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ASSESSMENT OF RELIABILITY, AVAILABILITY AND MAINTAINABILITY OF RAIL GAUGE CHANGE SYSTEMS

OCENA NIEUSZKADZALNOŚCI, GOTOWOŚCI I PODATNOŚCI UTRZYMANIOWEJ KOLEJOWYCH SYSTEMÓW PRZESTAWCZYCH*

The paper provides a comparative assessment of the reliability of two rail gauge change systems: wagon bogie exchange and SUW 2000 self-adjusted wheel sets. In the applied method of assessment, reliability is treated as a comprehensive feature comprising such system characteristics as reliability itself together with availability and maintainability. The calculations of selected reliability ratios, based on operation data, demonstrated that the SUW 2000 system may be an alternative method for overcoming the barrier of different track gauges compared to the current wagon bogie exchange.

Keywords: reliability analysis, gauge change system, track gauge change.

Praca dotyczy porównawczej oceny niezawodności dwóch kolejowych systemów przestawczych: systemu wymiany wózków wagonowych i systemu samoczynnie rozsuwanych zestawów kołowych SUW 2000. W zastosowanej metodzie oceny, niezawodność jest traktowana jaka właściwość kompleksowa obejmującą takie cechy systemów jak: nieuszkadzalność, gotowość i podatność utrzymaniową. Przeprowadzone obliczenia wyselekcjonowanych wskaźników niezawodnościowych, oparte na danych eksploatacyjnych wykazały, że system SUW 2000 może stanowić alternatywną metodę pokonania bariery rożnej szerokości toru w stosunku do aktualnie stosowanej wymiany wózków wagonowych.

Słowa kluczowe: analiza niezawodności, system przestawczy, zmiana szerokości toru.

1. Introduction

Economic development depends largely on an efficient transport system which should enable reliable, safe and efficient cargo transport both domestically and internationally. It is particularly difficult to ensure such conditions for railway transport between Europe and Asia. This relates to the different track gauges on the Euro-Asian continent. Most European states, Poland included, have 1435 mm tracks while the railways within the former Commonwealth of Independent States (CIS) and other countries, such as Lithuania, Latvia and Estonia, are 1520 mm in width. In Asia, trains move along 1520 mm tracks, to go back again, in China and Korea, to normal gauge lines of 1435 mm. In Spain and Portugal, the tracks are even wider – 1668 mm.

The need for research aimed at facilitating the methods of overcoming the barrier of different track gauges may be demonstrated through the fact that the theme is addressed by international consortia under EU programmes and by the International Union of Railways (UIC) [3, 7, 10]. In 1995–2005, at the Institute of Rail Vehicles, Cracow University of Technology, a number of research and development assignments and goal-oriented projects were done on this issue [2, 21, 31, 33, 38]. Recent international writings too, include studies into the transport between railways of different track gauges, and in particular between Europe and Asia [5, 13, 22, 27, 36, 40]. Their authors emphasize that the development of railway transport on the Euro-Asian continent is possible through the implementation of new effective methods of overcoming the barrier of different track gauges. Currently, the time lost at border crossing points to handle goods or replace the vehicle running assemblies, together with the document flow, amounts to as much as 46% of the total time of transport [13, 23].

In cargo transport, two technologies to overcome the barrier of different track gauges are now in place [2, 31]:

– handling, and
– gauge changing.

The handling technology consists in reloading the cargo at border-crossing points from normal to wide gauge wagons or vice versa. Depending on the type of goods, the following can be distinguished in this technology: reloading, pumping or pouring [31].

Rail gauge change systems, which are discussed in this paper, are based on the other possible method of transport between railways with different track gauges, so-called gauge change technology [2]. In such systems, cargo is moved by the same means of transport which is shifted at the border-crossing point from one track gauge to another. The shifting may be done through wagon bogie exchange; exchange of the wheel sets or the use of self-adjusted wheel sets. Currently, cargo transport uses only wagon bogie exchange with the lifting of the wagon body. Methods which consist in exchanging the wheel sets were analysed under research project [21], but have not been put into practical application. In the second half of last century, intensive research was done in Germany, Spain, Russia, Bulgaria, Poland and Japan on automated technologies to overcome the barrier of different track gauges (so-called self-adjusted wheel set systems). The systems which have found practical application include: Talgo (Spain), DB Rafil (Germany), BT (Bulgaria) and the Polish SUW 2000. Under project [3], a comparative analysis of these systems was performed. The main emphasis was placed on legal, economic and logistic aspects, as well as the benefits for railway operators. The research demonstrated that the Polish SUW 2000 system designed by Dr hab. inż. R. Suwalski [5] was most elaborate and technologically advanced. The first years of the system's operation were devoted to work on eliminating the phenomenon of fretting between the axle bearing and the wheel nave bushing. Analysis of different options for the structure and materials enabled the introduction of the self-adjusted wheel sets

system into commercial supervised operation. Papers [5, 40] present the results of research into supervised operations of the SUW 2000 system, done in 2003–2008 in passenger and cargo transport between Poland and Ukraine. Currently, the SUW 2000 self-adjusted wheel sets system is applied in passenger transport only between Poland and Ukraine (Wroclaw–Lviv train).

All work done to date on the application of the SUW 2000 system to cargo transport has been limited to comparative analyses of this concept in technical and economic terms, no account being taken of its reliability. Hence, an attempt has been made to provide an assessment of the SUW 2000 self-adjusted wheel sets system compared with wagon bogie exchange which is currently used to transport hazardous materials. Analysis of the existing situation demonstrates that the gauge change transport system requires to be improved, in the transport of hazardous material in particular. The current concepts applied at border crossing points along Poland's eastern border for this cargo group are characterised by low efficiency and pose a serious threat to the environment and the safety of the handling personnel. This allows a supposition that the results represented herein are new and important for further research and development work on innovative methods of overcoming the barrier of different track gauges in cargo transport.

