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## ASSESSMENT OF THE INFLUENCE OF PREVENTIVE MAINTENANCE ON THE RELIABILITY AND AVAILABILITY INDEXES OF DIESEL LOCOMOTIVES

**Summary.** The article investigates the influence of preventive maintenance on the reliability and availability indexes of the railway means of transport, which also determine the economic aspects of their operation and maintenance. The research was done using the method based on fault tree analysis (FTA) and Monte Carlo simulation. The authors performed a cause and effect analysis of the occurrence of undesirable events during the operation of selected vehicles. They identified the weakest components of the rail vehicle that affect the downtime and mean availability most significantly. Specialized software including Weibull++, BlockSim, and MiniTab aided calculations were used to illustrate the application of the results of a modernization project involving a 6Dg diesel locomotive, carried out in cooperation with the biggest Polish rail carrier. The applicability of the proposed tools has been verified on the example of a selected sample of 75 diesel locomotives employing data on their use and maintenance acquired in the real operation process. The obtained results indicate that the proposed approach can be particularly useful in practice when assessing the applied rail vehicle maintenance strategy, and while developing new strategies and selecting the best one to implement.

### 1. INTRODUCTION

The paper presents a new approach to assess the effectiveness of preventive maintenance of rail vehicles. The applied method is based on the fault tree analysis (FTA), Monte Carlo simulation, and selected indicators related to reliability and availability. The necessary calculations were performed using the specialized ReliaSoft package.

Various types of maintenance strategies for technical objects are described in professional writings [31]. The two main types of maintenance are corrective maintenance and preventive maintenance [24]. Corrective maintenance consists in restoring the suitability of an object that has been damaged and putting it back into operation. Repairs carried out only when damage occurs is not economically justified in many situations. Therefore, in the case of complex technical objects such as rail vehicles, preventive maintenance is applied, which is carried out within the framework of an established maintenance plan. It is intended to ensure high reliability and an appropriate level of operational safety of vehicles, control the wear and tear of their assemblies and subassemblies, and to reduce the number

of damage and unscheduled decommissioning, which result in lower technical availability and involve additional costs. The most commonly used strategies in preventive maintenance include, among others: strategy of preventive replacement by age of the object, strategy of periodic replacement, and group replacement strategy. These and many other models are described in detail in the writings [5, 9, 12, 16, 19, 22, 35]. In paper [9] the authors emphasize that in order to adopt the optimum maintenance strategy, it is necessary to know various characteristics of the means of transport, such as time to failure (TTF), time to renewal (TTR), expected costs of failure, and expected costs of preventive maintenance and preventive repairs.

As part of the study of the writings, publications on the construction of rail vehicle maintenance strategies were analyzed in detail. Paper [28] presents a method of setting the optimum maintenance plan intended to minimize the total maintenance costs and the scope of maintenance activities. The solution can be applied to vehicles, infrastructure, and rail traffic control systems. Paper [34] demonstrates that changes in the maintenance plan of a railway vehicle may consist in reducing the frequency of individual inspections and periodic repairs, i.e., extending the duration of intervals between them. Publication [6] presents the problem of optimizing the maintenance system of selected tram elements account being taken of the risk involved. The costs of dealing with the risk and the values of risk reduction achieved as a result of avoiding damage to the elements of the object have been assumed as components of the objective function. Papers [1, 2] emphasize that safety should be the most important factor taken into account when choosing a maintenance strategy for railway vehicles. In turn, in paper [33], using three types of performance indicators related to reliability, availability, and maintenance costs, the authors describe a method for changing the times to repair of rail vehicles. The method has been implemented in order to reduce the maintenance costs of rolling stock for the Dutch carrier. The authors point to proper identification of the subassemblies affecting the maintenance strategy. In turn, paper [11] notes that already at the time of implementation of a maintenance strategy, there is a trend toward an increase in mileage between particular maintenance activities. Papers [21, 37], as part of the criteria for selecting the appropriate maintenance strategy, the Life Cycle Cost (LCC) and the technical availability index are taken into account when determining the maintenance intervals for assemblies and sub-assemblies of a railway vehicle. On the basis of research and development projects conducted at the Institute of Rail Vehicles of the Cracow University of Technology in 2006–2019, the share of unavailability costs in the LCC of diesel locomotives over the operation period of 25 years reaches only up to 13.2% depending on the type of vehicle and the maintenance cost share approximately 25-40% of total costs depending on the type and operating conditions of the vehicle [30, 32].

