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SELECTED ISSUES OF THE RELIABILITY AND OPERATIONAL ASSESSMENT OF A FIRE ALARM SYSTEM

WYBRANE ZAGADNIENIA OCENY NIEZAWODNOŚCIOWO-EKSPLOATACYJNEJ SYSTEMÓW SYGNALIZACJI POŻARU*

The article discusses an analysis of the operational and reliability issues, which regards selected fire alarm systems (FAS) exhibiting different functional structures. These systems are operated in a vast transport area, within a specific environment. We can distinguish three basic structures of these systems – focused, dispersed and mixed. A given system functional structure, utilized within a facility (a given area) is a function depending on the configuration, internal connections of elements and devices, and a developed fire scenario. The application of a given system structure for fire protection also depends on the legislation determining the approval of a facility (area) for use. The process of executing a scenario in the event of a fire is ensured by an algorithm implemented in the alarm central unit and other elements of the system. The implementation of all the system requirements specified within a given procedure algorithm depends on, e.g., an appropriate reliability structure and environmental conditions. The article analyses the operational process of selected FAS, which are operated within a vast transport area. It discusses the actual results of the operational process tests, e.g., repair and damage durations. Next, operational relationship graph, taking into account the conducted operational test, was developed. This enabled the determination of relationships that allow to specify the operating and reliability parameters in terms of a FAS staying in the states distinguished for the research. The FAS test methodology presented in the article, owing to meeting specific performance requirements, can be used in the course of developing a fire scenario and designing systems, taking into account various available technical solutions.

Keywords: operation, reliability, fire alarm systems.

W artykule przeprowadzono analizę problemów eksploatacyjnych i niezawodnościowych, która dotyczy wybranych systemów sygnalizacji pożaru (SSP) o różnej strukturze funkcjonalnej. Systemy te są użytkowane na rozległym obszarze transportowym, w określonym środowisku. Można wyróżnić trzy podstawowe struktury tych systemów - skupiona, rozproszona i mieszana. Dany rodzaj struktury funkcjonalnej systemu, który jest użytkowany w obiekcie (na danym obszarze) jest funkcją zależną od konfiguracji, wewnętrznych połączeń elementów i urządzeń oraz opracowanego scenariusza postępowania na wypadek pożaru. Zastosowanie danej struktury systemu do ochrony pożarowej zależy także od przepisów prawnych warunkujących dopuszczenie danego obiektu (obszaru) do użytkowania. Proces realizacji scenariusza w czasie pożaru jest gwarantowany przez algorytm zaimplementowany w centrali alarmowej oraz innych elementach systemu. Realizacja wszystkich wymagań wobec systemu określonych w danym algorytmie postępowania uwarunkowana jest np. odpowiednią strukturą niezawodnościową i warunkami środowiskowymi. W artykule przedstawiono analizę procesu eksploatacji wybranych SSP, które są użytkowane na obszarze transportowym. Zaprezentowano rzeczywiste wyniki badań procesu eksploatacji, np. czasy trwania naprawy oraz uszkodzenia. Następnie opracowano graf relacji eksploatacyjnych z uwzględnieniem przeprowadzonych badań eksploatacyjnych. Umożliwiło to wyznaczenie zależności pozwalających na określenie parametrów eksploatacyjnych i niezawodnościowych przebywania SSP w wyróżnionych do rozważań stanach. Przedstawiona w artykule metodyka badania SSP ze względu na spełnienie określonych wymagań eksploatacyjnych może być użyta podczas opracowywania scenariusza pożarowego oraz projektowania systemów z uwzględnieniem różnych dostępnych rozwiązań technicznych.

Słowa kluczowe: eksploatacja, niezawodność, systemy sygnalizacji pożaru.

1. Introduction

Transport fire alarm systems function in different, often extreme, operational condition. Type A, B fire alarm circuits, detection loops, alarm control units are located inside buildings (e.g. railway stations, signal boxes, transformer stations, switchgear), as well as outside, within an open access environment (e.g. railway stations, walkways, storage sheds, etc.) [10,11,12]. Long-term studies of the FAS operation process support the thesis that the proper functioning of these safety platforms is a reliability function of the components – sensors, modules, control units, etc. The maintenance and servicing process,

spare parts availability and conducting periodic inspections also determine an appropriate reliability level [4, 6, 16, 17, 19]. The analysis of the operational phenomena, occurring within a FAS should take into account two important issues: the reliability approach already at the stage of developing the design fire scenario, as well as the efficient operational management of these complex technical objects – i.e., for example, service availability, conducting preventive inspections and the parameters of their environments [7, 12, 16]. For this purpose, the authors of the article selected two representative FAS, which are most commonly used within vast transport areas and attempted to imitate

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie www.ein.org.pl

the occurring operational phenomena in the form of developed research models [10, 11].

Fire alarm systems are ones of the most important electronic safety systems (frequently installed at facilities due to the applicable statutory and legal requirements), which are operated within vast transport areas. The proper functioning of safety platforms involves the implementation of a previously assumed transport process with an acceptable risk level of adverse external and internal impacts (e.g. fire, burglary, assault, terrorist attack, etc.). [6, 16, 19]. The unreliability of individual electronic devices and systems, as well as the mistakes of operators supervising the operational process in real-time can lead to the occurrence of safety hazard or unreliability states [5, 8, 18, 21]. The safety and risk theory answers, e.g. questions regarding the effects of failures, damage and operator mistakes. This is the cause for unacceptable states within these systems, e.g., unreliability or safety hazard. An important issue, which should be clarified by safety platform operators is the determination of a set of acceptable and unacceptable FAS states in terms of the safety of a given transport facility. [6, 16, 19, 23, 28, 29]. The scope of interest of the theory of safety and risk includes the results of damage and errors, which lead to the states of safety unreliability and hazard of the systems. The issue of correct clarification, which of the FAS states can be deemed acceptable or unacceptable from the perspective of safety or the initial fire scenario developed for a transport facility is very significant in this case [10, 11, 12, 16, 19].

A set of unacceptable states of an FAS can be reversible in the event of such a system having elements or devices, which initiate or interrupt a damage or failure process (including faulty operator actions) [6, 16, 19]. The counter-actions must be executed during the available time, where there is a possibility to remedy a dangerous situation [16]. Such actions are possible when safety platforms have a “reservoir” of permissible counter-failure operations. In such a case, it is impossible to move from permissible (e.g. surveillance) to prohibited (e.g. failure of a module or control unit – safety hazard state) states [6, 10, 11, 16, 19].

The service life of safety platforms in the case of adverse impacts can be increased by executing the available actions, e.g. by using redundancy or technical solutions improving the reliability of the devices themselves [10, 12, 16, 19]. A sensor(s) that uses numerous detectors reacting to the phenomenon of fire. Using redundancy means tolerating certain damage, as well as system expansion. The second case is preventing catastrophic damage, e.g. sensors within the system.