2. Assessment of reliability, availability and maintainability

Rail gauge change systems are amongst renewable facilities. Methods used for items which operate until the first failure, i.e. with the use of the functions of reliability $R(t)$ or intensity of failures $\lambda(t)$ are insufficient for such facilities. In the assessment method as herein applied, reliability is treated as a comprehensive characteristic which encompasses such features of the systems as reliability itself together with availability and maintainability (RAM). These may be defined as follows [16, 19]:

– Reliability is understood as the system's capability to perform a required function under stated conditions for a specified period of time;
– Availability is the system's capability of being in an operable state to perform the required functions under stated conditions, at a specified moment or for a specified time, presuming that the required external means are provided;
– Maintainability is defined as a characteristic of adaptation to restoration done in order to restore the item to a specified condition of operation with the use of prescribed methods and resources.

For a system to be in the state of availability means that it is not out of operation due to preventive maintenance or is not incapable of use due to failure. Availability depends not only on maintenance downtimes but also on the probability of the system's failure to perform its functions (unreliability effect) [15]. Maintainability in respect of rail gauge change systems concerns corrective and preventive maintenance. Corrective maintenance enables restoration of the item's capability and its being put back into operation. Preventive maintenance, on the other hand, is done as part of a prescribed item's maintenance cycle in order to improve its reliability and control its wear [25]. The aim behind effective maintenance is to minimise the Mean Down Time (*MDT*) and the related costs [39].

General guidelines on the analysis of reliability, availability and maintainability are provided in the PN-EN 50126 standard on *Railway Applications – Specification and Demonstration of Reliability, Availability, Maintainability and Safety* [19]. Professional writings on this problem offer a detailed description, definitions and calculation formulae for the different ratios used in the assessment [1, 8, 14, 17, 26]. The reliability, availability and maintainability analysis has been the subject of many research projects in recent decades. It is currently

applied in various industries, including aviation, armaments, power engineering, food processing and transport [6, 9, 11, 15, 24, 25, 35]. For instance, in paper [9], the authors describe potential applications of the RAM model in industrial practice to identify equipment which is critical due to frequent failures or high maintenance requirements. Paper [24] presents an application of the RAM analysis as a helpful tool to design systems, introduce constructional changes in order to achieve the minimum number of failures and increase the Mean Time between Failures (*MTBF*). Paper [35] analyses the problem of relation between the availability and maintainability of means of rail transport, and the costs of planned vehicle downtimes and maintenance. A model for optimum inspections and periodical restorations has been set from the viewpoint of costs, taking into account current data on vehicle failures. In the present paper, the reliability, availability and maintainability analysis applies to rail gauge change systems.

3. Comparative analysis of rail gauge change systems

3.1. Systems under analysis

Two systems for transporting hazardous materials are assessed for their reliability, availability and maintainability:

– **System 1** where track gauge change is effected through wagon bogie exchange, with the lifting of the wagon body, as currently applied;
– **System 2** where the track gauge is changed with the use of the prospective method – the SUW 2000 self-adjusted wheel sets.

Figure 1 shows a comparison of the process of operation of the analysed systems. The analysis leaves out the duration of the operations which consist of the train receipt, i.e. checking the securities and conformity of the shipping documents, customs clearance and wagon weighing.
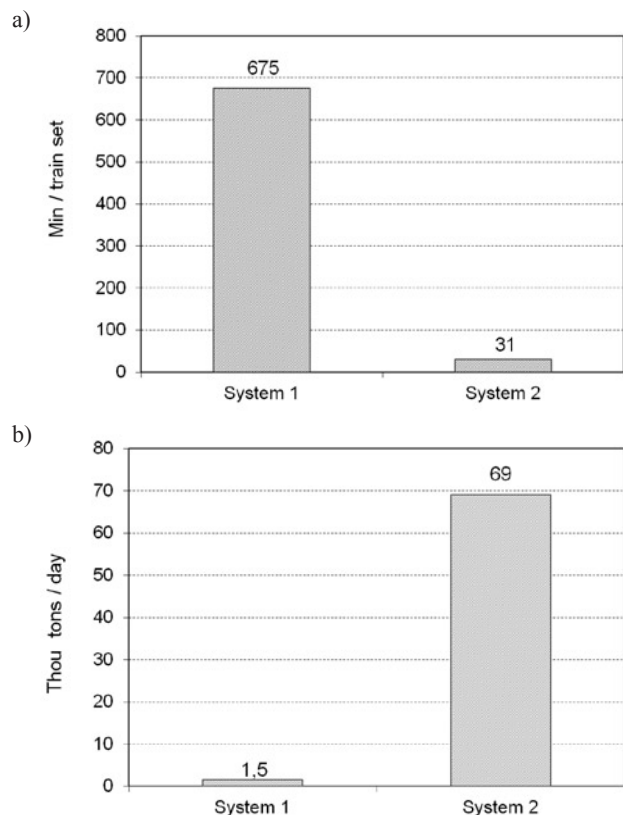
a)

b)

Fig. 1. a) Service time at the border crossing point, b) System performance [30, 32]

Considering the time needed for the servicing of a train at a border crossing point and the resulting performance, the option with the SUW 2000 with self-adjusted wheel sets is unrivalled. The application of the system shortens considerably the time of transport down by up to 18 hours depending on the cargo [4, 29]. There are, however, limitations relating to the universality of the service. This technology requires full-train transports orpreliminary distribution before the contact point of different track gauges.