Technical availability is a particularly important indicator enabling an estimation of the impact of different maintenance strategies on the total downtime of rail vehicles. These vehicles are complex structures, with different elements in terms of reliability. Therefore, the assessment of the impact of the chosen maintenance strategy on technical availability requires a correct presentation of the reliability structure, e.g. by means of the FTA method, followed by a simulation of operation and maintenance over a preset time. This simulation should allow the testing of the TTF and the TTR behaviour. The Monte Carlo simulation method is often proposed in the writings, as a calculation tool applied according to a complex fault tree. There are few papers focused on the practical applications of FTA and Monte Carlo simulation for the rail vehicles [4, 7, 15, 26, 36]. FTA has been widely applied as a method of quantitative and qualitative assessment of the reliability for railway vehicles. In work [36] the authors developed fault tree model for the locomotive runaway accident, happened on the local railway in China. They also proposed the corresponding safety countermeasures to avoid such accidents in the future. Monte Carlo simulation is a valuable method commonly used in the solution of various engineering problems [14, 38]. The use of computer simulation, in particular the Monte-Carlo simulation, to analyze the reliability of complex systems is described by many researches, for example in papers Kaczor and colleagues [8, 13, 15, 18]. The analysis of operational data can be made using the two- or three-parameter Weibull distribution, which allows to take into account complex operation scenarios. The literature provides numerous examples of the application of the Monte Carlo method to learn the deterministic and random properties of the reality being experienced [3]. Recently, this method has been used increasingly in the analysis of the availability of

complex technical systems. For example, the authors of work [10] proposed an availability analysis method for a complicated repairable system. They considered five states of each component and showed a practical application of the presented method. Młynarski et al. [17] presented the possibility of assessing the reliability of complex systems using multistage structural decomposition of the system. Paper [23], on the other hand, contains a method of achieving the required levels of reliability and readiness of systems through the use of preventive restoration of elements.

The purpose of this work is to evaluate the impact of the preventive maintenance process on the reliability and availability of a 6Dg diesel locomotive using the selected reliability and availability indexes. The analysis was performed on the basis of the data obtained during real operation of a given sample of locomotives. The obtained results showed the scale of unavailability costs, which are limited by introducing the preventive maintenance strategy. The fundamental task in unavailability costs minimization is to identify the weakest components of the locomotive, which are of the highest contribution to its total downtime.

## 2. CHARACTERISTIC OF THE RESEARCH OBJECT – 6Dg DIESEL LOCOMOTIVE

In 2007 NEWAG S.A. performed prototype modernization of the 6D diesel engine, which has been used in Poland for over 40 years. 6D is the most common series of locomotives in Poland (in December 2012 there were 1013 such vehicles). The main job of the locomotive is shunting maneuvers at hump yards. In 2009, after a two-year testing of the prototype vehicle, the first modernized locomotive was delivered to PKP Cargo S.A., the biggest Polish rail carrier. After the modernization the locomotive was given the symbol 6Dg (Fig. 1a). The modernization scope included the replacement of the a8C22 diesel engine used till then by a new 12-cylinder C27 Caterpillar diesel engine of 653 kW power (since 2010 of 708 kW power), meeting the exhaust emission standard according to 2004/26/WE Directive. Selected technical parameters of 6Dg locomotive are shown in Fig. 1b, and its detailed description is given in [32].

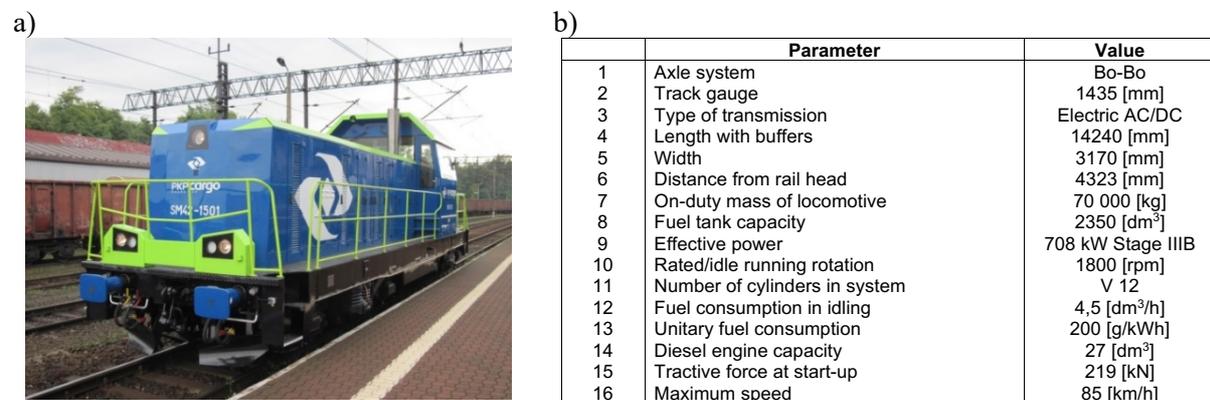


Fig. 1. a) 6Dg locomotive, b) Selected parameters of 6Dg locomotive

### 2.1. Characteristic of the maintenance process

The maintenance plan for an SM42 6Dg diesel locomotive presented in Table 2 is defined in Maintenance System Records No. NS/6Dg-B1/2806/14, approved by the President of the Rail Transport Office by decision DBK-WUP.443.229.2015.Akr of 29 July 2015. The maintenance levels are adopted in accordance with the Regulation of the Minister of Infrastructure of 12 October 2005 on the general technical conditions for the operation of rail vehicles (Consolidated text in: Dz.U. /Official Journal/ of 2016 item 226, as amended). The assumptions for the maintenance plan are presented in Table 1.

Detailed list of activities included in the scope of individual service levels (P1 – P5) performed according to the plan in Table 2 is presented in [32].