The quality of information [13, 14, 15, 16, 20] received by the systems from detectors [10, 11], installed over a vast transport area with a distorted electromagnetic environment (high levels of interfering signals) is also important. Certain research papers propose the application of fuzzy logic [22] or artificial neural networks [6, 13, 14, 15, 16, 23, 24], which are already used in detectors for developing alarm signals [10, 11]. The functionality of electronic transport systems is also significantly impacted by environmental conditions, temperature, humidity, vibrations and oscillations [3], as well as electromagnetic interference [1, 7, 18, 20, 21] but they are not included in this article. The article presents an operational and reliability analysis of a FAS, operated over a vast transport area. The analysis of the obtained results regarding the operational process, i.e., the measurement of times of restoration and damage occurrence enabled developing a FAS research model, and then, conducting an operational and reliability analysis taking into account the determined restoration and damage times [2, 8, 9, 16, 17, 19, 26, 28].

2. Representative transport fire alarm systems.

In the age of rapid technological progress and a constant development of the infrastructure, transport facilities are exposed to numerous hazards [6, 16, 19, 25, 26, 27]. The hazards not directly associated with fire, such as the threat of terrorism, can be its source [6, 16, 19]. This is why, a correct protection of transport facilities using active and passive fire safety equipment is an extremely important issue – Fig. 1.

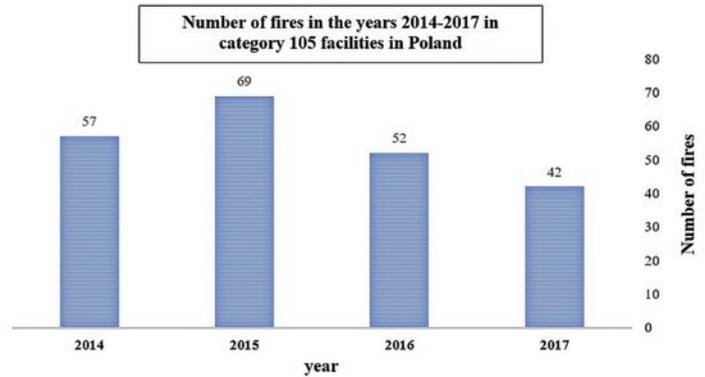


Fig. 1. Statistics regarding the number of fires in passenger service facilities, railway and bus stations, river and sea ports, and airports in particular, 2014-2017

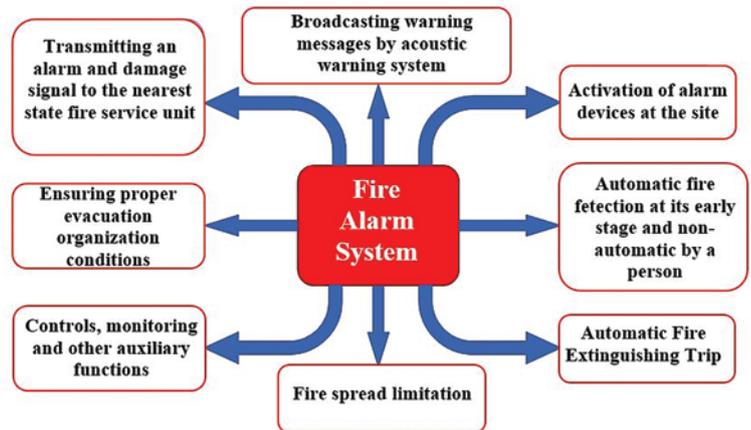


Fig. 2. Basic tasks executed by a fire alarm system.

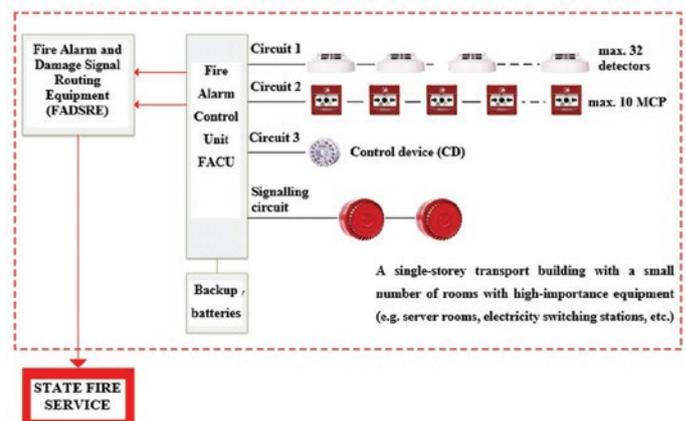


Fig. 3. Focused FAS with open detection circuits connected to an SFS fire signal and damage signal monitoring system (FACU – fire alarm control unit)

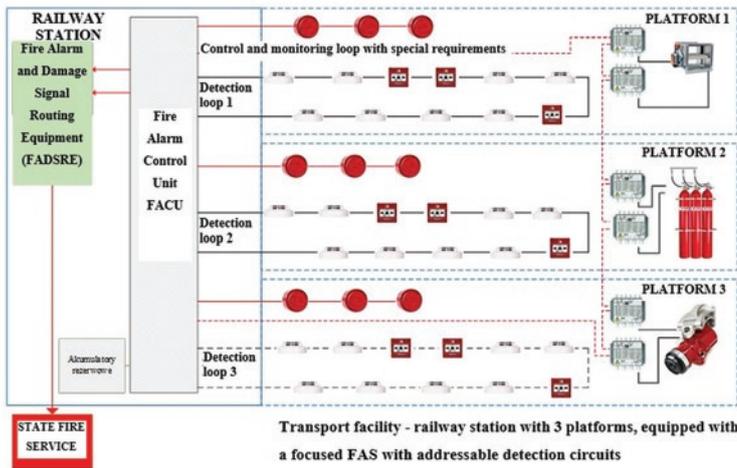


Fig. 4. Diagram of a focused fire alarm system with addressable detection circuits at a railway station with three platforms

According to the Regulation of the Minister of Interior and Administration (MSWiA) Dz. U. No. 109, item 719, by technical fire safety measures one should understand devices, equipment, systems and construction solutions designed to prevent the formation and spread of fires. The regulation understands fire safety equipment to be devices (fixed or semi-fixed, activated manually or automatically) aimed at preventing the formation of, detecting and fighting a fire or limiting its results. In particular, these include fixed and semi-fixed extinguishing and protecting devices, inerting devices, devices being part of an acoustic warning system (AWS) and FAS. FAS is a system, which includes signalling-alarm devices intended for automatic detection and transmittance of fire information, as well as receivers of fire alarms and receivers for damage signals – Figure 2 [6, 10, 11, 16, 19].

Several FAS types depending on the design, configuration and type of used linear elements are distinguished – Figure 3. The application of a given FAS type depends on the legal requirements for such systems, a fire scenario, which must be implemented, legal requirements for a given facility subject to protection, the adopted protection scope and the functional and utility requirements, which must be satisfied by the system. The fire origin (fire source) location indication accuracy depends on the used FAS. On the other hand, the requirement regarding the fire location accuracy is a criterion for the selection of a fire alarm system [10, 12].

In the case of a conventional (non-addressable) FAS, indicating the fire detection location, is limited to the detection circuit, whereas in the case of an addressable system, the control unit indicates the fire source location with an accuracy down to a fire detector (depending on the configuration, down to a fire zone) [11, 12]. The type of an FAS installed at a transport facility impacts its division into the so-called detection zones. The control and monitoring loop must be executed in accordance with the special requirements, and in a manner so as to maintain the power supply or signal transmission continuity for the time period required for device commissioning and operation, pursuant to §187 art. 2 of the Regulation by the Minister of Infrastructure of 12 April 2002 (Dz. U. No. 75, item 690, as amended) [10, 11, 12, 16].

