied to various railway transport aspects

Traditional experimental research of technical objects is an excellent source of knowledge about their condition, but has serious limitations, including:

– a large number of objects are required in order to obtain reliable and sufficient information on state sets and parameter sets of diagnostic signals (technical condition symptoms);
– limiting the possibility to experiment on single objects (e.g. track sensors);
– long time of experimental research;
– high research costs.

In such a situation, there is a need to replace experimental research with simulation research – the so-called simulation experiment, which uses a model of the object. Experimenting with a model is no different in principle to experimenting with an object, so all methods of planning an experiment are used. Concretisation of model structure and parameters must be based on actual experimental material.

1.1. The essence of simulation experimental research

Simulation models are the basis of the simulation experiment (Figure 1), while the base of the simulation models are objects models. Having a model of a technical object developed, an algorithm is drawn up, followed by a computer program, which should function according to a formal model (e.g. reliability, binary matrix, etc.). The computer program created is called a simulation model or a computer model of the technical object. Such a model is the basis for carrying out simulation experiments and, as a result, developing inference models, i.e. algorithms for predicting and generating states of a technical object.

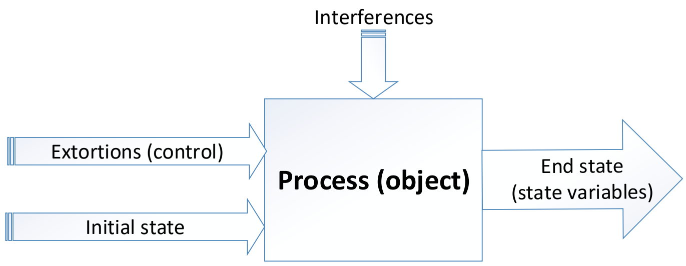


Fig. 1. General structure of the simulation model [7]

Simulation involves studying the behaviour of a model so that, operating at an altered time and space scale, it is possible to capture interactions and behaviours that would be difficult to see and analyse in real space-time.

A computer model is a computer program that allows the input of parameters of the modelled system and its initial state, obtaining by calculation the time courses of phenomena and characteristics of the modelled system. Computer simulation, on the other hand, uses computer technology to solve dynamic system model problems. It should therefore be assumed that the purpose of computer simulation is to reproduce the course of the process under study on the basis of its mathematical model by means of computer technology and to study the influence of the environment (input signals) and the internal properties of the object (process parameters) on the characteristics of the object [8].

It can be assumed that the simulation model and simulation studies, are important tools for investigating and assessing the states of technical objects.

1.2. Characteristics of selected applications of simulation experimental research in railway transport

There are many areas of railway transport where simulation experimentation has been used. An example area is the training of train drivers using simulators for traffic control devices and railway infrastructure as well as simulators for typical railway locomotives.

Due to the ever-increasing complexity of railway control systems, mainly in terms of the logic of the dependencies they implement, experimental research using applications that simulate the operation of devices (using their visual presentation) or other processes taking place and the simulations that arise for them are increasingly making sense. When conducting experimental research, the test bench usually contains a complete set of possible equipment variants and situations that have a high probability of occurring in reality. Information directly from railway control devices can significantly increase the accuracy of simulations and replicate real traffic situations, as well as making the behaviour of rail vehicles more realistic.

Following the tragic railway disaster in Poland in the town of Szczekociny in 2012, a program of measures to improve traffic safety on the railway network was launched in Poland. The result of this process was the construction of new or the improvement of existing computer simulators created by, among others, PKP PLK S.A. (Figure 2) or the Mazovian Railways (Figure 3).

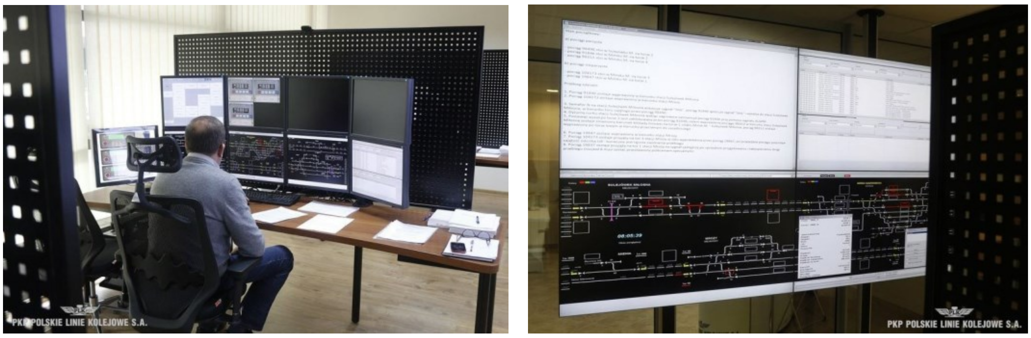


Fig. 2. Examples of simulators of railway traffic control devices of PKP PLK S.A. [9]