3.2. Reliability data

The basis for assessing the systems' reliability, availability and maintainability was the operational data gathered in collaboration with PKP Cargo S.A. in actual work conditions covering about 7 years of operation for the wagon bogie exchange system, and almost 4 years for the self-adjusted wheel sets. This enabled observation of the course of operation of system elements in a variety of conditions and thus provided accurate data for reliability assessment. The reliability data was gathered in internal reports and records of PKP Cargo S.A., which performed the function of operation sheets. The documents contained detailed information on:

- date of failure,
- circumstances in which the failure was identified,
- causes for failure,
- maintenance time characteristics, i.e. duration of corrective maintenance, organisational downtime (waiting for the restoration, waiting for collection after restoration),
- labour intensiveness of corrective maintenance,
- figures for the different measurable characteristics before and after the restoration,
- labour intensiveness and duration of scheduled restorations (inspections, periodical restorations),
- consumption of materials and spare parts,
- technologies of restorative operations, and
- other additional information.

The detailed data on the process of operation, number and types of recorded failures of the examined systems are provided in [33].

3.3. Presumptions for and structures of the systems' reliability

The assessment of the reliability, availability and maintainability of the systems concerned was comparative in its nature. Thus, the common elements which have the same effect in both systems, e.g. 1435 and 1520 mm rail infrastructure, traction vehicles and others, were excluded from the analysis and hence from the reliability structure. The interest in the compared systems focused on elements of technical equipment of the points of junction between the different track gauges, and the rolling stock engaged in the transport process.

In system 1, wagon bogie exchange stands together with the cooperating gantry cranes are used to move a wagon from one track gauge to another (Figs. 2a and 2b). In system 2, the extended technical infrastructure of the wagon bogie exchange point is replaced with a track gauge change stand (Fig.3).

As regards the rolling stock, the most significant differences in the reliability assessment concern wagon bogies directly responsible for transport safety. In system 1, two sets of bogies assigned to one wagon are required to effect transport along tracks of different gauges: a 2XTa bogie for a1435 mm track (Fig. 4a) and a 18-100 type bogie for a track of 1520 mm, which are exchanged at the border crossing point. In system 2, on the other hand, bogies of one type – 4RS/N (Fig. 4b) – equipped with adjusted wheel sets are used thus enabling the wagon to move along 1435 and 1520 mm rail tracks.

In order to ensure practical usefulness of the paper, in formulating the presumptions necessary for the assessment of reliability, availabilityand maintainability, reference was made to the current condition
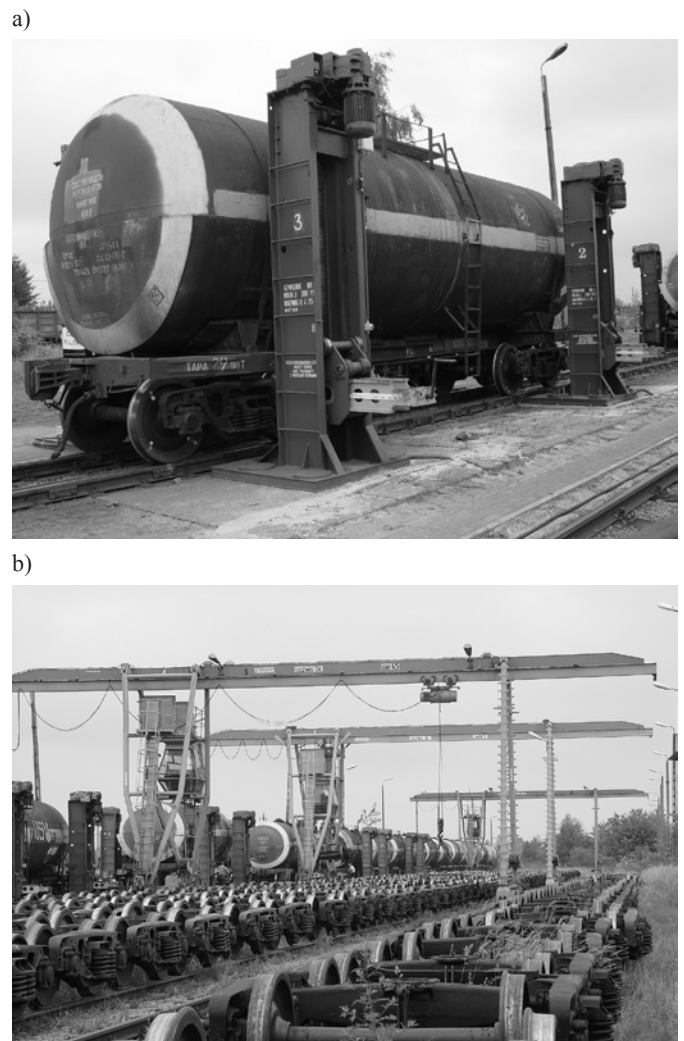
a)

b)

Fig.2. a) Wagon bogie exchange stand b) Gantry cranes to operate the gauge change stands (Photo: M. Szkoda)

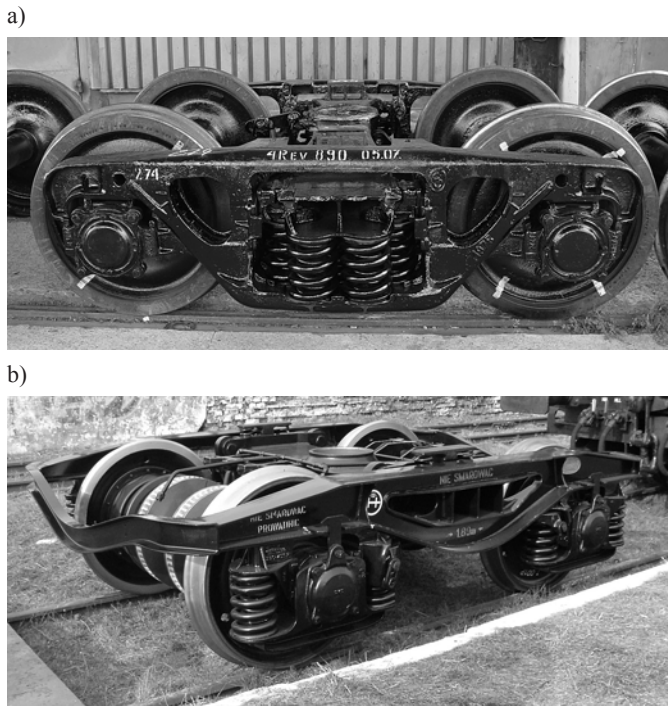Fig. 3. Rail gauge change stand for the SUW 2000 system [28]

a)

b)

Fig. 4. a) 2XTa wagon bogie for a 1435 mm track, b) 4RS/N wagon bogie for a 1435/1520 mm track (Photo: M. Szkoda)

at the bogies exchange point of PKP Cargo S.A., located at the largest Polish-Ukrainian border crossing point at Medyka/Mostiska. The assumptions for the analysis are shown in Table 1.