Due to the small extent of the transport facility, short distance of the loop cabling routes and a low number of controls and monitoring devices, often a single control and monitoring loop is used, which can handle e.g. all platforms – Figure 4.

3. The analysis of selected fire alarm system reliability and operational process

A focused fire alarm system based on a conventional fire alarm control unit with a single detection open circuit equipped with a maximum of 32 fire detectors and a signalling circuit with two sounders is shown in Figure 5. Whereas Figure 6 shows the relationships occurring within a focused system with a fire alarm control unit with connected open detection circuit with optical smoke detectors and a signalling circuit with sounders.

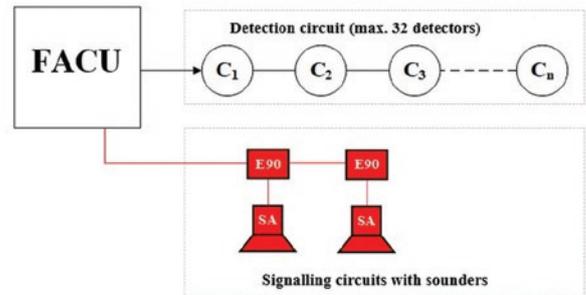


Fig. 5. Focused FAS with an open detection circuit and a signalling circuit with sounders

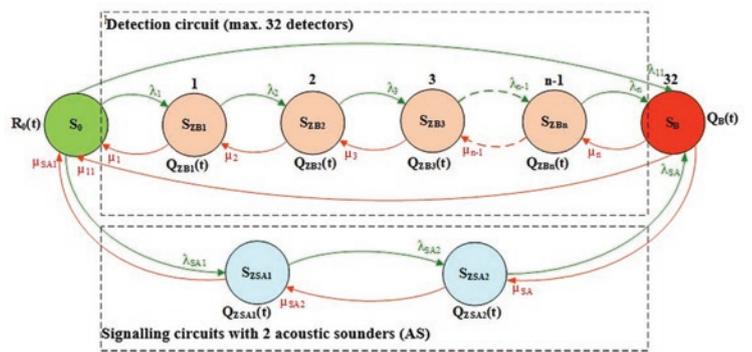


Fig. 6. Relationships occurring within a focused system with a fire alarm control unit with connected open detection circuit with optical smoke detectors and a signalling circuit with sounders

Relationships occurring within a system – fig. 6 can be described with the following relations [10, 19] (1):

$$\begin{aligned}
 R_0'(t) &= -\lambda_{11} \cdot R_0(t) - \lambda_1 \cdot R_0(t) - \lambda_{SA1} \cdot R_0(t) + \mu_{11} \cdot Q_B(t) + \mu_1 \cdot Q_{ZB1}(t) + \mu_{SA1} \cdot Q_{ZSA1}(t) \\
 Q'_{ZB1}(t) &= -\lambda_2 \cdot Q_{ZB1}(t) - \mu_1 \cdot Q_{ZB1}(t) + \lambda_1 \cdot R_0(t) + \mu_2 \cdot Q_{ZB2}(t) \\
 Q'_{ZB2}(t) &= -\lambda_3 \cdot Q_{ZB2}(t) - \mu_2 \cdot Q_{ZB2}(t) + \lambda_2 \cdot Q_{ZB1}(t) + \mu_3 \cdot Q_{ZB3}(t) \\
 Q'_{ZB3}(t) &= -\lambda_{n-1} \cdot Q_{ZB3}(t) - \mu_3 \cdot Q_{ZB3}(t) + \lambda_3 \cdot Q_{ZB2}(t) + \mu_{n-1} \cdot Q_{ZBn}(t) \\
 \dots \\
 Q'_{ZBn}(t) &= -\lambda_n \cdot Q_{ZBn}(t) - \mu_{n-1} \cdot Q_{ZBn}(t) + \lambda_{n-1} \cdot Q_{ZB3}(t) + \mu_n \cdot Q_B(t) \\
 Q'_{ZSA1}(t) &= -\lambda_{SA2} \cdot Q_{ZSA1}(t) - \mu_{SA1} \cdot Q_{ZSA1}(t) + \lambda_{SA1} \cdot R_0(t) + \mu_{SA2} \cdot Q_{ZSA2}(t) \\
 Q'_{ZSA2}(t) &= -\lambda_{SA} \cdot Q_{ZSA2}(t) - \mu_{SA2} \cdot Q_{ZSA2}(t) + \lambda_{SA2} \cdot Q_{ZSA1}(t) + \mu_{SA} \cdot Q_B(t) \\
 Q'_B(t) &= -\mu_{11} \cdot Q_B(t) - \mu_n \cdot Q_B(t) - \mu_{SA} \cdot Q_B(t) + \lambda_{11} \cdot R_0(t) + \lambda_n \cdot Q_{ZBn}(t) + \lambda_{SA} \cdot Q_{ZSA2}(t)
 \end{aligned}
 \tag{1}$$

Adopting the baseline conditions [10, 19] (2):

$$R_0(t) = 1$$

$$Q_{ZB1}(0) = Q_{ZB2}(0) = Q_{ZB3}(0) = \dots = Q_{ZBn}(0) = Q_B(0) = Q_{ZSA1}(0) = Q_{ZSA2}(0) = 0 \quad (2)$$

where [10,19]:

- $R_0(t)$ – probability function of the system staying in the state of full fitness S_{PZ} ;
- $Q_{ZB1}(t), Q_{ZBn}(t), Q_{ZSA1}(t), Q_{ZSA2}(t)$ – probability function of the system staying in individual safety hazard states;
- $Q_B(t)$ – probability function of the system staying in the state of safety unreliability S_B ;
- λ_{11} – intensity of transition from the state of full fitness S_{PZ} to the state of safety unreliability S_B ;
- μ_{11} – intensity of transition from the state of safety unreliability S_B to the state of full fitness S_{PZ} ;
- $\lambda_1, \lambda_1, \dots$ – intensity of transitions from the state of full fitness S_{PZ} or the state of safety hazard $S_{ZB1,2,\dots}$ to the state of safety unreliability $Q_B(t)$ or the state safety hazard or the state of safety reliability S_{ZB} – according to the designation in Figure 6;
- μ_1, μ_2, \dots – intensity of transitions from the state of safety hazard S_{ZB} to the state of full fitness S_{PZ} , from the state of safety unreliability to the state of safety hazard $Q_{ZBn}, Q_{ZB}, Q_{ZB2}, \dots$ – according to the designations as in Figure 6.

Figure 7 shows a focused FAS, based on an addressable FACU, with connected open detector and manual call point circuits. All elements are equipped with short-circuit isolators. The system consists of loop circuits, some of which have programmed detectors in coincidence systems, a control loop with a module controlling fire safety devices, as well as technical and safety systems within the signal box room. A signalling circuit with sounders is also hooked in to the control unit [6, 10, 11, 12].