Table 1

Assumptions for the maintenance plan [own study]

Parameter	Unit	Value
Daily mileage	[km]	333
Average vehicle daily operation time	[h]	20
Average daily engine operation time	[h]	20
Average annual mileage	[km]	121545

Table 2

Maintenance plan for a SM42 6Dg type diesel locomotive [own study]

No.	Symbol	Unit	Value <sup>*)</sup>
1	P1	[days] / [km]	15 days +1 day or max 5000 km
2	P2	[years] / [km]	90 days +3 days or max 25000 km
3	P3	[years] / [km]	max 4 years or max 250000 km
4	P4	[years] / [km]	max 8 years or max 500000 km
5	P5	[years] / [km]	max 30 years or max 2000000 km

### 3. OPERATIONAL INVESTIGATION AND TYPES OF FAILURES OF MODERNIZED 6Dg LOCOMOTIVE

The reliability evaluation of modernized 6Dg locomotive was based on the operation data of a selected sample of seventy-five vehicles in service at PKP Cargo S.A. in a duration of 15 months. Over this period the operation of the selected sample of locomotives was observed, which provided reliable and extensive data for further reliability analysis. The investigation was conducted after a plan  $[n, R, t]$ , where  $n$  is the number of vehicles examined. The vehicles that failed during the tests were undergoing corrective repairs in order to recover the state of availability. The investigation was terminated after time  $t$ . In the analysis of the operation and maintenance data, the occurrence of right censored data had to be accommodated. In the adopted time only part of the vehicles failed, the observation duration time was strictly defined, and the number of failed vehicles was a random variable.

The reliability data were collected in the carrier's internal reports and an IT system assisting the haulage potential management, which enabled precise recording of corrective repairs. The documentation included detailed data on: date of failure, circumstances of detecting the failure, causes of failure, time characteristics of services, i.e. repair time, organization downtime, labor consumption of corrective repairs, labour consumption and duration of preventive repairs, materials and spare parts used, and repair operations technology. Table 3 presents the basic data on the operation process of the investigated locomotives.

Table 3

Maintenance plan for an SM42 6Dg-type diesel locomotive [own study]

Period of observation [month]	Number of locomotives	Labour time		Mileage	
		Total [h]	Mean [h/day]	Total [km]	Mean [km/day]
15	75	550125	16.3	3564000	105.6

In the analyzed period of operation, a total of 490 failures were recorded. The structure of failures following a division into their 29 components is shown in in Fig. 2. Notation following Table 4 (column 1 "Code").

#### 4. FAILURES MODELS OF 6Dg LOCOMOTIVE

The locomotive’s reliability and availability can be analyzed considering the proper functioning of its subsystems or components.

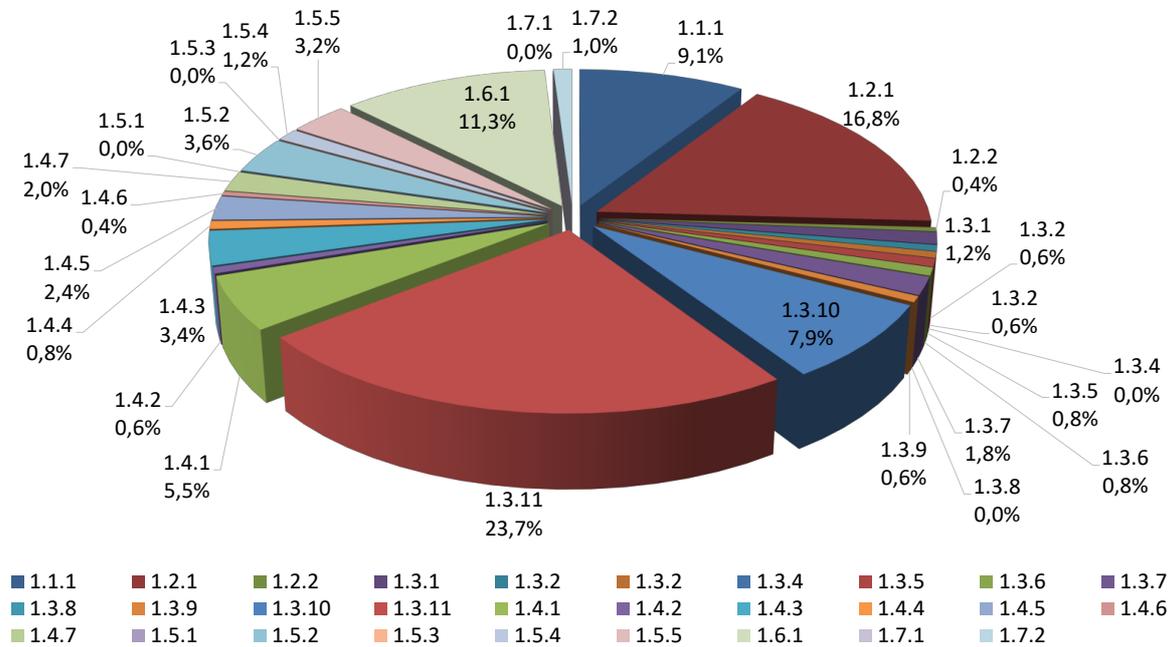


Fig. 2. Structure of 6Dg locomotive’s failures as divided into components

The models of reliability were estimated for all the components of 6Dg locomotive using the time to failure data and the Weibull++ software. Performed chi-squared tests with an assumed significance level of 0.05 confirmed that two-parameter Weibull distribution is a proper model to describe TTF in each case. The probability density function of the model applied is expressed by the formula [20]

$$f(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta}\right)^{\beta-1} \exp - \left(\frac{t}{\eta}\right)^{\beta}, t \geq 0 \tag{1}$$

where  $\beta$  – parameter of shape,  $\eta$  – parameter of scale.