Table 1.   Assumptions for the reliability analysis

No.	ELEMENT	ASSUMPTIONS
1	Type of cargo transported	Hazardous materials in cistern wagons
2	Number of wagons exchanged at the border crossing point	5,483.0 [weight/year]
3	Capacity of the exchanged wagon	48.0 [tonnes]
4	Wagon turnover:	
	- system 1	10.6 [days]
	- system 2	8.0 [days]
5	Transport distance (one way, half along a 1435 mm track and half along a 1520 mm track)	1,100.0 km

In Table 2, for the presumed transport distance, the demand for means of transport was calculated, including the wagon bogies involved in the transport using both systems. The lower demand in system 2 is due to a much shorter servicing process at the border crossing point.

The foregoing presumptions, combined with the analysis of the actual situation, make it possible to determine the reliability structures of the analysed systems. Various structures were used to describe reliability: serial structure, with sliding reserve and the structure k out of

Table 2. Required number of wagon bogies

Parameter / System	Wagon turnover [days]	Demand for wagons [pcs]	Required number of wagon bogies [pcs]	Annual wagon mileage [km/year]
System 1	10.6	80	160 (for 1435 track) 160 (for 1520 track)	75,456.0 km
System 2	8.0	60	120	100,521.0 km

n type. The methodical basis for assessing the reliability of systems with sliding reserve and one with the k out of n type are presented, *inter alia*, in [34].

The reliability structure of system 1 (Fig. 5) is mapped through serially connecting four subsystems – P1.1, P1.2, P1.3 and P1.4:
Denotations in Fig.5:

   P1.1, P1.2, P1.3, P1.4 –subsystems of system 1,

   1.1_i, 1.2_i, 1.3_i, 1.4_i – elements which are comprised in system 1 (1.1 –2XTa wagon bogies, 1.2 –18-100 wagon bogies, 1.3 –bogie exchange stands, 1.4 – gantry cranes).

– subsystem P1.1 comprises a total of 176 bogies of the 2XTa type for a 1435 mm track (element 1.1), making up a reliability structure with sliding reserve with the order of redundancy k = 10. It means that for 160 basic bogies, an operational reserve of 16 elements is presumed, each of which can replace any basic bogie in the event it fails;

– subsystem P1.2 is made of a total of 176 bogies of the 18-100 type for a 1520 mm track (element 1.2), which, by analogy to subsystem P1.1, are mapped by a reliability structure with sliding reserve with the order of redundancy k = 10. Analysis of subsystems P1.1 and P1.2 assumes that the reserve bogies cannot fail when not in operation and that a bogie's non-operating condition does not affect its reliability. It is assumed further that the time during which a destroyed bogie is replaced by a reserve element practically equals zero;

– subsystem P1.3 consists of 14 bogie exchange stands (element 1.3) which are mapped as a threshold structure of the 10 out of 14 type. At least 10 stands are necessary to achieve the assumed number of wagons exchanged in a year at the border crossing point. The 10 out of 14 threshold structure means that subsystem P1.3 is in the state of correct operation when at least 10 out of 14 bogie exchange stands perform the functions they are allocatedin a correct fashion;

– subsystem P1.4 includes 3 gantry cranes (element 1.4) which are mapped by means of the serial reliability structure.

The reliability structure of system 2 (Fig. 6) is mapped through serially connecting two subsystems P2.1 and P2.2:

– subsystem P2.1 consists of a total of 132 bogies of the 4RS/N type for 1435 and 1520 mm tracks (element 2.1), which make up a reliability structure with sliding reserve with the order of redundancy k = 10. It means that for 120 bogies of the 4RS/N type an operational reserve is presumed comprising 12 elements each of which can replace any basic bogie in case of its failure. Like in subsystems P1.1 and P1.2 in system 1, it is presumed that the time during which a failed bogie is replaced with a reserve element is equal to zero;

– subsystem P2.2 comprises one track gauge change stand (element 2.2).

Denotations in Figure 6:

   P2.1, P2.2 – subsystems of system 2,

   2.1_i, 2.2 – elements comprised in system 2 (2.1–4RS/N wagon bogies with self-adjusted wheel sets, 2.2 – rail gauge change stand).