Figure 7 shows the relationships occurring within a focused system with an addressable fire alarm control unit with looped open circuits and a signalling circuit. The system presented in Fig. 7 can be described by the following Chapman–Kolmogorov equations (3). The relationships occurring within a focused system are shown in Fig. 8.

Owing to the various structures of FASs operated within a vast transport area, the relationships between individual devices in the system can differ, which is shown in Figures 6 and 8. The

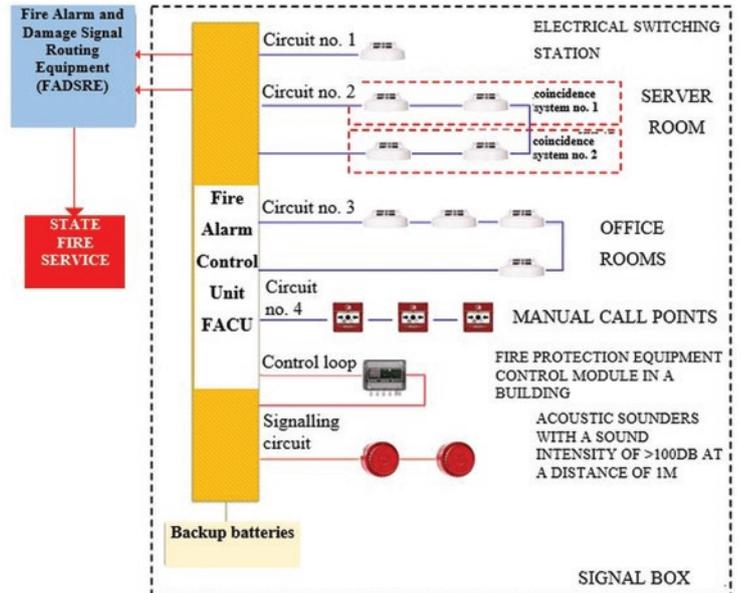


Fig. 7. Focused FAS with addressable fire alarm control units with open, looped circuits and a signalling circuit

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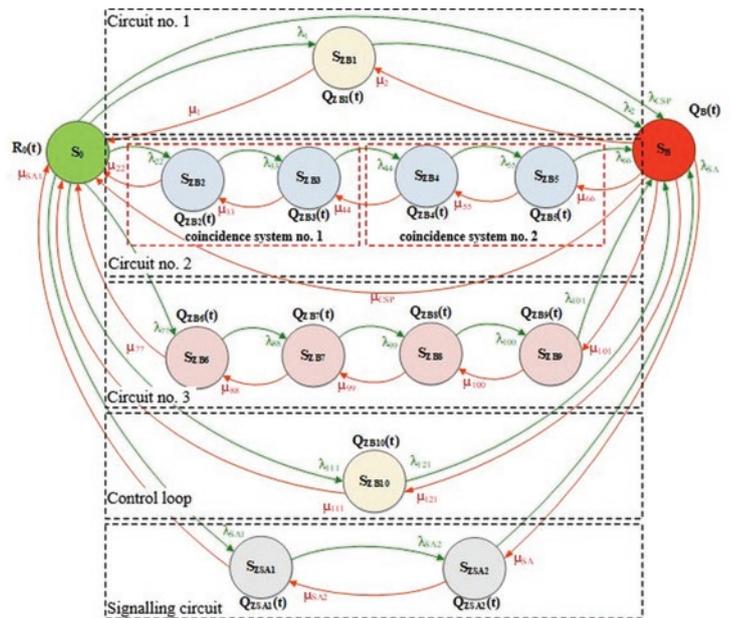


Fig. 8. Relationships occurring within a focused system with addressable fire alarm control unit with open, looped circuits and a signalling circuit

Table 1. Studying the operational process of FASs used in transport facilities

No.	Damage type	Failure time	Failure removal time	Repair duration	Repair type
1	Circuit no. 3 interference	3/1/2018 14:32	03/01/2018 18:10	3h 38 min.	Improving the tie-in of the circuit to control unit terminals and control unit reset
2	Failure of detector 3/57	1/2/2018 18:10	2/2/2018 23:30	5h 20 min.	Replacing detector with a new one
n-2	Circuit no. 1 interference	1/12/2018 04:15	1/12/2018 09:00	4h 45 min.	Central unit reset
n-1	Failure of detector 3/11	15/12/2018 11:15	15/12/2018 14:20	4h 5 min.	Replacing detector socket
n	CSO2 communication error	27/12/2018 15:05	28/12/2018 09:05	18h 5 min.	CSO2 and fire alarm control unit

system shown in Figure 7 has a more complex reliability structure due to the presence of more fire-protected objects – server rooms, office areas and an electrical switching station. For this reason, separate detection circuits 1, 2 and 3, a control loop and a signalling circuit can be distinguished. In addition, the detection circuit no. 2 utilizes alarms in the coincidence system. In the case of such a designed FAS, one should distinguish more operating states, which is why the system of equations (3) describing the behaviour of the system within the operational process becomes complex.