Mean time to failure (MTTF) can be obtained from the equation [20]:

$$MTTF = \int_0^{\infty} t \cdot f(t) dt \tag{2}$$

The analysis includes also the values of maintainability parameters MTTR (mean time to repair) and MLDT (mean logistic delay time) obtained from the technical operation of the locomotive. MTTR may be calculated as [25] follows:

$$MTTR = \frac{\sum_{i=1}^n r_i}{n} \tag{3}$$

where  $r_i$  – the duration time of “i” renewal,  $n$  – the total number of renewals.

MLTD can be obtained from the following formula [25]:

$$MLDT = \frac{\sum_{i=1}^n d_i}{n} \tag{4}$$

where  $d_i$  – duration time of “i” logistic delay,  $n$  – total number of logistic delays.

The reliability distributions, obtained on the basis of right-censored data, together with maintainability parameters (MTTR, MLDT), listed for the analyzed locomotive’s subsystems and components, are presented in Table 4.

In the assumed approach to estimating reliability and availability indexes, a simplified perfect repair approach was applied, and the duty cycle coefficient taking into account the change in load of the locomotive components for the individual operating phases was not considered.

Table 4

Reliability distribution parameters and maintainability data of  
the locomotive's components and operators

Code	System/Subsystem/ Components	Number of failures	Parameters of Weibull distribution ( $\beta, \eta$ )		MTTF [h]	MTTR [h]	MLDT [h]
			$\beta$	$\eta$ [h]			
<b>1</b>	<b>6Dg locomotive</b>						
<b>1.1</b>	<b>Locomotive's operator</b>						
1.1.1	Failures caused by improper use	45	1.5242	1531.0	1379.5	2.0	1.0
<b>1.2</b>	<b>Locomotive's power transmission system</b>						
1.2.1	IC engine (including fuel system, cooling system with fan and pump, lubrication system, heat exchanger)	83	1.7098	2811.9	2507.9	12.5	24.0
1.2.2	Engine speed governor	2	21447	14613.3	12941.7	3.0	24.0
<b>1.3</b>	<b>Locomotive's electrical system</b>						
1.3.1	Railway motors	6	1.0975	3567.0	3444.5	14.0	8.0
1.3.2	Master generator	3	2.8388	11167.4	9949.3	16.0	24.0
1.3.3	Auxiliary generator	3	6.5558	4395.8	4097.8	10.5	12.0
1.3.4	Converter	0	no data	no data	no data	no data	no data
1.3.5	Contactator	4	1.8212	15556.2	13826.3	2.0	1.0
1.3.6	Other connectors (running controller, disconnecting switch, circuit breaker, etc itp.)	4	1.6539	17253.2	15425.2	4.0	1.0
1.3.7	Relay (protective or control)	9	0.9006	30012.5	31567.2	2.0	1.0
1.3.8	Starting resistance	0	no data	no data	no data	no data	no data
1.3.9	Conductors (cables, rails, etc.)	3	2.2063	10916.9	9668.4	2.0	2.0
1.3.10	Storage batteries	39	1.2462	6619.2	6169.3	2.5	1.0
1.3.11	Other components of electrical circuits	117	1.9503	2275.1	2017.4	1.5	1.0
<b>1.4</b>	<b>Locomotive's pneumatic and braking systems</b>						
1.4.1	Master or auxiliary compressor	27	1.1252	9608.0	9204.0	12.0	24.0
1.4.2	Master or auxiliary compressor driving motor	3	1.2142	41034.1	38483.2	8.0	12.0
1.4.3	Pneumatic valve (including driver's master or auxiliary valve, pressure reducing valve, stop valve, safety valve)	17	1.7262	6010.3	5357.3	4.0	2.0
1.4.4	Freeze protection	4	0.7204	186192.0	229515.0	3.0	1.0
1.4.5	Pneumatic conductors	12	1.0096	22993.4	22901.9	3.5	1.0
1.4.6	Servo-motor in braking system	2	1.0221	115243.0	114214.0	6.0	2.0
1.4.7	Other elements in pneumatic circuit	10	1.7743	5867.3	5221.5	2.5	1.5
<b>1.5</b>	<b>Locomotive's running gear mechanical system</b>						
1.5.1	Axle set bearings (including traction engine mounting bearings)	0	no data	no data	no data	no data	no data
1.5.2	Elements of axle sets	18	1.5193	6336.1	5711.2	12.0	8.0
1.5.3	Springing elements (e.g. leaf spring, rubber elements)	0	no data	no data	no data	no data	no data
1.5.4	Brake elements (e.g. levers, brake rods, pins, sleeves, connectors, brake shoes)	6	2.4482	8806.2	7809.6	12.0	8.0
1.5.5	Other elements of running gear	16	2.0962	5820.7	5155.5	8.0	8.0
<b>1.6</b>	<b>Vehicle motion safety automatic control devices</b>						
1.6.1	Sensors, Measurement instruments (speedometer, ammeter), radio-telephone	56	1.0042	6909.6	6897.3	8.0	2.5
<b>1.7</b>	<b>Other systems of vehicle</b>						
1.7.1	Elements of cars heating system	0	no data	no data	no data	no data	no data
1.7.2	Vehicle body	5	0.8422	77751.2	85083.7	8.0	1.0