3.4.   Reliability ratios applied in the analysis

Rail gauge change systems may be analysed at various complexity levels. With respect to an element, a subsystem and a system, the relevant reliability ratios relating to reliability, availability and maintainability were assigned, including:
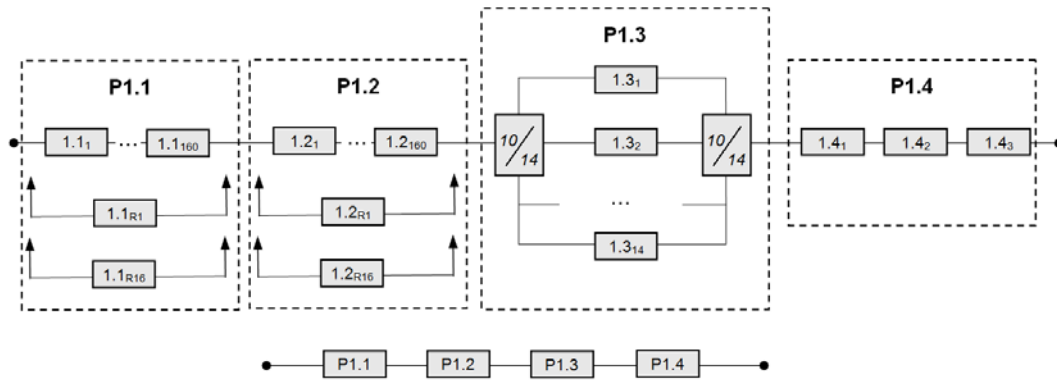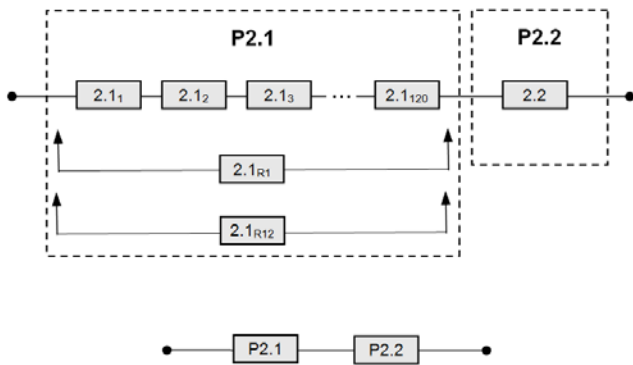
Fig. 5. Reliability structure of system 1

Fig. 6. Reliability structure of system 2

- Cumulative distribution of time of operation until the first failure $F(t)$,
- Intensity of failure stream $z(t)$,
- Renewal function in the maintenance cycle $H(t)$,
- Mean Time To Failure, $MTTF$,
- Mean Time Between Failures $MTBF_k$,
- Operational Availability Ratio A_o,
- Technical Availability Ratio A,
- Mean Accumulated Down Time $MADT$,
- Cumulative distribution of restoration $G(t)$,
- Mean Time To Restoration $MTTR_B$,
- Mean Time To Maintenance (Periodical Inspection) $MTTM_P$,
- Mean Time To Maintenance (Revision) $MTTM_N$.

The definitions and denotations of the ratios follow the PN-EN 50126 and the PN-EN 61703 standards [19, 20], and the calculations use the capacities of the following packages: Statistica, MiniTab and BlockSim. Owing to the wide range of the analyses, points 3.4.1 ÷ 3.4.3 present only the calculations of selected ratios used to compare the analysed systems.

3.4.1. Reliability ratios

In order to compare system reliabilities, the ratio of the mean number of failures (MNF) in a year of operation was applied, which, for a single element, is defined as follows:

$$MNF_i = \left(\frac{H_i(t)}{T_i} \right) \cdot 8{,}760.0 \quad \left[\text{failures} \big/ \text{year} \right] \qquad (1)$$

where:
MNF_i – mean number of failures of element "i" in a year of operation,

$H_i(t)$ – renewal function of element "i" in the maintenance cycle,
T_i – duration of operation of element "i" in the maintenance cycle (in hrs).

In the formula above, the renewal function $H(t)$ is applied which, assuming that the duration of renewal is negligibly short compared with the duration of correct operation of the item, expresses the expected number of renewals equal to the number of failures until time t and is defined as follows [8]:

$$H(t) = \sum_{n=1}^{\infty} F_n(t) \qquad (2)$$

where:

$F_n(t)$ – distribution function of the object's operation until the occurrence of the n-th failure (renewal)

For system 1, the mean number of failures in a year of operation (MNF_1) is the total of failures of four subsystems:

$$MNF_1 = MNF_{P1.1} + MNF_{P1.2} + MNF_{P1.3} + MNF_{P1.4} =$$
$$= \left(\frac{H_{P1.1}(t)}{T_{1.1}} + \frac{H_{P1.2}(t)}{T_{1.2}} + \frac{H_{P1.3}(t)}{T_{1.3}} + \frac{H_{P1.4}(t)}{T_{1.4}} \right) \cdot 8{,}760.0 \quad \left[\text{failures} \big/ \text{year} \right] \qquad (3)$$

where:
$H_{P1.1}(t) \div H_{P1.4}(t)$ – renewal functions of subsystems P1.1÷P1.4,
$T_{1.1} \div T_{1.4}$ – time of operation of subsystems P1.1÷P1.4 in the maintenance cycle (in hrs).

With the numerousness of 2XTa and 18-100 bogies together with the reserve elements taken into account, the renewal function of subsystems P1.1 and P1.2 is:

$$H_{P1.1}(t) = H_{P1.2}(t) = \sum_{i=1}^{176} H_{1.1}(t) = \sum_{i=1}^{176} H_{1.2}(t), \quad for\ 0 < t \le 34{,}960\ \text{[hrs]} \qquad (4)$$

where:
$H_{1.1}(t)$, $H_{1.2}(t)$ – renewal function of elements 1.1 and 1.2 (2XTa and 18-100 bogie) in the maintenance cycle:

$$H_{1.1}(t) = H_{1.2}(t) = \sum_{n=1}^{\infty} F_n(t) = F_1(t) + F_2(t) =$$

$$= \left[0,5 \left(1 + \Phi \left(\frac{t - 18104}{6887\sqrt{2}} \right) \right) \right] + \left[0,5 \left(1 + \Phi \left(\frac{Ln(t) - 11.269}{0.7822\sqrt{2}} \right) \right) \right] \quad for \ 0 \le t \le 34,894 \ [hrs] \tag{5}$$

where:

$$\Phi(z) = \frac{2}{\sqrt{\Pi}} \int_0^z \exp(-t^2) dt \qquad - \text{Gauss distribution function}$$