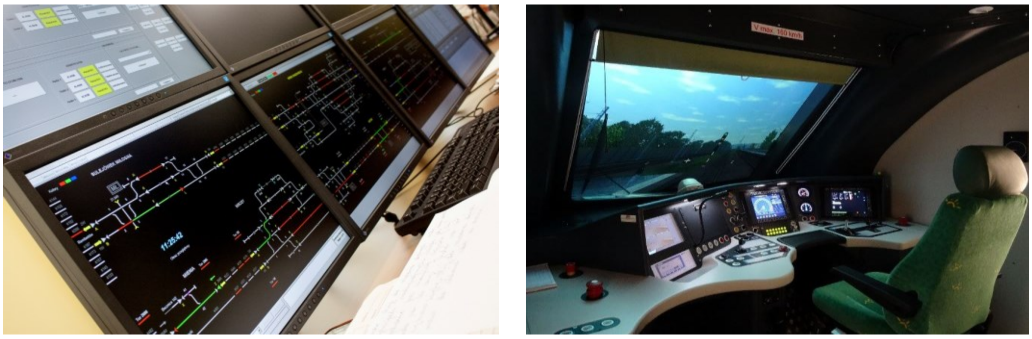


Fig. 3. Stations of the railway control traffic and communication devices simulator for train dispatchers [10] **and the interior of the simulator of a locomotive type 22WEe-76 of the Mazovian Railways** [11]

Another example of the use of computer technology to solve problems of dynamic models of traffic control systems is the simulator of railway traffic management ISDR [12]. It makes it possible to operate E-type station devices (control panel), which is the basic system of relay devices used in Polish railways. This simulator mapping the operation of railway traffic and railway control devices in a sample station, equipped with E-type station devices and line interlockings of various types, including Eac-type automatic, Eap-type semi-automatic and C- type semi-automatic. In addition to operating the devices in normal situations, provision is also made for the simulation of typical faults that can be caused by the user or occur randomly.

Railway traffic is simulated on the basis of an accurate model of the station's track layout and a preset timetable, which can be modified. Accelerations and decelerations of rail vehicles are calculated based on the equation of train motion, resulting in start-up and braking times close to reality. It is also possible to transmit signals and commands directly to traction vehicles, so that traffic can also be conducted in simulated situations that do not allow the transmission of signals through trackside signals [13].

Further development versions of the ISDR simulator for actual train timetables in Poland are made available on the Internet (example in Figure 4), with a significant proportion of trains start or finish their run.

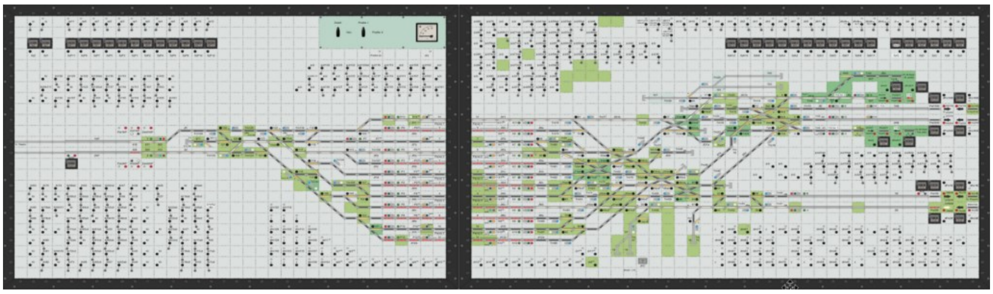


Fig. 4. View of the ISDR simulator (control panel) designed for controlling train traffic at the exemplary Kraków Główny Station [12]

A further example of the use of simulation research is the ability to track the functioning of a railway station. The operation of the station can be described as a sequence of rail vehicles traffic simulations, e.g. in the computer program AnyLogic. This programme allows almost any transport category to be modelled (Figure 5) using the appropriate libraries.

Fig. 5. Available libraries of dynamic blocks [14]

AnyLogic program allows any category of transport, including railway, to be modelled using an appropriate library of ready-made components (Fig. 6a). Simulation research can be carried out and the workings of a railway station or even a large section of the railway network can be visualized. The railway library includes many types of carriages, tracks, railway switch points and locomotives (Figure 6b and 6c), as well as other station objects such as platforms, roads and even people. Figure 6d shows how a locomotive and wagons are combined to form a one train [14-15].

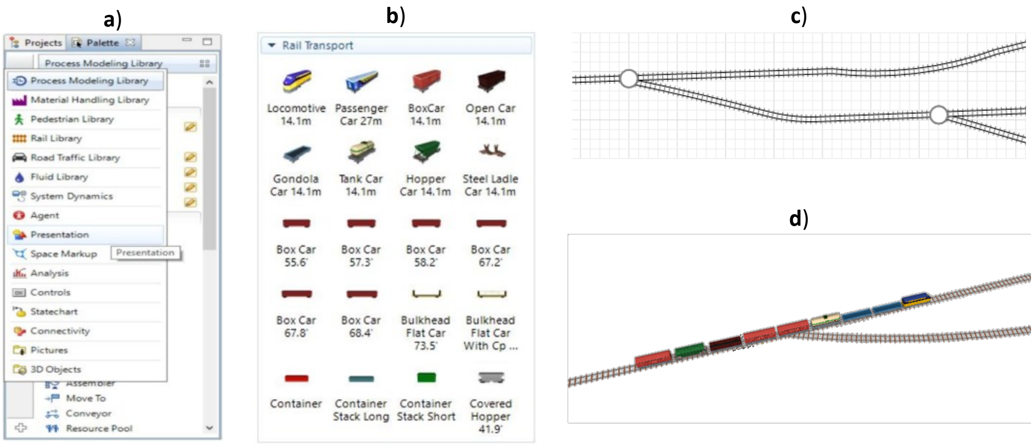


Fig. 6. Simulation capabilities of AnyLogic software [14]: **a) libraries of the program including the railway library; b) 3D models of trains available in the library; c) railway switch design; d) connecting the wagons of a train on a track**

By choosing the Rail Library, one can conduct appropriate simulation research and visualize railway stations, including passengers and even large fragments of the railway network.