$$\begin{aligned}
 R_0'(t) = & -\lambda_{CSP} \cdot R_0(t) - \lambda_1 \cdot R_0(t) - \lambda_{22} \cdot R_0(t) - \lambda_{77} \cdot R_0(t) - \lambda_{111} \cdot R_0(t) - \lambda_{SA1} \cdot R_0(t) + \\
 & + \mu_{CSP} \cdot Q_B(t) + \mu_1 \cdot Q_{ZB1}(t) + \mu_{22} \cdot Q_{ZB2}(t) + \mu_{77} \cdot Q_{ZB6}(t) + \mu_{111} \cdot Q_{ZB10}(t) + \mu_{SA1} \cdot Q_{ZSA1}(t) \\
 Q'_{ZB1}(t) = & -\mu_1 \cdot Q_{ZB1}(t) - \lambda_2 \cdot Q_{ZB1}(t) + \mu_2 \cdot Q_B(t) + \lambda_1 \cdot R_0(t) \\
 Q'_{ZB2}(t) = & -\mu_{22} \cdot Q_{ZB2}(t) - \lambda_{33} \cdot Q_{ZB2}(t) + \mu_{33} \cdot Q_{ZB3}(t) + \lambda_{22} \cdot R_0(t) \\
 Q'_{ZB3}(t) = & -\mu_{33} \cdot Q_{ZB3}(t) - \lambda_{44} \cdot Q_{ZB3}(t) + \mu_{44} \cdot Q_{ZB4}(t) + \lambda_{33} \cdot Q_{ZB2}(t) \\
 Q'_{ZB4}(t) = & -\mu_{44} \cdot Q_{ZB4}(t) - \lambda_{55} \cdot Q_{ZB4}(t) + \mu_{55} \cdot Q_{ZB5}(t) + \lambda_{44} \cdot Q_{ZB3}(t) \\
 Q'_{ZB5}(t) = & -\mu_{55} \cdot Q_{ZB5}(t) - \lambda_{66} \cdot Q_{ZB5}(t) + \mu_{66} \cdot Q_B(t) + \lambda_{55} \cdot Q_{ZB4}(t) \\
 Q'_{ZB6}(t) = & -\mu_{77} \cdot Q_{ZB6}(t) - \lambda_{88} \cdot Q_{ZB6}(t) + \mu_{88} \cdot Q_{ZB7}(t) + \lambda_{77} \cdot R_0(t) \\
 Q'_{ZB7}(t) = & -\mu_{88} \cdot Q_{ZB7}(t) - \lambda_{99} \cdot Q_{ZB7}(t) + \mu_{99} \cdot Q_{ZB8}(t) + \lambda_{88} \cdot Q_{ZB6}(t) \\
 Q'_{ZB8}(t) = & -\mu_{99} \cdot Q_{ZB8}(t) - \lambda_{100} \cdot Q_{ZB8}(t) + \mu_{100} \cdot Q_{ZB9}(t) + \lambda_{99} \cdot Q_{ZB7}(t) \\
 Q'_{ZB9}(t) = & -\mu_{100} \cdot Q_{ZB9}(t) - \lambda_{101} \cdot Q_{ZB9}(t) + \mu_{101} \cdot Q_B(t) + \lambda_{100} \cdot Q_{ZB8}(t) \\
 Q'_{ZB10}(t) = & -\mu_{111} \cdot Q_{ZB10}(t) - \lambda_{121} \cdot Q_{ZB10}(t) + \mu_{121} \cdot Q_B(t) + \lambda_{111} \cdot R_0(t) \\
 Q'_{ZSA1}(t) = & -\mu_{SA1} \cdot Q_{ZSA1}(t) - \lambda_{SA2} \cdot Q_{ZSA1}(t) + \mu_{SA2} \cdot Q_{ZSA2}(t) + \lambda_{SA1} \cdot R_0(t) \\
 Q'_{ZSA2}(t) = & -\mu_{SA2} \cdot Q_{ZSA2}(t) - \lambda_{SA} \cdot Q_{ZSA2}(t) + \mu_{SA} \cdot Q_B(t) + \lambda_{SA2} \cdot Q_{ZSA1}(t) \\
 Q'_B(t) = & -\mu_{CSP} \cdot Q_B(t) - \mu_2 \cdot Q_B(t) - \mu_{66} \cdot Q_B(t) - \mu_{101} \cdot Q_B(t) - \mu_{121} \cdot Q_B(t) - \mu_{SA} \cdot Q_B(t) + \\
 & + \lambda_{CSP} \cdot R_0(t) + \lambda_2 \cdot Q_{ZB1}(t) + \lambda_{66} \cdot Q_{ZB5}(t) + \lambda_{101} \cdot Q_{ZB9}(t) + \lambda_{121} \cdot Q_{ZB10}(t) + \lambda_{SA} \cdot Q_{ZSA2}(t)
 \end{aligned} \tag{3}$$

Adopting the baseline conditions (4):

$$\begin{aligned}
 R_0(t) &= 1 \\
 Q_{ZB1}(0) &= Q_{ZB2}(0) = Q_{ZB3}(0) = Q_{ZB4}(0) = Q_{ZB5}(0) = Q_{ZB6}(0) = Q_{ZB7}(0) = \\
 &= Q_{ZB8}(0) = Q_{ZB9}(0) = Q_{ZB10}(0) = Q_{ZSA1}(0) = Q_{ZSA2}(0) = Q_B(0) = 0
 \end{aligned}$$

4. Operational statistics (repairs, damage) regarding representative FAS

The analysis in the scope of FAS operational process was conducted for n=20 various systems. The structure of the studied FAS corresponded to the fire safety systems used at transport facilities. The FAS operational studies covered: restoration, damage occurrence time and repair time.

Table 2. Repair time with the maximum time T_{max} annualized

No.	Repair of a given damage type	Failure time	Failure removal time	Maximum repair time [T _{max}]
Detection loop 1 damage				
	Circuit no. 3 interference	3/1/2018 14:32	3/1/2018 18:10	3h 38 min.
	Circuit no. 2 interference	11/3/2018 15:00	11/3/2018 16:30	1h 30 min.
	Ground fault of loop no. 1	2/5/2018 13:30	2/5/2018 19:00	5h 30 min.
	Circuit no. 1 interference	1/12/2018 04:15	1/12/2018 09:00	4h 45 min.
	Communication error loop 1	30/11/2018 10:30	30/11/2018 14:30	4h
Manual call point damage				
	Failure of MCP 1/10	15/6/2018 09:20	15/6/2018 13:20	4h
	Failure of MCP 1/10	16/6/2018 14:00	16/6/2018 19:05	5h 5 min.
FAS power supply failure				
	230V power failure	27/2/2018 11:30	27/2/2018 11:45	15 min.
	FACU battery failure	16/4/2018 19:00	17/4/2018 08:10	13h 10 min.

The studies were conducted for the following FAS types operated within a transport area:

- FAS with an addressable fire alarm control unit and one detection loop (n=15 units);
- FAS with an addressable fire alarm control unit and two detection loops (n=3 units);
- FAS with an addressable FACU, three detection loops, one control-detection loop for monitoring fixed extinguishing devices and generating their tripping signal (n=2 units).

All of the aforementioned FAS were operated in similar environmental conditions (temperature, humidity, pressure, etc.) in transport buildings. Owing to the importance of FAS in ensuring the transport process safety, the service team dealing with repairs and restorations was available within 2 hours from the damage being reported by persons monitoring the operation (for n=15 FAS). Other systems (n=5) had the damage report response time extended to 4 hours due to the supervision over transport facilities – buildings, which do not pose a direct threat for the passenger transport (e.g. warehouses, sheds, etc.). Tables 1-3 show examples of the FAS operational process study results.

Table 1 shows representative types of damage for selected FAS. The data were compiled based on a set of damage for n = 20 FAS, operated over a vast transport area. A maximum repair time was adopted for a given type of FAS damage (n=20 units). The repair time does not include the service personnel travel time (in the case of such FAS, such personnel should be on site).

5. FAS operational process modelling in the RELIASOFT BLOCKSIM software

Calculations involving the probability for a system to be in the states of safety hazard, safety unreliability and full fitness for the FAS operational process model were conducted using a commercial, specialized computational BlockSim software by ReliaSoft. The computations were conducted for a focused FAS model – open circuits, no notifications. Tables 4 and 5 show the calculated parameters, e.g. initial and average probability, availability coefficient for time t for individual states or time the FAS spends in a given state.

For the example operating time t = 4 201 h, the values of the availability coefficient $K_g(t)$ for individual states S_B , S_{ZB1} , S_{ZB2} , S_{ZB3} , S_{ZBP1} , S_{ZBP2} of a fire alarm system are shown in table 6, and the percentage share of FAS in individual states in Figure 12. Figure 13 shows the growth rate of state availability coefficient for a selected FAS operating interval.

Table 3. Damage intensity along with marked times of fire alarm system unfitness, annualized (example).