With the numerousness of the bogie exchange stands (element 1.3) taken into account, the renewal function of subsystem P1.3 is:

$$H_{P1.3}(t) = \sum_{i=1}^{14} H_{1.3}(t), \quad for \ 0 \le t \le 4.218 \ [hrs] \tag{6}$$

where:

$H_{1.3}(t)$ – renewal function of element 1.3 in the maintenance cycle:

$$H_{1.3}(t) = \sum_{n=1}^{\infty} F_n(t) = F_1(t) + F_2(t) + F_3(t) + F_4(t) = \left[1 - 1090.06 \times 10^{-3} \cdot \Gamma \left(1.203; \frac{t}{1441} \right) \right] + \left[1 - \exp \left(-4.0973 \times 10^{-7} \cdot t^{1,7056} \right) \right] +$$

$$+ \left[\frac{1}{1 + \exp(-0.00122 \cdot (t - 5462.92))} \right] + \left[0.5 \left(1 + \Phi \left(\frac{t - 7382.96}{2102.68\sqrt{2}} \right) \right) \right] \qquad for \ 0 \le t \le 4.218 \ [hrs] \tag{7}$$

where:

$$\Gamma \left(1,203; \frac{t}{1441} \right) = \int_{t/1441}^{+\infty} t^{0,203} \cdot e^{-t} dt \qquad - \text{incomplete gamma function}$$

$$\Phi(z) = \frac{2}{\sqrt{\Pi}} \int_0^z \exp(-t^2) dt \qquad - \text{Gauss distribution function}$$

With the numerousness of gantry cranes (element 1.4) taken into account, the renewal function of subsystem P1.4 is:

$$H_{P1.4}(t) = \sum_{i=1}^{3} H_{1.4}(t), \quad for \ 0 \le t \le 8.504 \ [hrs] \tag{8}$$

where:

$H_{1.4}(t)$ – renewal function of element 1.4 in the maintenance cycle:

$$H_{1.4}(t) = \sum_{n=1}^{\infty} F_n(t) = F_1(t) + F_2(t) + F_3(t) + F_4(t) + F_5(t) + F_6(t) + F_7(t) =$$

$$= \left[1 - \exp \left(-2.878 \times 10^{-4} \cdot t^{1,104} \right) \right] + \left[1 - 9242.48 \times 10^{-4} \cdot \Gamma \left(2.166; \frac{t}{1465} \right) \right] +$$

$$+ \left[0.5 \left(1 + \Phi \left(\frac{Ln(t) - 8.231}{0.5238\sqrt{2}} \right) \right) \right] + \left[1 - \exp \left(-1.866 \times 10^{-10} \cdot t^{2.5681} \right) \right] + \left[0.5 \left(1 + \Phi \left(\frac{t - 6991.75}{2079.25\sqrt{2}} \right) \right) \right] +$$

$$+ \left[0.5 \left(1 + \Phi \left(\frac{Ln(t) - 9.0647}{0.4212\sqrt{2}} \right) \right) \right] + \left[1 - \exp \left(-1.393 \times 10^{-18} \cdot t^{4.4912} \right) \right] \qquad for \ 0 \le t \le 8.504 \ [hrs] \tag{9}$$

Substituting (5), (7) and (9) to relation (3), we get the mean number of failures in a year of operation of system 1:

$$MNF_1 = \left(\frac{201.2}{35,040.0} + \frac{201.2}{35,040.0} + \frac{22.9}{8,760.0} + \frac{16.6}{17,520.0} \right) \cdot 8,760.0 = 131.8 \quad \left[failures \middle/ year \right] \tag{10}$$

For system 2, the mean number of failures in a year of operation (MNF_2), relates solely to the failures of 4RS/N bogies and is:

$$MNF_2 = MNF_{P2.1} = \frac{H_{P2.1}(t)}{T_{2.1}} \cdot 8,760.0 \quad \left[\text{failures} / \text{year} \right] \quad (11)$$

where:
$H_{P2.1}(t)$ – renewal function of subsystem P2.1,
$T_{2.1}$ – duration of operation of subsystem P2.1 in the maintenance cycle (in hrs).

With the numerousness of 4RS/N bogies (element 2.1) together with the reserve bogies taken into account, the renewal function of subsystem P2.1 is:

$$H_{P2.1}(t) = \sum_{i=1}^{132} H_{2.1}(t) \quad for \ 0 \le t \le 8,140 \ [\text{hrs}] \quad (12)$$

where:
$H_{2.1}(t)$ – renewal function of element 2.1 (4RS/N bogie) in the maintenance cycle:

$$H_{2.1}(t) = \sum_{n=1}^{\infty} F_n(t) = F_1(t) + F_2(t) + F_3(t) = \left[1 - \exp(-10.9 \times 10^{-4} \cdot t) \right] +$$

$$+ \left[1 - \exp(16.16 \times 10^{-5} \cdot t) \right] + \left[0.5 \left(1 + \Phi \left(\frac{t - 21520.9}{10734.2\sqrt{2}} \right) \right) \right], \quad (13)$$

$$for \ 0 \le t \le 31,191 [\text{hrs}]$$

where:

$$\Phi(z) = \frac{2}{\sqrt{\Pi}} \int_0^z \exp\left(-t^2\right) dt \qquad \text{– Gauss distribution function}$$

Hence, the mean number of failures in a year of operation of system 2 is:

$$MNF_2 = \frac{H_{P2.1}(t)}{T_{2.1}} = \left(\frac{370.9}{8760} \right) \cdot 8,760.0 = 370.9 \quad \left[\text{failures} / \text{year} \right] \quad (14)$$

3.4.2. Assessment of technical availability

Assuming that all elements operating in a system are described with identical probability distribution functions of the duration of operation and the duration of restoration, the system availability $A(t)$ can be described with the following function [8]:

$$A(t) = 1 - F(t) + \int_0^t \left[1 - F(t - \tau) \right] h(\tau) d\tau \quad (15)$$

where:

$h(t)$ – renewal density function: $h(t) = \dfrac{H(t)}{dt}$

The above formula is rarely used in practice due to a considerable degree of complexity of the calculations. Usually, the so-called technical availability ratio is applied, defined as the mean proportion of the time in which the system under consideration is available for use [12]:

$$A(\infty) = \lim_{t \to \infty} A(t) \quad (16)$$

In order to compare the technical availabilities of the analysed systems, the technical availability ratio A and the Mean Accumulated Down Time ($MADT$) were applied. The ratio A presents the mean technical availability in the maintenance cycle, between the subsequent maintenance (revision) activities of the analysed items. For an individual item, the availability ratio is defined as follows:

$$A_i = \frac{\text{TZ}_i}{\text{TZ}_i + \text{TN}_i + \text{TO}_i} \quad (17)$$

where:
TZ_i – mean time of availability of item "i" (in hrs),
TN_i – mean time of unavailability of item "i" due to corrective maintenance (in hrs),
TO_i – mean time of unavailability of item "i" due to preventive maintenance activities (in hrs).

The Mean Accumulated Down Time ($MADT$), in turn, was defined as follows:

$$MADT_i = 8,760.0 \cdot \left(1 - A_i \right) \quad [\text{hrs/year}] \quad (18)$$

For system 1, the availability ratio is the product of the availability of four subsystems, P1.1, P1.2, P1.3 and P1.4:

$$A_1 = A_{P1.1} \cdot A_{P1.2} \cdot A_{P1.3} \cdot A_{P1.4} \quad (19)$$

For subsystems P1.1 and P1.2, account being taken of the numerousness of the bogies and the reliability structure with sliding reserve [18]:

$$A_{P1.1} = A_{P1.2} = \prod_{i=1}^{n} \left(1 - (1 - A_{1.1})^{k+i} \right) = \prod_{i=1}^{160} \left(1 - (1 - 0.9991)^{16+i} \right) \approx 1.0 \quad (20)$$

where:
n – number of basic bogies in the structure of subsystem P1.1 (P1.2),
k – number of reserve bogies in the structure of subsystem P1.1 (P1.2),
$A_{1.1}$ – technical availabilityratio for 2XTa bogie (18-100).

For subsystem P1.3, account being taken of the numerousness of the stands and the threshold reliability structure of the 10 out of 14 type [37]:

$$A_{P1.3} = \sum_{i=k}^{n} \binom{n}{i} A_{1.3}^i (1 - A_{1.3})^{n-i} = \sum_{i=10}^{14} \binom{14}{i} 0.9710^i (1 - 0.9710)^{14-i} = 0.9999 \quad (21)$$

where:
n – number of all bogie exchange stands in the structure of P1.3 subsystem,
k – required number of stands necessary for correct operation of subsystem P1.3,
$A_{1.3}$ – technical availability ratio of the bogie exchange stand.

For the P1.4 subsystem, account being taken of the numerousness of the gantry cranes and the serial reliability structure:

$$A_{P1.4} = \prod_{i=1}^{n} A_{1.4i} = (0.9615)^3 = 0.8889 \quad (22)$$

where:

n — number of gantry cranes in the structure of subsystem P1.4,

$A_{1.4}$ — technical availability ratio for the gantry crane.

Substituting (20), (21) and (22) to relation (19), we get the technical availability ratio for system 1:

$$A_1 = A_{P1.1} \cdot A_{P1.2} \cdot A_{P1.3} \cdot A_{P1.4} = 1.0 \cdot 1.0 \cdot 0.9999 \cdot 0.8889 = 0.8888 \quad (23)$$

In turn, the accumulated down time in a year of operation of system 1 is:

$$MADT_1 = 8,760.0 \cdot (1 - A_1) = 8,760.0 \cdot (1 - 0.8888) = 973.8 \text{ [hrs/year]} \quad (24)$$

For system 2, the technical availability ratio is the product of the availabilities of two subsystems P2.1 and P2.2:

$$A_2 = A_{P2.1} \cdot A_{P2.2} \quad (25)$$

For subsystem P2.1, account being taken of the numerousness of 4RS/N bogies and the reliability structure with sliding reserve, the ratio is:

$$A_{P2.1} = \prod_{i=1}^{n} \left(1 - (1 - A_{2.1})^{k+i}\right) = \prod_{i=1}^{120} \left(1 - (1 - 0.9954)^{12+i}\right) \approx 1.0 \quad (26)$$

where:

n — number of basic bogies in the structure of subsystem 2.1,

k — number of reserve bogies in the structure of subsystem 2.1,

$A_{2.1}$ — technical availability ratio for 4RS/N bogie.

For P2.2 subsystem which consists of one rail gauge change stand, the technical availability ratio equals the availability of element 2.2:

$$A_{P2.2} = A_{2.2} = 0.9977 \quad (27)$$

Substituting (26) and (27) to relation (25), we get the availability ratio for system 2:

$$A_2 = A_{2.1} \cdot A_{2.2} = 1.0 \cdot 0.9977 = 0.9977 \quad (28)$$

The accumulated down time of system 2 is:

$$MADT_2 = 8,760.0 \cdot (1 - A_2) = 8,760.0 \cdot (1 - 0.9977) = 20.2 \text{ [hrs/year]} \quad (29)$$

3.4.3. Maintainability ratios

In order to compare the systems' maintainabilities, the mean maintenance time (*MMT*) in a year of operation was applied, which includes the total time spent on corrective and preventive maintenance of the system. For a single element, this ratio is defined as follows:

$$MMT_i = \left(\frac{(H_i(t) \cdot MTTR_{Bi}) + (NPMA_{Pi} \cdot MTTR_{Pi}) + (NPMA_{Ni} \cdot MTTR_{Ni})}{T_i} \right) \cdot 8,760.0 \quad \left[\text{hrs}/\text{year} \right] \quad (30)$$

where:

$H_i(t)$ — renewal function of element "i" in the maintenance cycle,

$MTTR_{Bi}$ — mean time to restore element "i" (in hrs),

$NPMA_{Pi}$ — number of periodic maintenance activities on element "i" in the maintenance cycle,

$MTTM_{Pi}$ — mean time to maintain (periodical inspection) of element "i" (in hrs),

$NPMA_{Ni}$ — number of revision maintenance activities of element "i" in the maintenance cycle,

$MTTM_{Ni}$ — mean time to maintain (revision) on element "i" (in hrs),

T_i — time of operationof element "i" in the maintenance cycle (in hrs).