The functioning of the station under study can be presented as a series of simulations of the total railway traffic. Simulation research should take into account the different situations of station track occupation by trains, typical of passenger and freight traffic. Dynamic process modeling allows the use of open structures, with the possibility of agent-based models.

In order to visualise the operation of a railway station, it is possible to make a 3D model of the station where passenger and train movements should be taken into account. A railway station may have several platforms and tracks. Preparation of composition of train means designing a sequence of several carriages connected to each other that can run on the tracks of a railway station [15].

Figure 7 shows the 3D model of the railway station prepared for the simulation and how the logic of its functioning was taken into account using the available AnyLogic Rail Library, Process Modeling Library and Pedestrian Library working together.

a) **b**)

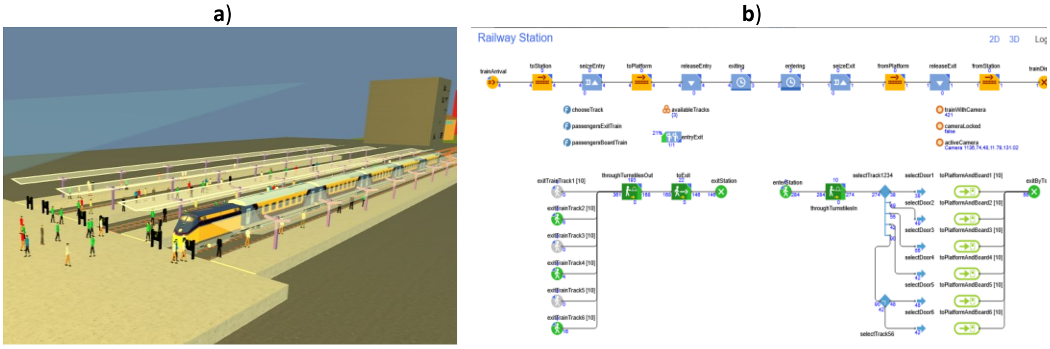


Fig. 7. Preparation of the railway station model in AnyLogic program [15]: **a**) **on a physical level** (**implementation in 3D**); **b**) **on a logical level**

2. THE USE OF COMPUTER SIMULATION IN THE STUDIES OF THE EXPLOITATION PROCESS OF RAILWAY CONTROL DEVICES

The main part of this publication is concerned with the research into the process of exploiting railway control objects and the use of computer simulation in them. Exploitation research carried out on the objects of the railway traffic control system allows to obtain relevant information about the behavior of the devices in real conditions.

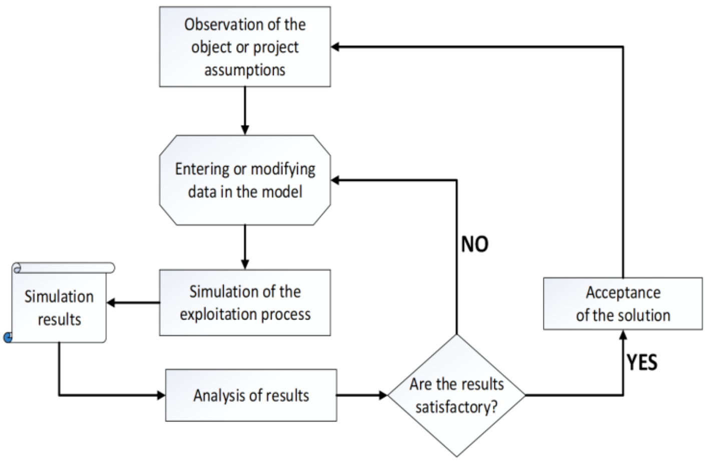


Fig. 8. The flow of the exploitation process taking into account the decision-making mechanism [17]

Modeling of exploitation processes is effective using the latest achievements of various scientific fields, effectively and quickly providing information on the correctness of the exploitation of machinery/devices. The development of exploitation models that provide information about the changing state of devices is the basis for exploitation decisions and the basis for building simple and effective exploitation models and strategies [8], [16-17].

The model used in the research (Figure 8) allows to make decisions that control the course of the exploitation process depending on its condition and the obtained quality indicators of the process. This model is adaptive and can be applied widely [18].

The simulation model of the railway traffic control system adopted for the experimental study takes into account typical railway traffic control objects occurring in the selected control area covered, for example, by the Local Control Center (LCS) zone. This is a part of the railway network, in which the following objects can be distinguished (Figure 9):

1. The railway traffic control subsystems
   – railway line (No/Name),
   – railway station (name/km),
   – junction post (name/km)
2. Devices (types)
   – computer signal box,
   – automatic line interlocking,
   – automatic level crossing system
3. Elements (types)
   – track signal,
   – switch drive,
   – track section,
   – level crossing.