No.	Repair of a given damage type	Failure time	Failure removal time	Repair time [T _{max}]
Detection loop damage				
1.	Circuit no. 3 interference	3/1/2018 14:32	3/1/2018 18:10	3h 38 min.
2.	Ground fault of loop no. 1	2/5/2018 13:30	2/5/2018 19:00	5h 30 min.
3.	Circuit no. 1 interference	1/12/2018 04:15	1/12/2018 09:00	4h 45 min.
4.	Communication error loop 1	30/11/2018 10:30	30/11/2018 14:30	4h
Total FAS unfitness time, annualized:				19h 23 min.
FAS power supply failure				
1.	230V power failure	27/2/2018 11:30	27/2/2018 11:45	15 min.
2.	FACU battery failure	16/4/2018 19:00	17/4/2018 08:10	13h 10 min.
Total FAS unfitness time, annualized:				13h 25 min.

Table 4. Fire alarm system parameters for time t = 8 760 [h]

Name of state	Initial probability	Average probability	Availability for time t [8760 h]	Reliability for time t	Time in a given state
S ₀	1	0,999993444	0,999993439	0,991489928	8759,94257
S _B	0	2,245 E-07	2,24528 E-07	0,001526641	0,001966621
S _{ZBI}	0	3,75408 E-06	3,75731 E-06	0,003920964	0,032885763
S _{ZBI2}	0	8,25865 E-07	8,26355 E-07	0,001033117	0,00723458
S _{ZBI3}	0	7,10979 E-07	7,11386 E-07	0,000996234	0,006228174
S _{ZBP1}	0	8,16121 E-07	8,16726 E-07	0,001033117	0,007149221
S _{ZBP2}	0	2,24374 E-07	2,24529 E-07	0	0,001965516

Table 5. Intensity matrix for individual FAS states for t = 8 760 [h]

From → to	S ₀	S _B	S _{ZBI}	S _{ZBI2}	S _{ZBI3}	S _{ZBP1}	S _{ZBP2}
S ₀	-	1,7502 E-07	4,49514 E-07	1,1844 E-07	1,14212 E-07	1,1844 E-07	0
S _B	0,0759	-	0,1818	0,1968	0,125	0	0,2
S _{ZBI}	0,1305	2,52906 E-07	-	0	0	0	0
S _{ZBI2}	0,1968	5,70919 E-08	0	-	0	0	0
S _{ZBI3}	0,2	1,4161 E-08	0	0	-	0	0
S _{ZBP1}	0,2	0	0	0	0	-	1,18 E-07
S _{ZBP2}	0	1,4161 E-08	0	0	0	0,2	-

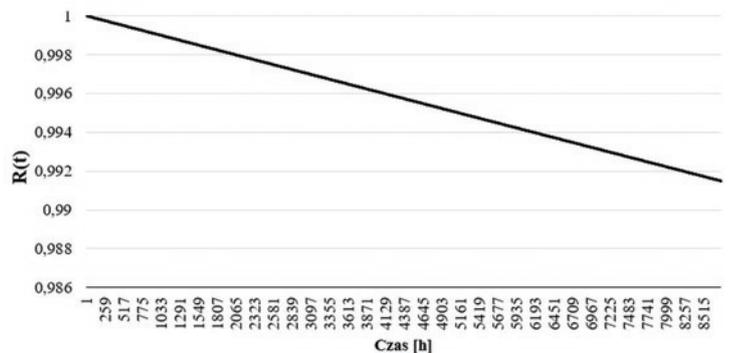
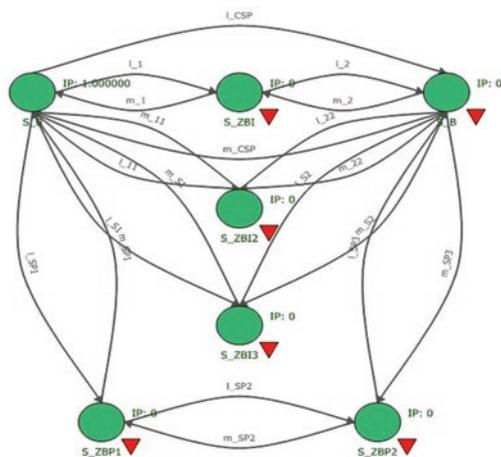


Fig. 10. Reliability R(t) of a FAS with open circuits, without SFS notifications

Fig. 9. Migration of possible focused FAS with open circuits, without notifying the SFS (where: SFS – State Fire Service).

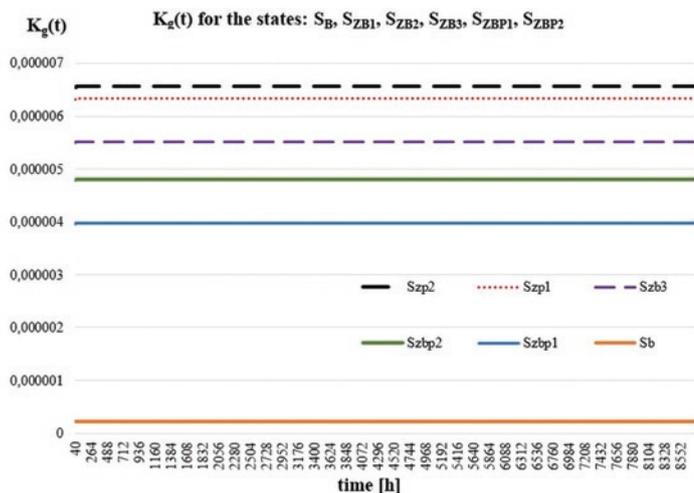


Fig. 11. Zonal (partial) availability coefficient for the states of $S_B, S_{ZB1}, S_{ZB2}, S_{ZB3}, S_{ZBP1}, S_{ZBP2}$ SSP (safety unreliability and hazard); the graph does not show state S_0 (for $t = 0, S_0(t) = 1$)

Tab. 6. Values of $K_g(t)$ coefficient for individual FAS over time

Time [h]	Fire alarm system state					
	S_B	S_{ZB1}	S_{ZB2}	S_{ZB3}	S_{ZBP1}	S_{ZBP2}
	Value of coefficient $K_g(t)$					
4 201	$2245282 \cdot 10^{-6}$	$3757312 \cdot 10^{-5}$	$82635535 \cdot 10^{-6}$	$71138635 \cdot 10^{-6}$	$81672633 \cdot 10^{-6}$	$2245287 \cdot 10^{-6}$

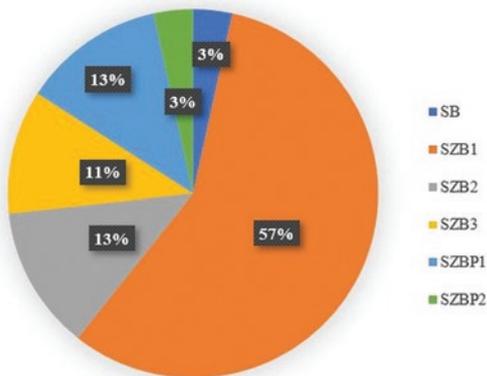


Fig. 12. Percentage share of FAS staying in a given state, according to table 6

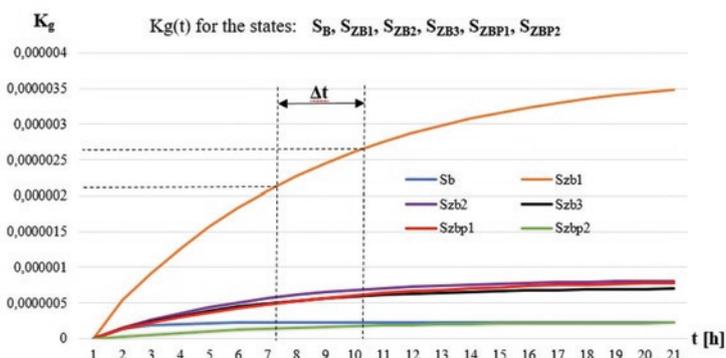


Fig. 13. Growth rate for the availability coefficients of states $S_B, S_{ZB1}, S_{ZB2}, S_{ZB3}, S_{ZBP1}, S_{ZBP2}$ of a fire alarm system (safety unreliability and hazard); the graph does not show the state S_0 (for $t = 0, K_g(t) = 1$), adopted time $t = 21$ h in order to reflect the parameter change rates at the initial stage of transition state changes