## 5. ANALYSIS OF LOCOMOTIVE'S RELIABILITY AND AVAILABILITY

### 5.1. Reliability and Availability indexes

Rail means of transportation can be analyzed at various complexity/decomposition levels. As referred to the 6Dg locomotive investigated in this study the reliability and availability indexes are characterized in what follows in items (1) - (8):

(1) Point availability,  $A(t)$

Availability has to do with two separate events – failure and renewal. Point availability  $A(t)$  can be described by the function [29]

$$A(t) = 1 - F(t) + \int_0^t [1 - F(t - \tau)]h(\tau)d\tau \quad (5)$$

where  $F(t)$  – distribution function of time to failure,  $h(\tau)$  – probability density function of repair.

(2) Mean availability,  $A$

Formula (5) in practice is not used infrequently because of a considerable degree of calculation complexity. What is commonly used instead of it is the so-called index of mean availability  $A$ , defined as a mean contribution of the time in which the investigated vehicle remains in the state of availability, divided by the total time of its operation and maintenance [29]. For an individual object the availability index is defined as [12]:

$$A(t) = \frac{\sum_{i=1}^N TZ_i}{\sum_{i=1}^N TZ_i + \sum_{i=1}^N TUB_i + \sum_{i=1}^N TUP_i} \quad (6)$$

where  $TZ_i$  – time of vehicle “i” in availability state,  $TUB_i$  – time of vehicle “i” in unavailability state due to corrective repairs,  $TUP_i$  – time of vehicle “i” in unavailability state due to preventive repairs,  $N$  – sample size of vehicles taken for tests.

(3) Mean time between failures of vehicle,  $MTBF$  [27]:

$$MTBF = \frac{TT_o}{N_F} \quad (7)$$

where  $TT_o$  – total time of operation,  $N_F$  – number of failures.

(4) Mean time between failures of a component,  $MTBF_C$  [27]:

$$MTBF_C = \frac{TT_o - CFDownTime}{Component_{NF}} \quad (8)$$

$TT_o$  – total time of operation,  $CFDownTime$  – downtime of the selected component due to failures only,  $Component_{NF}$  – the total number of failures of a component.

(5) Mean time to the first failure of the vehicle,  $MTTFF$  [27]:

$$MTTFF = \frac{2T_S N}{\chi_{0.05;2}^2} \quad (9)$$

where  $T_S$  – simulation end time,  $N$  – number of failures,  $\chi_{0.05;2}^2$  – is the chi-squared statistic with a probability of 0.05 and 2, where 2 is the number of quantities jointly estimated.

(6) *RS DECI* (ReliaSoft's Downing Event Criticality Index) is a relative index showing the percentage of times that a downing event of the component caused the vehicle to fail (i.e., the number of vehicles downing events caused by the component divided by the total number of vehicle downing events). This is obtained from [27]:

$$RS DECI = \frac{C_{NSDE}}{N_{ALLdown}} \quad (10)$$

where  $C_{NSDE}$  – number of system downing events, which is the number of downing events for the vehicles caused by a selected component,  $N_{ALLdown}$  – total number of downing events of the whole system.

(7) *RS DTCI* (ReliaSoft Downtime Criticality Index) is a relative index showing the contribution of the components to the vehicles total downtime (i.e., the vehicle downtime caused by the component divided by the total vehicle downtime). This is obtained from [27]:

$$RS\ DTCI = \frac{DT_{VDCC}}{DT_{VDT}} \quad (11)$$

where  $DT_{VDCC}$  – total duration of vehicle downtimes caused by the component,  $DT_{VDT}$  – total vehicle downtime.

(8) *RS FCI* (ReliaSoft Failure Criticality Index) is a relative index showing the percentage of times that a failure of a component caused a vehicle failure. This is obtained from [27]:

$$RS\ FCI = \frac{C_{NSDF}}{N_F} \quad (12)$$

where  $C_{NSDF}$  – number of failures of a component caused by a vehicle failure,  $N_F$  – total number of failures.

## 5.2. Results of calculations

The analysis of the 6Dg locomotive fault tree model (Fig. 2) with the application of the Monte Carlo simulation was conducted with ReliaSoft – BlockSim reliability analysis package. This software offers advanced solutions for reliability and availability simulation of rail vehicles.