The simulation model of the railway traffic control system used for exploitation experiments is a universal model, as it allows any number of types of devices and elements to be taken into account and allows different configurations of reliability structures to be adopted [19].

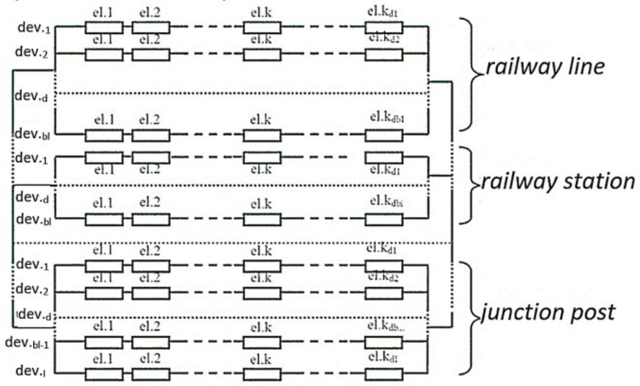


Fig. 9. Structure of the reliability model of the railway traffic control system used for simulation research

According to the structure of the adopted system model, the analyzed section of the E-65 railway line was divided into 9 subsystems, which are: junction post (1 unit), railway line (4 units), railway stations (4 units).

Preliminary assumptions were made to carry out the simulation process:

1. All railway traffic control objects appearing in the model have been classified into types.
2. The theoretical distributions of times between failures and times of repair of the objects highlighted in the railway traffic control model and the distributions of the number of damages in each object were assumed for the simulation of the exploitation process.
3. T-Student's statistic will be used to verify the statistical hypotheses of the consistency of the mean values, while Chi-square (χ^2 Pearson) and λ-Kolmogorov tests will be used to test the consistency of the empirical distributions with the hypothetical distributions and the consistency of the empirical distributions [20-22].

4. Exploitation data collected in one calendar year from a selected section of the E-65 railway line were used for the simulation process.
5. A period of 8700 hours (approximately 1 year) was taken as the statistics collection cycle, with a maximum simulation time of 20000 hours and statistics collected from a time interval of 9500 to 18200 hours. The preceding period, i.e. from 0 to 9500 hours, was treated as a time of stabilisation and saturation of the railway control system with damage and repair events.

In the railway traffic control simulation model, analysis of exploitation data (damages and renovations) using statistical inference methods was used for calculations. A research of basic reliability parameters such as mean value, standard deviation, damage and damages and renovation intensity, readiness indicator, etc. was carried out.

In the method used, statistical hypotheses were initially set for the unknown values of the parameters of the times between failures distributions and times of repair distributions of each element type and each device type, as well as the number of defects distributions in each device type and element type of the railway control traffic and of their unknown type (shape) [21-24].

The study assumes that time of serviceability of the railway control object will be replaced by the generally accepted time between failures of that object in reliability studies, while the time of failure of an object will be replaced by the time of its repair.

The classic indicators of the process of exploitation of the railway control objects are the mean time between failures (MTBF) and the mean time to repair (MTTR). The following are definitions of these time indicators.

– MTBF is the mean time between failures of an object;
– MTTR is the average time it takes to repair a device/system after a failure has occurred.

Formulas for calculating mean time between failures and mean time to repair:
MTBF = total time between failures / number of failures [21]

$$MTTB=\frac{\sum_{i=1}^{N} T_{Fi}}{N} \tag{1}$$

MTTR = total time to repair / number of failures [21]

$$MTTR=\frac{\sum_{i=1}^{N} T_{Wi}}{N} \tag{2}$$

where:
N – number of failures,
T_{Fi} – failure time,
T_{Wi} – working time.

The distributions of the number of damages in the distinguished objects of the railway control system were calculated from the relationship:

$$p_i = \frac{n_i}{n} \quad \text{for } i = 1, 2, ..., k, \tag{3}$$

where:
n_i – the number of events highlighted in the i-th device (or element),
n – the size of the research sample.

The following scheme was used to determine the distributions of times between failures and times of repair of the objects in the system under study [25-26]:
1) The sample was divided into k compartments of length each, according to the formula (4):

$$\Delta t = \frac{t_{max} - t_{min}}{k} \tag{4}$$

where:
t_{max} – maximum value of time out of sample,
t_{min} – minimum value of time from the sample,
k – number of intervals.

2) All intervals are assumed to be left-closed, except for the last interval (closed on both sides):

$$< t_{min} ; t_{min} + \Delta t), < t_{min} + \Delta t; t_{min} + 2\Delta t), \ldots, < t_{max} - \Delta t; t_{max} > \quad (5)$$

3) The counts of nj occurrences of tr values in the j-th interval (for j = 1, 2, ..., k; r = 1, 2, ..., n) were determined
4) Empirical frequencies fj were calculated from the formula (6):

$$f_j = \frac{n_j}{n} \quad (6)$$

5) The value sample mean was determined based on the formula (7):

$$\bar{t} = \frac{1}{2} \sum_{j=1}^{k} t_j^o \cdot n_j \quad (7)$$

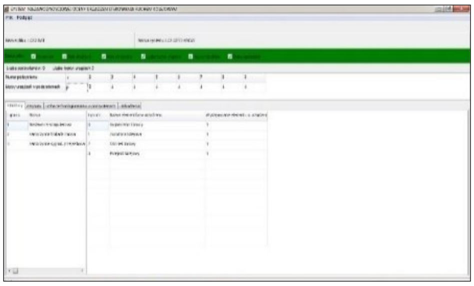
where:
t_j^o – time value occurring in the middle of the j-th interval
6) The standard deviation was calculated using the formula (8):

$$s = \sqrt{\frac{1}{2} \sum_{j=1}^{k} \left(t_j^o - \bar{t}\right)^2 \cdot n_j} \quad (8)$$

where designations as before.