For system 1, the mean maintenance time (*MMT₁*) in a year of operation is the total of maintenance times of four subsystems and is:

$$MMT_1 = MMT_{P1.1} + MMT_{P1.2} + MMT_{P1.3} + MMT_{P1.4} \quad \left[\text{hrs}/\text{year} \right] \quad (31)$$

With the numerousness of 2XTa and 18-100 bogies taken into account, the mean maintenance time in a year of operation for subsystems P1.1 and P1.2 is:

$$MMT_{P1.1} = MMT_{P1.2} = \left[176 \cdot \left(\frac{(1.1431 \cdot 5.9) + (1 \cdot 6.0) + (1 \cdot 19.5)}{35,040.0} \right) \right] \cdot 8,760 = 1,418.9 \quad \left[\text{hrs}/\text{year} \right] \quad (32)$$

With the numerousness of the bogie exchange stands taken into account, the mean maintenance time in a year of operation for subsystem P1.3 is:

$$MMT_{P1.3} = \left[14 \cdot \left(\frac{(1.634 \cdot 11.2) + (12 \cdot 6.5) + (1 \cdot 29.6)}{8,760.0} \right) \right] \cdot 8,760.0 = 1,762.6 \quad \left[\text{hrs}/\text{year} \right] \quad (33)$$

With the numerousness of the gantry cranes taken into account, the mean maintenance time in a year of operation for subsystem P1.4 is:

$$MMT_{P1.4} = \left[3 \cdot \left(\frac{(5.5263 \cdot 9.3) + (23 \cdot 11.0) + (1 \cdot 36.0)}{17,520.0} \right) \right] \cdot 8,760.0 = 573.1 \quad \left[\text{hrs}/\text{year} \right] \tag{34}$$

Substituting (32), (33) and (34) to relation (31), we get:

$$MMT_1 = MMT_{P1.1} + MMT_{P1.2} + MMT_{P1.3} + MMT_{P1.4} = 5,137.2 \quad \left[\text{hrs}/\text{year} \right] \tag{35}$$

For system 2, the mean maintenance time (MMT_2) in a year of operation amounts to the total of mean maintenance times of two subsystems and is:

$$MMT_2 = MMT_{P2.1} + MMT_{P2.2} \quad \left[\text{hrs}/\text{year} \right] \tag{36}$$

With the numerousness of 4RS/N bogies taken into account, the mean maintenance time in a year of operation for subsystem P2.1 is:

$$MMT_{P2.1} = \left[132 \cdot \left(\frac{(8.4291 \cdot 7.9) + (3 \cdot 7.0) + (1 \cdot 25.2)}{35.040.0} \right) \right] \cdot 8,760.0 = 3,722.1 \quad \left[\text{hrs}/\text{year} \right] \tag{37}$$

For subsystem P2.2, on the other hand:

$$MMT_{P2.2} = \left[1 \cdot \left(\frac{(2 \cdot 5.0)}{4,380.0} \right) \right] \cdot 8,760.0 = 20.0 \quad \left[\text{hrs}/\text{year} \right] \tag{38}$$

Substituting (37) and (38) to relation (36), we get the mean maintenance time in a year of operation for system 2:

$$MMT_2 = MMT_{P2.1} + MMT_{P2.2} = 3,742.1 \quad \left[\text{hrs}/\text{year} \right] \tag{39}$$

4. Conclusions

The subject of the paper was a comparative assessment of the reliability, availability and maintainability of two rail gauge change systems: wagon bogie exchange and SUW 2000 self-adjusted wheel sets. Analysing the results of calculations, one should take into account the fact that supervised operation of the SUW 2000 system concerned a prototype solution. During the tests of the solution, a number of failures occurred which were caused by constructional errors to be eliminated in the new upgraded version of the gauge change system. The following observations result from the analysis:

 – The SUW 2000 system is characterised by a higher rate of failures compared with the wagon bogie exchange system. The mean number of its failures in a year of operation (MNF) is more than twice as high. This is due to failures of 4RS/N bogies, in particular flat spots on the wheels' rolling surfaces which were most frequent to occur during supervised operation;
 – The SUW 2000 system is characterised by a higher technical availability ratio *(A)* and more than 40-times shorter Mean Accumulated Down Time (MADT) compared with the wagon bo-

gie exchange system. The calculations demonstrate, however, that in order to ensure high availabilityof the system in actual operation, it is necessary to have an at least 10-percent operation reserve for bogies with gauge change systems;
 – As regards maintainability, thanks to the replacement of the extended and costly technical equipment of the wagon bogie exchange point (Kutruff lifts, gantry cranes and other) with reliable highly available rail gauge change stands, the mean maintenance time (MMT) in a year of operation for the SUW 2000 system is nearly 30% shorter compared with the bogie exchange system.

The analysis, based on reliable data from supervised operation, demonstrated that in future the SUW 2000 system may be an alternative method for overcoming the barrier of different track gauges in the transport of hazardous materials compared with the wagon bogie exchange now in place. The next stage of the work to assess the possibilities of applying the SUW 2000 system should be an assessment of performance with the use of Life Cycle Costs (LCC).

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