The Monte Carlo simulation applied in ReliaSoft package is based on generating random values of TTF according to the parameters of the probability distribution assigned to each of the system's components. The random number generator is based on L'Ecuyer algorithm with a post Bays-Durham shuffle. From Weibull distribution, the reliability equation is given by [27]

$$R(T) = \exp\left(-\left(\frac{T}{\eta}\right)^\beta\right) \quad (13)$$

Then, to generate a random operation time using the Weibull distribution with given parameters  $\beta$  and  $\eta$ , a uniform random number from 0 to 1,  $U_R[0,1]$ , is first obtained. The random time according to the Weibull distribution is then obtained from [27]:

$$T_R = \eta \cdot \{-\ln[U_R[0,1]]\}^{\frac{1}{\beta}} \quad (14)$$

The equation above is valid for  $0 < U_R < 1$ . The random value of time to failure  $T$  is determined on the basis of the parameters of shape and scale. The Monte Carlo simulation was performed using the ReliaSoft package and the following input data:

- simulation end time: 35040 [h],
- point results every: 10 [h],
- number of simulations: 10000.

The simulation calculations were carried out for the data presented in Table 4. These are data obtained from the actual process of operation of the locomotives under consideration, and the presented probability distributions describe the operating time to failure of individual subassemblies. For obvious reasons, the locomotives in service are subject to preventive maintenance and renewal (within the framework of the so-called maintenance levels, as previously described). Therefore, the results of the calculations presented as “obtained in the absence of preventive renewal” (“CM”, Table 5) refer to failures occurring in the process of operation despite the preventive activities carried out in reality. The results of the calculations are presented as “obtained taking into account preventive renewal” (“CM + PM”, Table 5) refer to a simulated operational process in which other preventive activities are carried out (however, the same probability distribution of operating time to failure as in the previous case is used as the basic reliability model). Such a simplification assumption was necessary because it is not possible for the vehicles concerned to actually be operated (and tested) in the absence of any preventive measures. Nevertheless, the results obtained (Table 5) clearly show that some modification of the initial (i.e. current, actual) preventive renewal strategy may significantly improve the availability of the locomotives used. This fact shows the great practical importance of the

results of the research and analyses carried out. The results of the simulation calculations in the form of indices characterized in Section 5.1 are provided in Table 5 and in Figs. 4 - 8.

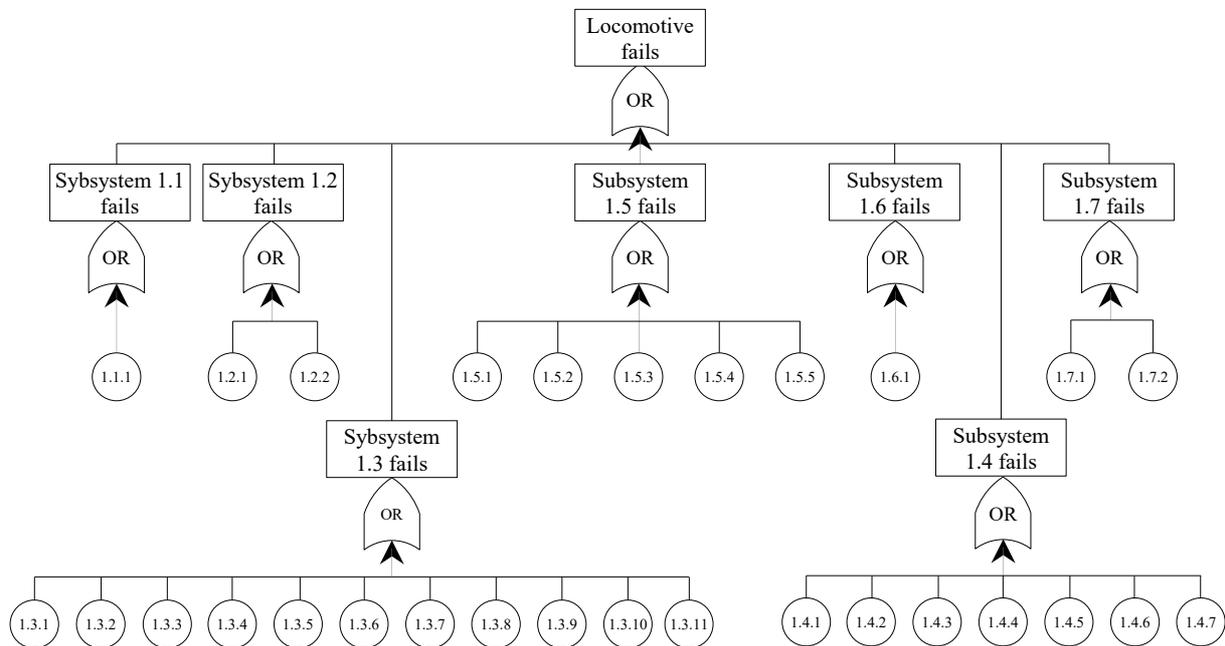


Fig. 3. Fault tree diagram of the 6Dg locomotive

The results obtained and presented in Table 5 clearly show an improvement in the availability and downtime rates after the inclusion of preventive maintenance in the locomotive maintenance strategy. The mean availability increased by 4.55%, while the total downtime decreased by 64.73%. As a result of the restriction of the occurrence of the expected failures from 168 to 62, the mean time between failures extended from 209 to 560 h. The benefits of application of preventive maintenance together with corrective maintenance translate directly into a reduction of the costs of unavailability, which were not considered within the paper presented.

Fig. 4 presents changes in the availability of the locomotive in both cases concerned. It is clear that the introduction of other preventive maintenance operations has resulted in a stable and significantly higher value of the locomotive availability index.