The λ-Kolmogorov and Chi-square tests were used to verify the consistency of the empirical distributions with the most common distributions used in reliability theory, i.e. exponential, normal and log-normal, while the parametric Student's t-test was used to verify the mean values of the compared distributions [21].

a)



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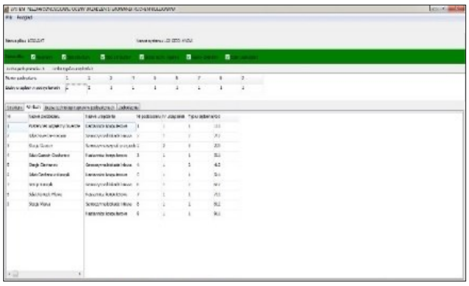

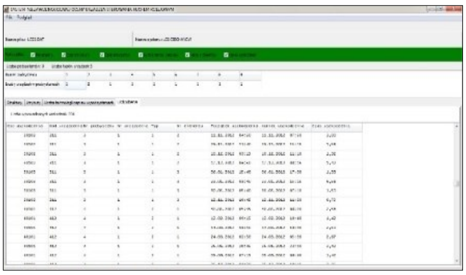

c)

Fig. 10. Simulation program windows: a) with information on the structure of the railway system; b) with information on the attributes of the railway system; c) for archiving the exploitation data of the railway control system

The research used a simulation program to determine the reliability parameters of the railway control system. The computer program contains advanced mathematical, logical, graphical and system functions. It allows you to assign railway traffic control objects to the appropriate hierarchical levels of the system, create a database of structure (Figure 10a) and attributes (Figure 10b), and archives data from the exploitation of the system (Figure 10c). The application also makes it possible to carry out statistical calculations of basic exploitation parameters and to simulate the damage and renovation process of the railway traffic control system.

The simulation of the exploitation process using the simulation model of the railway control system is based on the so-called subsequent events method. The simulation process was based on a random number generator (RNG) and the repeated use of a procedure to draw new values according to the previously identified probability distributions of these quantities. The random number generator generates a stationary and ergodic random sequence of binary elements, organized as a sequence of random numbers. Random numbers are numbers that have no pattern or order and are unpredictable [8], [23], [27].

A distributant inversion method was used to develop software algorithms for random number generators. The property of the „pseudo-inverse" function was used. The inverse distributant method involves assuming that a given random variable has a distributant of the form $F(x) = P(X<x)$ and can be easily calculated from empirical distributions by summing the relative frequencies of the random variables. Values are then drawn from the interval (0; 1) and the value of the random variable is read out for the drawn probability value (Figure 11) [27-28].

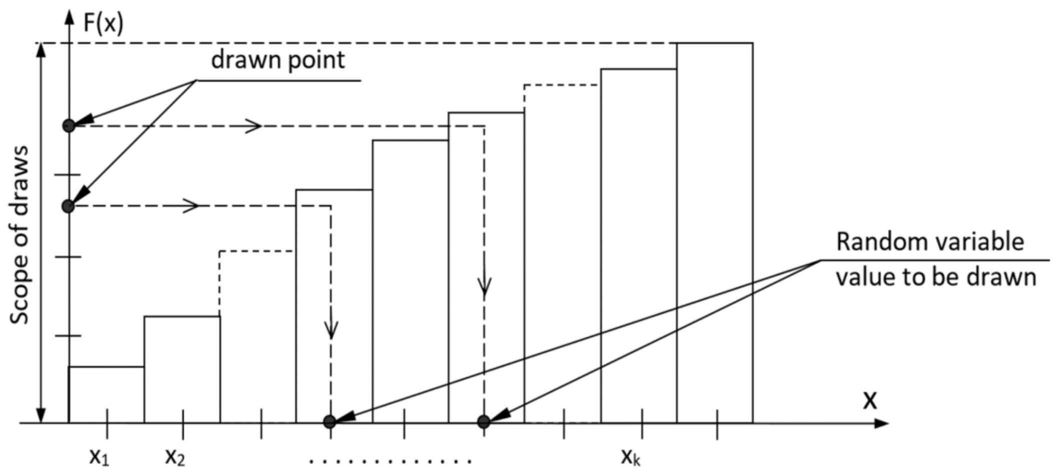

Fig. 11. Application of the inversion of distributant method [own elaboration]

A verification of the exploitation model of the railway control system was also carried out, which involved investigating discrepancies between the model and the real system.

The developed simulation model of the railway traffic control system allows the calculation of system exploitation parameters based on real data using statistical analysis. It also offers the possibility to simulate future exploitation states of the railway control system on the basis of the distributions of the reliability parameters of the system identified during the analytical calculations.

