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RELIABILITY AND AVAILABILITY ASSESSMENT OF DIESEL LOCOMOTIVE USING FAULT TREE ANALYSIS

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Abstract: *The article presents an application of a method based on fault tree analysis and the Monte Carlo simulation in the assessment of reliability and availability of the rail means of transport. The primary target of the presented method is a cause and effect assessment of the occurrence of undesirable events, the determination of selected reliability indices and identification of the weakest components of rail vehicle that affect the downtime and technical availability most strongly. To illustrate the application of the presented method, the results of a project involving a 6Dg diesel locomotive, carried out in cooperation with the biggest Polish rail carrier, are shown. The assessment of availability and reliability was based on real operation data of a selected sample of seventy-five locomotives. Based on the collected data from the operation of the 6Dg locomotives, the times-to-failure and the times-to repair models were determined. A fault tree model of the locomotive was developed to assess the influence of the faults of the components on the reliability of the vehicle. A discrete simulation process allows to obtain a chosen characteristics and values of the selected measures, which – according to the authors – may be applied to assess the reliability and availability of the rail vehicles. Specialist software including Weibull++, BlockSim and MiniTab aided calculations were performed. The software includes and advanced solutions in the range of the reliability and availability simulations. The test results indicate that the proposed solution has a wide applicability potential*

Key words: *reliability and availability assessment, Fault Tree Analysis, rail vehicles, Monte Carlo simulation.*

1. Introduction

The assurance of a high level of reliability and technical availability of rail vehicles is of fundamental importance in view of the huge financial losses caused by undesirable events in rail traffic. The classic reliability and availability analysis tends to be preceded by the decomposition of the investigated vehicle into basic systems and components, which is followed by the mathematical modelling of the effect of their failure on the functioning of the whole object. The graphical methods of the interpretation of the relationship between components and system, recommended in the literature and standards, include Markov models, Reliability Block Diagram (RBD) and Fault Tree Analysis (FTA).

Rail means of transport belong to a group of repairable objects, for which there is a distinction between description of reliability to first failure and description of reliability taking into account the number of failures and repairs. In the reliability and availability analysis Markov models can be applied when the distribution of failure-free service time and repair time are approximated by exponential distribution. In the case of rail vehicles the assumption of exponential distribution is a drastic simplification. The analysis of operational data indicates that only a small percentage of rail vehicle components have a constant rate of failures or repairs. In the assessment of rail vehicle time to failure what is applied are more complex distribution types such as two or three parameter Weibull distribution which allows taking into account complex operation scenarios (Jaźwiński et al., 2001). As for repair time, it is often assumed to begin immediately after the failure occurred, which in real conditions is practically impossible. Generally, repair time is characterised by log-normal distribution, and between the moment of failure occurrence and repair termination there are two time intervals: time of waiting for the repair and the actual time of repair. It is the simulation methods such as FTA and the Monte Carlo simulation (Manzini et al., 2010; O'Connor, 2010) that accommodate for the above requirements in the reliability and availability analysis. In the world literature covering the standards, reports, scientific journals and conference proceedings there are many publications devoted to FTA method and the Monte Carlo simulation, however, there are only few publications on the practical applications for rail vehicles (Rao et al., 2010; Han and Lim, 2012; Merle et al., 2014; Qui et al., 2014; Raidwan et al., 2013; CUT, 2007; Xia et al., 2012). FTA has been widely applied as a method of quantitative and qualitative assessment of the reliability of the rail means of transport. This method presents a combination of casual random events that lead to the occurrence of the top event. Monte Carlo simulation is a valuable method commonly used in the solution of various engineering problems. The literature provides numerous examples of the application of the Monte Carlo method to learn the causal and random properties of the reality being experienced (Chłopek, 2009). Recently this method has been used increasingly in the analysis of the availability of complex technical systems (Marquez et al., 2005; Zio et al., 2007).

The aim of the present paper is to discuss the application of the fault tree method together with the Monte Carlo simulation in the assessment of the reliability and availability of a modernized 6Dg diesel locomotive. From the beginning of its life cycle the locomotive is governed by LCC (Life Cycle Cost) which includes an LCC analysis at the design stage, its verification, to the operation costs optimization. In 2015 an analysis of unavailability costs (UNC), which result from the locomotive's unavailability state caused by corrective or preventive maintenance, was performed. Unavailability costs include, inter alia, liabilities costs, warranty costs, lost opportunity costs, costs of maintenance of stand-by locomotives. On the basis of research and development projects conducted at the Institute of Rail Vehicles of the Cracow University of Technology in the years 2006–15, the share of UNC in the LCC of diesel locomotives over the operation period of twenty-five years reaches up to 13,2% depending on the type of vehicle (Szkoda and Babeł, 2016; Szkoda and Tułecki, 2016). The fundamental task in UNC minimization is the identification of the weakest components of the locomotive of the highest contribution to the locomotive's downtiming.

2. Characteristics of research object – 6Dg diesel locomotive

Diesel engine locomotives are used as the parts of drive units in many rail vehicles. A very important issue due to the operation of the such units is to develop a preventive maintenance strategy to avoid unplanned and costly failures. The methods of diagnosing the diesel engines are particularly important (Tomaszewski & Szymański, 2012).