*RS DECI* considers all downing events (failures and preventive maintenance) that cause an interruption in the locomotive's operation. Fig. 5 shows the values obtained by the application of the simulation analysis for two different maintenance strategies. The results indicate that taking into account both the preventive and corrective maintenance strategies, the component causing the most of downing events is the locomotive's operator. *RS DECI* is equal to 15.53%, which implies that 15.53% of the events when the vehicle was down resulted from the improper use of it.

*RS DTCTI* (Fig. 6) illustrates the range of the components that contribute most to the downtime of the system. It refers to failure times and durations of repairs. Considering the corrective maintenance only, the weakest element is IC engine (1.2.1) which caused 83 failures and generated 12.5 h for a single repair. Considering both of these indexes, the above-mentioned component contributes to the longest downtime of the entire system. The situation may be improved by introducing the preventive maintenance strategy (Fig. 6a), which significantly decreases the total downtime from 2417 to 863 hours (Table 5).

A similar result may be observed on the basis of the *RS FCI* (Fig. 7), which takes into account the failures as the only reason for staying the locomotive in the downing state. Moreover, the difference between the weakest component and the rest of the components is greater than in the case when preventive maintenance is performed together with corrective maintenance.

Table 5

Results of simulation calculations

Parameter	CM + PM	CM	Change [%]
Mean Availability (All Events):	0.9860	0.9431	+4.55
Point Availability at 35040 [h]:	0.9753	0.9310	+4.76
Uptime [h]:	34177	32623	+4.76
Total Downtime [h]:	863	2417	-64.73
<b>Summary Metrics</b>			
MTTFF [h]:	714	591	+20.81
MTBF [h]:	560	209	+167.94
MTTR [h]:	11	14	-21.43
<b>System Failures</b>			
Expected Number of Failures:	62	168	-63.10
<b>CM Actions</b>			
Number of CMs:	63	168	-62.5
CM Downtime [h]:	673	2417	
<b>PM Actions</b>			
Number of PMs:	95	0	-
PM Downtime [h]:	190	0	-

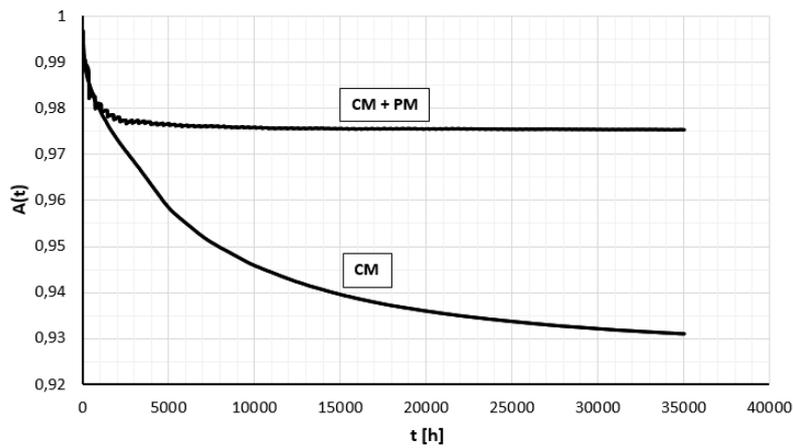


Fig. 4. Point availability  $A(t)$  of the locomotive: CM+PM – Preventive + Corrective Maintenance, CM – Corrective Maintenance only

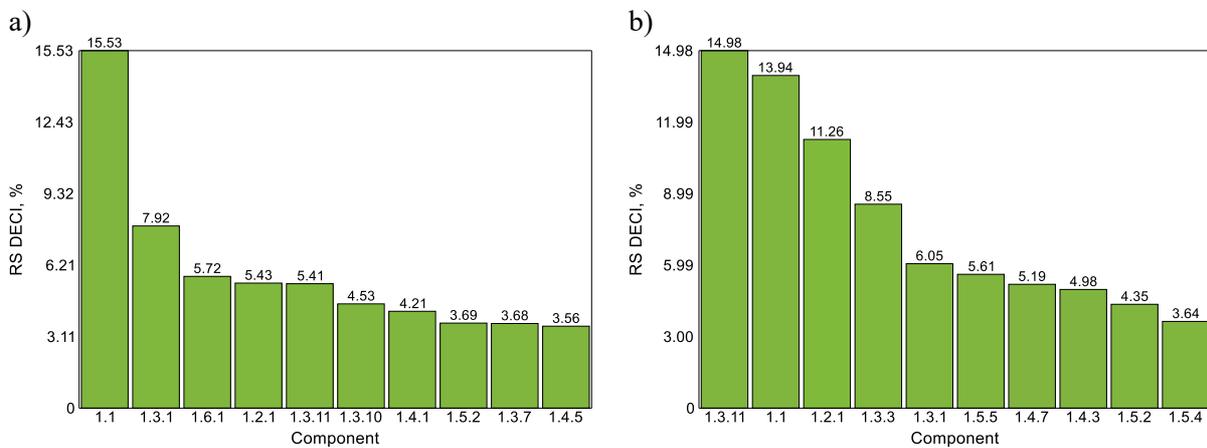


Fig. 5. RS DECI: a) Preventive + Corrective Maintenance, b) Corrective Maintenance only