Figure 12a shows the numerical distributions of damage to the railway control devices determined on the basis of statistical analysis of damage based on real data, while Figure 12b shows the distributions, based on simulation, relating to damage occurring in the different types of the railway control elements. The analysis shows that the faults of the dependency devices was determined by the high volume of railway traffic and the additional shunting traffic carried out.

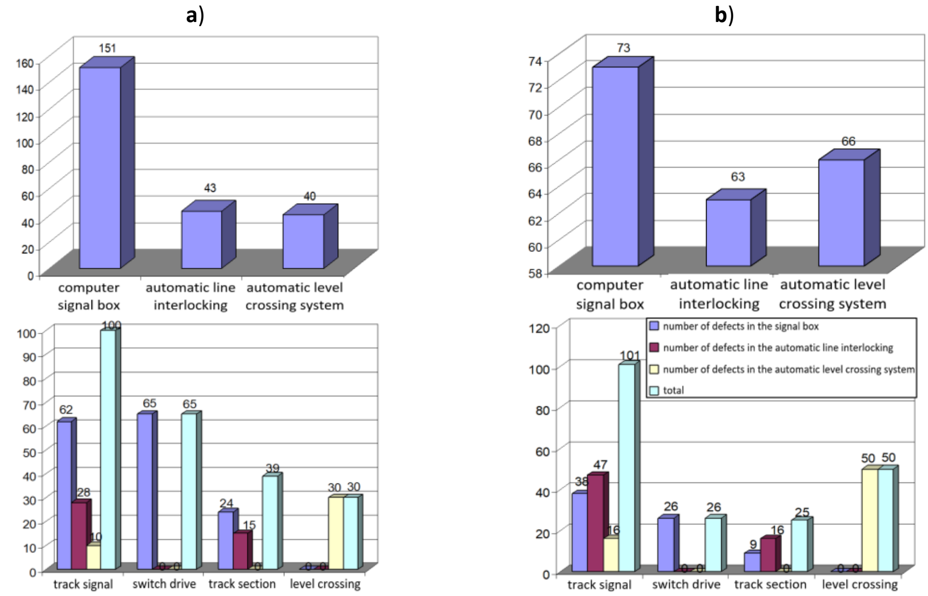

Fig. 12. Number of damages occurring: a) in distinguished types of railway control devices and elements on the basis of statistical calculations; b) in the different types of railway control devices and elements obtained by simulation research

In addition to the analysis of the results in terms of quantity, a lot of relevant information comes out of the analyses of the frequency distributions of the quantities studied. In particular, consideration should be given to the analysis of the distributions of times between failures and times of repair of selected types of the railway control devices and elements.

Figure 13 shows a frequency analysis of the distributions of times between failures and times of repair of a selected type device, which is a computer box.

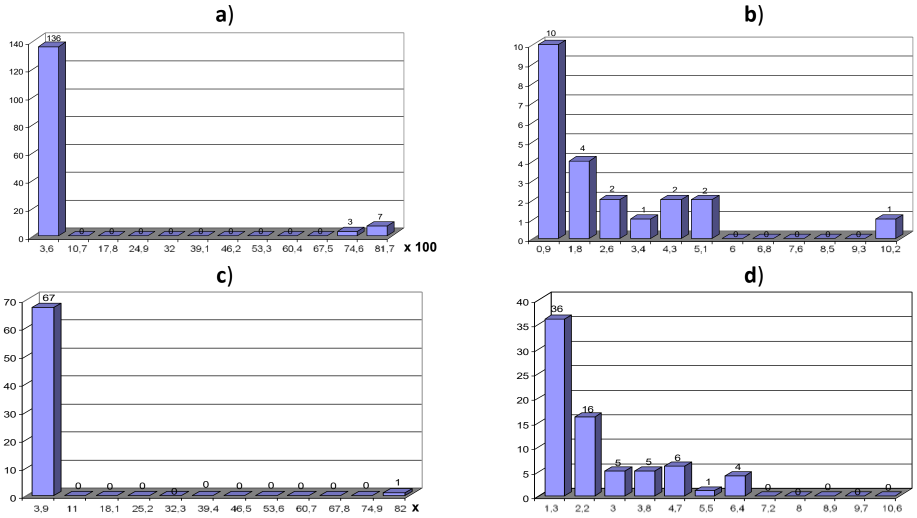

Fig. 13. Number of damages occurring: a) in distinguished types of railway control devices and elements on the basis of statistical calculations; b) in the different types of railway control devices and elements obtained by simulation research

To complete the analysis, Figure 14 shows the distributions of times between failures and times of repair for an exemplary railway control element, such as a track signal device.