The growth rate of a zonal availability coefficient for an individual state can be expressed using the formula (5):

$$S_{ZB1} = \frac{\Delta K_{g_{SZB1}}}{\Delta t} \left[\frac{1}{h} \right] \tag{5}$$

$$S_{ZB1} = \frac{(2,75466E-6) - (2,27438E-6)}{10,25 - 7,25} = 1,08915E-10 \left[\frac{1}{h} \right]$$

The growth rate values for the availability coefficient K_g for other fire alarm system states are shown in table 7 and Figure 14. Fig. 15 shows the probability of a FAS staying in individual states.

Growth rate $R(t)$ over time Δt for a particular state is described using the formula (6):

$$S_{ZB1} = \frac{\Delta R(t)_{SZB1}}{\Delta t} \left[\frac{1}{h} \right] \tag{6}$$

$$S_{ZB1} = \frac{(2,75466E - 6) - (2,27438E - 6)}{10,25 - 7,25} = 1,08915E - 10 \left[\frac{1}{h} \right]$$

Tab. 7. Growth rate of availability coefficients K_g for individual FAS states.

No.	FAS state	Growth rate S of the availability coefficient K_g [1/h]
1.	S_B	$1,37487E-10$
2.	S_{ZB1}	$2,08915E-10$
3.	S_{ZB2}	$4,99493E-11$
4.	S_{ZB3}	$2,2907E-11$
5.	S_{ZBP1}	$1,05053E-11$
6.	S_{ZBP2}	$4,81767E-12$

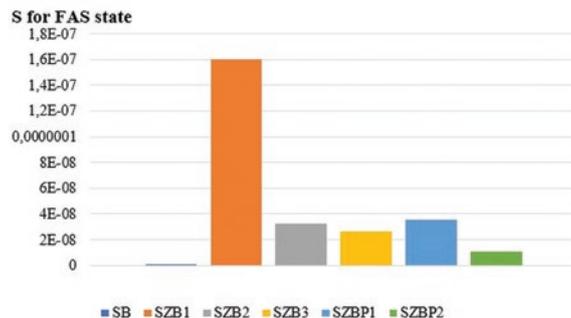


Fig. 14. Growth rate for the availability coefficients of states $S_B, S_{ZB1}, S_{ZB2}, S_{ZB3}, S_{ZBP1}, S_{ZBP2}$

6. Conclusions

Fire alarm systems operated over vast transport areas have various connection structures, which are a function of the executed tasks – fire monitoring of buildings [6, 10, 11, 12, 16].

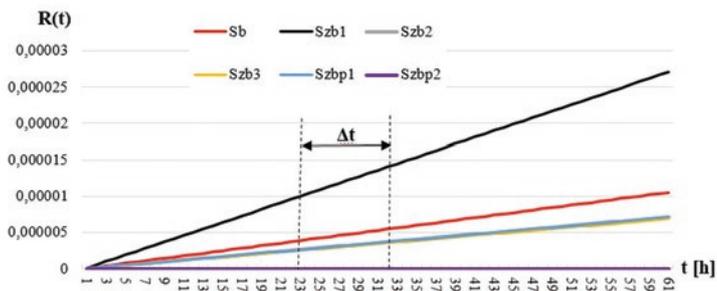


Fig. 15. Probability of an FAS staying in a state $R(t)$ for states S_B , S_{ZB1} , S_{ZB2} , S_{ZB3} , S_{ZBP1} , S_{ZBP2} ; the graph does not show $R(t)$ for the state S_0 (for $t = 0$, $R(t) = 1$), adopted time $t = 61$ h in order to depict the parameter change rate at the initial change phase

Complex FAS have a dozen or so detection loops, as well as signaller, desmoking control, gas suppression, etc. lines. Owing to the extent of the executed tasks and fire controls, the reliability and operational structure of such systems is mixed. Available technical measures are applied in order to increase FAS reliability. The article presents a model and operational and reliability analysis of a selected FAS, which is operated within a transport area. Seven operating states were distinguished for the system. The average value for the probability of a system staying in the state of fitness was $S_0 = 0,999993444$, whereas the time spent in this state was 8759, 94257 [h] (the simulation time was $t = 1$ year of FAS operation). When considering the so-called $Kgs(t)$ zonal (partial) availability coefficients for FAS states of S_B , S_{ZB1} , S_{ZB2} , S_{ZB3} , S_{ZBP1} , S_{ZBP2} it can be observed, that the S_{ZBP2} state is dominant at the initial operational stage. Therefore, when designing

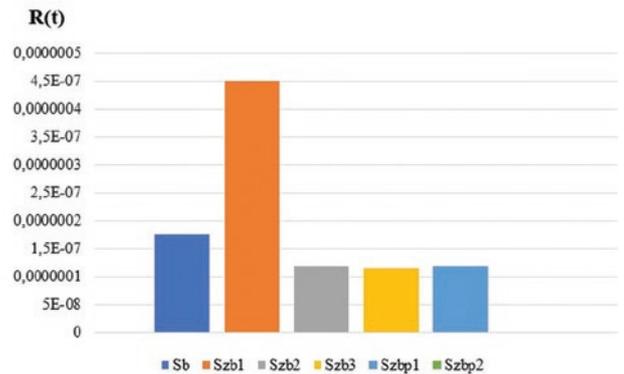


Fig. 16. Growth rate $R(t)$ values over time for selected FAS states

a FAS, particular attention to the transition between the states of fitness S_0 and the state of safety hazard S_{ZBP2} should be paid. In order to depict the parameter change rates at the initial stage of transition state changes, the growth rate for the availability coefficients for FAS states of S_B , S_{ZB1} , S_{ZB2} , S_{ZB3} , S_{ZBP1} , S_{ZBP2} was determined. At the initial FAS operational stage, the highest value was obtained for the state $S_{ZB1} = 2,08915E-10$ [1/h]. All zonal (so-called partial) availability coefficients stabilize their values throughout the further periods of the operational process – Fig. 1. The $R(t)$ probability of a FAS staying in a state is very low for individual states S_B , S_{ZB1} , S_{ZB2} , S_{ZB3} , S_{ZBP1} , S_{ZBP2} during the initial operational period – Fig. 15. The highest growth rate of the $R(t)$ value during the initial operational process was exhibited by FAS state S_{ZB1} .