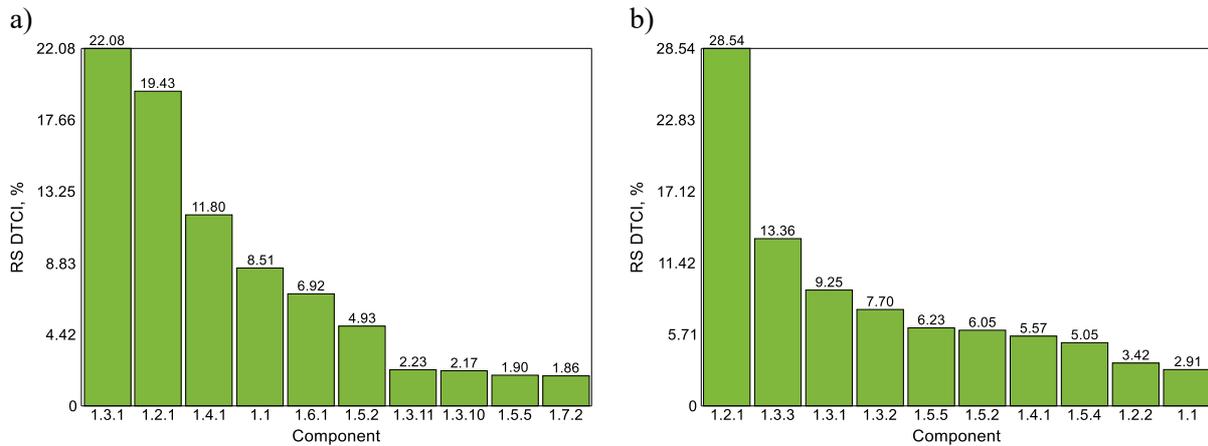


Fig. 6. *RS DTCl*: a) Preventive + Corrective Maintenance, b) Corrective Maintenance only

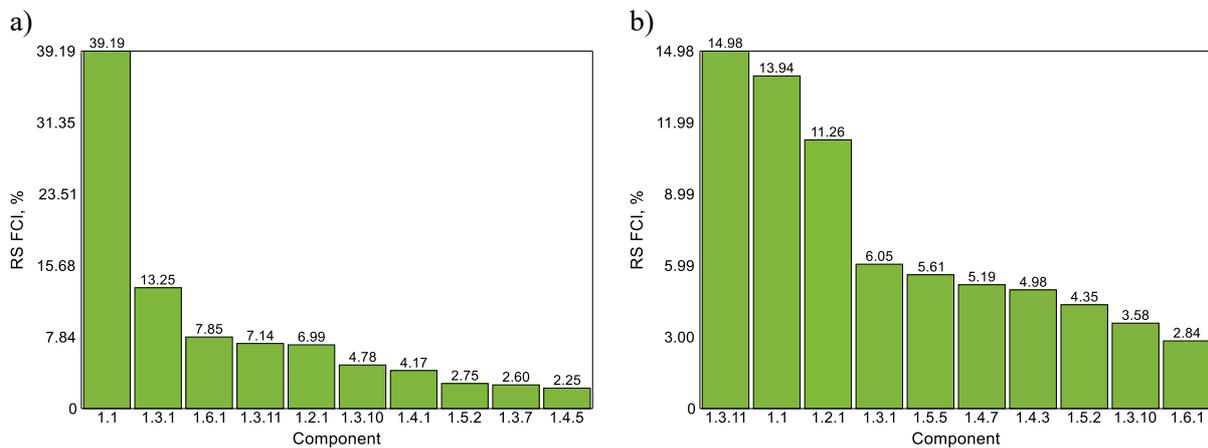


Fig. 7. *RS FCl*: a) Preventive + Corrective Maintenance, b) Corrective Maintenance only

## 6. CONCLUSIONS

In the research project presented in the paper, Monte Carlo simulation was performed to determine the reliability and availability of 6Dg locomotive. A fault tree model of the locomotive was developed to determine the effects of component failures on the locomotive operation process. Discrete simulation was conducted to estimate selected characteristics and indexes for the evaluation of reliability and availability of rail vehicles. The analyses were done on the basis of the empirical data, derived from the supervised operation of a sample of seventy-five 6Dg locomotives. In this way the weakest components were identified. Moreover, more than 20% of all the downing events of the locomotive were registered due to the operator's faults. The obtained results may be a basis for further improvement of preventive maintenance strategy in order to improve the reliability, availability, and reduce costs of the analyzed locomotive maintenance. Preliminary activities indicate that locomotive's MTBF can be improved by around 168% in the framework of overall maintenance plan and the possible savings in unavailability costs for the whole series of locomotives (119 vehicles) can be reached the amount of 387 thousand EUR/year.

The analysis took into account the renewal of the components for which the beta parameter is less than zero. This approach is in line with the maintenance manual documentation of the locomotive; however, it seems rationally unjustified. The results obtained indicate that changes in the maintenance manual are needed and that renewal of the components whose failure rate function is decreasing can

be omitted in selected period. In future studies, the authors plan to consider imperfect repairs for the individual components of the locomotive as well as changing the duty cycle during the operation of vehicles.

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