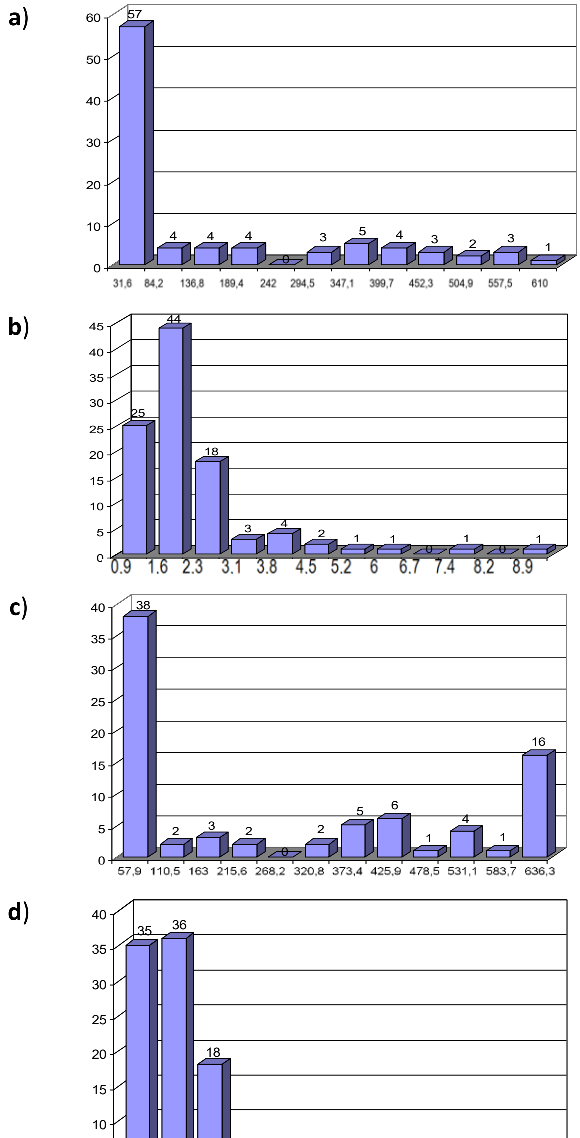

Fig. 14. Frequency distributions of a track signal type element including: a) times between failures obtained from statistical analysis; b) times of repair obtained from statistical analysis; c) times between failures obtained from simulation research; d) times of repair obtained from simulation research

The simulation results concerning the distribution of times between failures for the railway control device of the computer signal box type are in accordance with the given log-normal distribution (Chi-square test of consistency at the confidence level α=0.1 and Student's t-test at the confidence level α =0.05). However, in the case of the distributions of times of repair for the computer signal box, the tests differed, i.e. the Chi-square test at the confidence level α =0.1 did not confirm the correspondence of the distribution resulting from the simulation studies with the distribution obtained by analytical means, while the Student's t-test (on average values) at a confidence level of α =0.05 did not reject the hypothesis on the compatibility of these distributions.

In the case of the simulation of the distributions of times of repair for track signals, they were shown to be consistent with the assumed distribution obtained during the statistical analysis (Chi-square test at the confidence level α =0.1 and Student's t-test at the confidence level α =0.05). However, for the distributions of times between failures of trackside signals, the aforementioned tests (at the same confidence level) did not confirm the conformity of the distribution obtained from simulation studies with the distribution determined by analytical calculations.

The technical availability indicator *(I_{TA})* can be determined from the following relationship [21]:

$$I_{TA}(t) = \frac{T_u(t)}{T_u(t) + T_S(t)} \tag{9}$$

where:

$T_u(t)$ – the total dwell time of the railway control devices in the state of serviceability (state of use),

$T_S(t)$ – the total time of residence of railway control devices in the state of unserviceability (state of service or repair).

The technical availability indicator values (I_{TA}) of the objects highlighted in Figure 15 are comparable and are above the value of 0.98 (an exception is a track signal type element for which I_{TA} <0.95). This readiness indicator value for the track signal may be due to the poorer quality of the incandescent bulbs used in them. Similarly to the values obtained from the analytical calculations, the readiness indicators obtained through simulation are also close to each other and take values above 0.99, with the exception of the level crossing element. In this case, a readiness indicator value of I_{TA} = 0.9854 was obtained.