References

- Białek K, Paś J. Exploitation of selected railway equipment - conducted disturbance emission examination, *Diagnostyka* 2018; 19(3): 29-35, <https://doi.org/10.29354/diag/92003>.
- Branson D. Stirling numbers and Bell numbers, their role in combinatorics and probability, *Math. Scientist* 2000; 25: 1-31.
- Burdzik R, Konieczny Ł, Figlus T. Concept of on-board comfort vibration monitoring system for vehicles, In the monograph *Activities of Transport Telematics*, editors: Mikulski J, Springer 2013: 418-425, https://doi.org/10.1007/978-3-642-41647-7_51.
- Duer S, Zajkowski K, Duer R, Paś J. Designing of an effective structure of system for the maintenance of a technical object with the using information from an artificial neural network, *Neural Computing & Applications* 2012; 23(3): 913-925, <https://doi.org/10.1007/s00521-012-1016-0>.
- Duer S, Scaticailov S, Paś J, Duer R, Bernatowicz D. Taking decisions in the diagnostic intelligent systems on the basis information from an artificial neural network, *22nd International Conference on Innovative Manufacturing Engineering and Energy, MATEC Web of Conferences* 178, 2018; 178: 1-6, <https://doi.org/10.1051/mateconf/201817807003>.
- Dyduch J, Paś J, Rosiński A. The basic of the exploitation of transport electronic systems, Radom: Publishing House of Radom University of Technology, 2011.
- Dziula P, Paś J. Low Frequency Electromagnetic Interferences Impact on Transport Security Systems Used in Wide Transport Areas, *TransNav the International Journal on Marine Navigation and Safety of Sea Transportation* 2018, 12(2): 251-258, <https://doi.org/10.12716/1001.12.02.04>.
- Garmabaki A H S, Ahmadi A, Mahmood Y A, Barabadi A. Reliability modelling of multiple repairable units, *Quality and Reliability Engineering International* 2016; 32(7): 2329-2343, <https://doi.org/10.1002/qre.1938>.
- Jachimowski R, Żak J, Pyza D. Routes planning problem with heterogeneous suppliers demand, *21st International Conference on Systems Engineering, Las Vegas, USA 2011*: 434-437, <https://doi.org/10.1109/ICSEng.2011.85>.
- Klimczak T, Paś J. Analysis of reliability structures for fire signaling systems in the field of fire safety and hardware requirements, *Journal of KONBIN* 2018; (64): 191-214, <https://doi.org/10.2478/jok-2018-0030>.
- Klimczak T, Paś J. Analysis of solution of a fire signaling system for a choice railway building, *Biuletyn WAT* 2018; (67)4: 195-205, <https://doi.org/10.5604/01.3001.0012.8515>.
- Klimczak T, Paś J. Electromagnetic environment on extensive logistic areas and the proces of using electronic safety system, *Politechnika Warszawska, Prace Naukowe Transport* 2018; (121): 135-146.
- Krzykowski M, Paś J, Rosiński A. Assessment of the level of reliability of power supplies of the objects of critical infrastructure, *IOP Conf. Series: Earth and Environmental Science* 2019: 1-9, <https://doi.org/10.1088/1755-1315/214/1/012018>.
- Lewiński A, Perzyński T, Toruń A. The analysis of open transmission standards in railway control and management, *Communications in Computer and Information Science, Berlin Heidelberg Springer-Verlag*, 2012; 329: 10-17, https://doi.org/10.1007/978-3-642-34050-5_2.

15. Łubkowski P, Laskowski D. Selected issues of reliable identification of object in transport systems using video monitoring services, *Communication in Computer and Information Science*, Berlin Heidelberg Springer, 2015, Vol. 471: 59-68. https://doi.org/10.1007/978-3-662-45317-9_7
16. Paś J. Operation of electronic transportation systems. Radom: Publishing House University of Technology and Humanities, 2015.
17. Paś J, Duer S. Determination of the impact indicators of electromagnetic interferences on computer information systems. *Neural Computing & Applications* 2012; 23(7): 2143-2157, <https://doi.org/10.1007/s00521-012-1165-1>.
18. Paś J, Rosiński A. Selected issues regarding the reliability-operational assessment of electronic transport systems with regard to electromagnetic interference. *Eksploatacja i Niezawodność - Maintenance and Reliability* 2017; 19(3): 375-381, <https://doi.org/10.17531/ein.2017.3.8>.
19. Rosiński A. Modelling the maintenance process of transport telematics systems. Warsaw: Publishing House Warsaw University of Technology, 2015.
20. Siergiejczyk M, Paś J, Rosiński A. Train call recorder and electromagnetic interference, *Diagnostyka*, 2015, 16(1): 19-22.
21. Siergiejczyk M, Paś J, Rosiński A. Issue of reliability-exploitation evaluation of electronic transport systems used in the railway environment with consideration of electromagnetic interference, *IET Intelligent Transport Systems* 2016;10(9): 587-593, <https://doi.org/10.1049/iet-its.2015.0183>.
22. Skorupski J, Uchroński P. A fuzzy reasoning system for evaluating the efficiency of cabin luggage screening at airports, *Transportation Research Part C - Emerging Technologies* 2015; (54): 157-175, <https://doi.org/10.1016/j.trc.2015.03.017>.
23. Stawowy M. Model for information quality determination of teleinformation systems of transport, In: *Proceedings of the European Safety and Reliability Conference ESREL 2014*, CRC Press/Balkema 2015: 1909-1914, <https://doi.org/10.1201/b17399-261>.
24. Stawowy M, Kasprzyk Z. Identifying and simulation of status of an ICT system using rough sets, *Tenth International Conference on Dependability and Complex Systems DepCoS-RELCOMEX*, given as the monographic publishing series - "Advances in intelligent systems and computing", Springer 2015; 365: 477-484, https://doi.org/10.1007/978-3-319-19216-1_45.
25. Warczek J, Młyńczak J, Celiński I. Simulation studies of a shock absorber model proposed under conditions of different kinematic input functions, *Vibroengineering Procedia* 6, 2015: 248-253.
26. Weintrit A, Dziula P, Siergiejczyk M, Rosiński A. Reliability and exploitation analysis of navigational system consisting of ECDIS and ECDIS back-up systems, *The monograph Activities in Navigation - Marine Navigation And Safety Of Sea Transportation*, editors: Weintrit A, London: CRC Press/Balkema 2015: 109-115, <https://doi.org/10.1201/b18513-17>.
27. Weintrit A. Technical infrastructure to support seamless information exchange in e-Navigation, In: Mikulski, J. (ed.), *TST 2013*, Springer Heidelberg, CCIS 2013; 395: 188-199, https://doi.org/10.1007/978-3-642-41647-7_24.
28. Yang L, Yan X. Design for Reliability of Solid State Lighting Products, In: *Solid State Lighting Reliability*, eds: van Driel W, Fan X., *Solid State Lighting Technology and Application Series*, Springer, New York 2013; 1: 497-556, https://doi.org/10.1007/978-1-4614-3067-4_19.
29. Zajkowski K, Rusica I, Palkova Z. The use of CPC theory for energy description of two nonlinear receivers, *MATEC Web of Conferences* 2018; 178: 1-6, <https://doi.org/10.1051/mateconf/201817809008>.

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