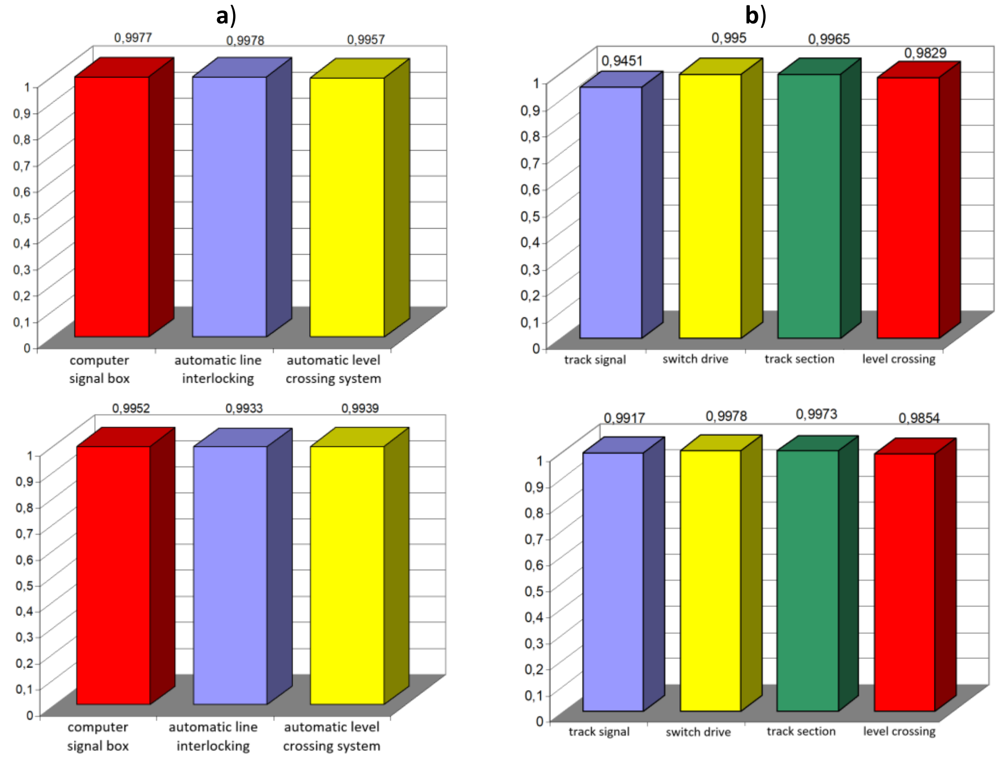

Fig. 15. The technical availability indicators for the distinguished types of devices and elements in the railway control system model obtained by: a) analysis and analytical calculations; b) simulation research

CONCLUSIONS

Simulation studies belonging to the experimental research group are now often used. Depending on the quality and accuracy of the model used for the simulation studies, they allow reliable information to be obtained. In the case of in-service research (described in this publication), a number of important data were obtained on the operation of the railway control devices under real-world conditions.

The basis of the simulation experiment is the simulation models, while the basis of the simulation models are models of existing objects. The simulation model of the railway control system developed and described has a parallel-array structure, i.e. it is parallel for the subsystems and devices, while it is serial for the elements included in the individual devices. The model is adaptive and can be applied widely.

As a result of statistical calculations based on actual data, the operating parameters of the basic types of the railway control devices and elements were determined. Significant data were also obtained for frequency distributions analyses of the characteristic exploitation quantities of the system under study. An analysis of the distribution of time between failures and time of repair for different types of the railway control devices and elements can be helpful in determining the maintainability of each type of the railway control object and particularly useful in making important exploitation decisions concerning, for example, their using or renovation processes.

The publication also presents simulation research on train traffic volumes carried out using the computer program AnyLogic. These studies confirmed the feasibility of upgrading the track layout of the station selected for detailed analysis, thereby improving and enhancing railway safety.

One of the biggest current problems of the studied railway station is the insufficient number of tracks that met the required usable length and had a sufficient number of platform edges. The current architecture of the station under study does not meet most of the design requirements. A way of upgrading the railway station was proposed and the validity of the changes was demonstrated through simulation research. Simulation research was also carried out for the existing track layout after the proposed station infrastructure upgrade for the current station load. The results of a number of tests carried out have confirmed the correctness of the decision to carry out an upgrade of the railway station under study.

The use of experimental research is creating ever-increasing research horizons for the perceived new scientific areas of transport now being explored, including those relating to railway transport.

ABBREVIATIONS

1. **ERTMS** – European Rail Traffic Management System;
2. **ETCS** – European Train Control System;
3. **ERSA** – software with Traffic Simulator and Operational Simulator modules;
4. **RailML** – specialised language for railway applications;
5. **ISDR** – simulator of railway traffic management;
6. **LCS** – Local Control Center;
7. **MTBF** – Mean Time Between Failures;
8. **MTTR** – Mean Time it Takes to Repair;
9. **RNG** – Random Number Generator.

WYKORZYSTANIE SYMULACYJNYCH BADAŃ EKSPERYMENTALNYCH W RÓŻNYCH OBSZARACH DOTYCZĄCYCH ZAGADNIEŃ STEROWANIA RUCHEM KOLEJOWYM

Artykuł ukazuje przykładowe zastosowania transportowe, w których symulacyjne badania eksperymentalne mają duże znaczenie i są szczególnie przydatne. W pierwszej części przedstawiono przykładowe ważne obszary transportu kolejowego, w których użyto symulacji komputerowych. W drugiej części opracowania w większym stopniu odniesiono się do badań procesu eksploatacyjnego urządzeń sterowania ruchem kolejowym z wykorzystaniem tzw. eksperymentu symulacyjnego. Ponieważ systemy srk są systemami złożonymi, to praktycznie nie ma możliwości przeprowadzenia bezpośrednich badań lub przeprowadzania diagnostyki bez odłączenia podzespołu od całego systemu. Wtedy pomocne stają się badania symulacyjne.

W symulacji procesu eksploatacji założono wstępnie znane dystrybuanty czasów trwania poprawnej pracy i uszkodzeń obiektów wyróżnionych w modelu systemu sterowania ruchem kolejowym oraz rozkłady liczby ich uszkodzeń. Następnie wyznaczono parametry eksploatacyjne i niezawodnościowe tych obiektów w oparciu o dane rzeczywiste, korzystając z analizy statystycznej oraz na podstawie symulacji przyszłych stanów eksploatacyjnych tego systemu. Przeprowadzono również weryfikację parametryczną i nieparametryczną empirycznych rozkładów parametrów niezawodnościowych wyznaczonych dla wybranych podzespołów systemu.

Słowa kluczowe: urządzenia sterowania ruchem kolejowym, proces eksploatacji, symulacyjne badania eksperymentalne, model symulacyjny, rozkłady czasu poprawnej pracy i czasu uszkodzeń.

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