In 2007 NEWAG S.A. performed prototype modernisation of the 6D diesel engine used in Poland for over forty years. These locomotives are the most common series of locomotives in Poland (in December 2012 there were 1013 such locomotives). The main job of the locomotive was shunting manoeuvres at hump yards. In 2009, after two-year testing of the prototype locomotive, the first locomotive was manufactured for PKP Cargo S.A., the biggest Polish rail carrier. After the modernisation the locomotive was given the symbol 6Dg (Fig.1a). The modernisation scope included the replacement of the a8C22 diesel engine used till then by a new 12-cylinder diesel C27 Caterpillar engine, of 653 kW power (since 2010 of 708 kW power), meeting the exhaust emission standard after 2004/26/WE Directive. Selected technical parameters of 6Dg locomotive are shown in figure 1b, its detailed description is given in (Szkoda and Babeł, 2016).

At present there are over 180 modernised 6Dg locomotives in service, 119 of which used by PKP Cargo S.A.

3. Operational investigation and the structure of failures of modernized 6Dg locomotive

The reliability assessment of modernised 6Dg locomotive was based on the operation data of a selected sample of seventy-five vehicles in service at PKP Cargo S.A. in the period of January 2014 till March 2015. Over this period the locomotive's operation was observed, its subassemblies and components in various conditions, which provided reliable and extensive data for reliability analysis. The investigation was conducted after a plan [n, R, t], in which n number of vehicles were examined, the vehicles failed during tests underwent corrective repairs in order to recover the state of availability, and the investigation terminates after time t. In the analysis of the operation data the occurrence of right censored data had to be accommodated.

a)

b)

No.	Parameter	Value
1	Axle system	Bo-Bo
2	Track gauge	1435 mm
3	Type of transmission	AC/DC
4	Length with buffers	14240 mm
5	Width	3170 mm
6	Distance from rail head	4323 mm
7	On-duty mass of locomotive	70 000 kg
8	Fuel tank capacity	2350 l
9	Effective power	653 kW Stage IIIA 708 kW Stage IIIB
10	Rated/idle running rotation	1800 rpm
11	Number of cylinders in system	V 12
12	Fuel consumption in idling	4,5 l/h
13	Unitary fuel consumption	200 g/kWh
14	Diesel engine capacity	27 l
15	Tractive force at start-up	219 kN
16	Maximum speed	90 km/h

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

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 information on:

- date of failure,
- circumstances of detecting the failure,
- causes of failure,
- time characteristics of services, i.e. repair time, organization downtime,
- labour-consumption of corrective repairs,
- labour consumption and duration of preventive repairs,
- used materials and spare parts,
- repair operations technology.

Table 1 presents the basic information on the operation process of the investigated locomotives.

In the analysed period of operation the total of 490 failures were recorded. The structure of the failures for the investigated sample of locomotives as divided into seven separate systems of the locomotive is shown in figure 2, while the structure of failures following a division into 29 components in figure 3.

4. Fault tree model of 6Dg locomotive

The locomotive's reliability and availability assessment can be analysed from the point of view of the effect of any system or component. On this choice the fault tree structure is based. Figure 4 illustrates a fault tree model of 6Dg locomotive failures, with the division into subsystems and components, considered in the analysis.

Using the operation based data reliability models of time to failure (TTF) and time to repair (TTR) for 6Dg locomotive were made. In the TTF analysis two-parameter Weibull distribution was used, for which the probability density function of fault-free performance is expressed by formula (O'Connor, 2010):

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

where:

β – parameter of shape,

η – parameter of scale.

Table 1. Information on operation process of 6Dg locomotives

Start of observation	End of observation	Number of locomotives	Labour time		Mileage	
			Total (hrs)	Mean (hrs/day)	Total (km)	Mean (km/day)
1.01.2014	31.03.2015	75	550.125,0	16,3	3.564.000,0	105,6

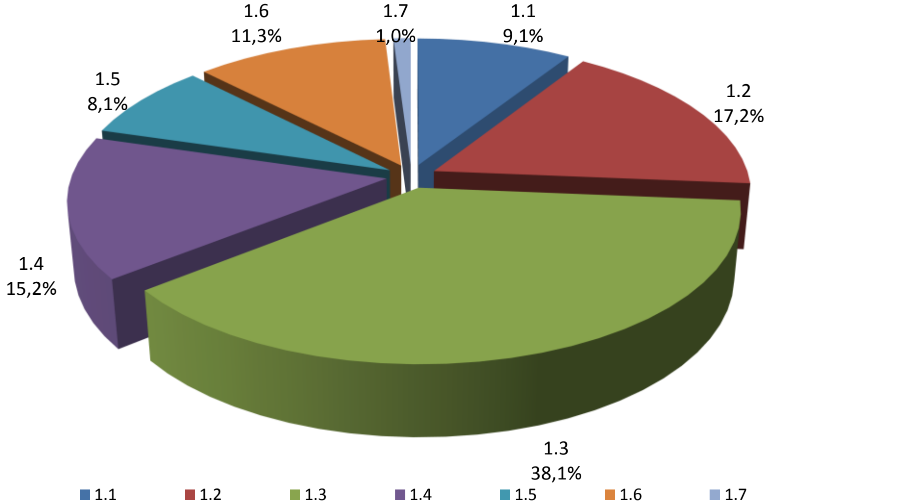

Fig. 2. Structure of 6Dg locomotive's failures as divided into locomotive systems. Notation as in Table 2 (column 1 "Code")

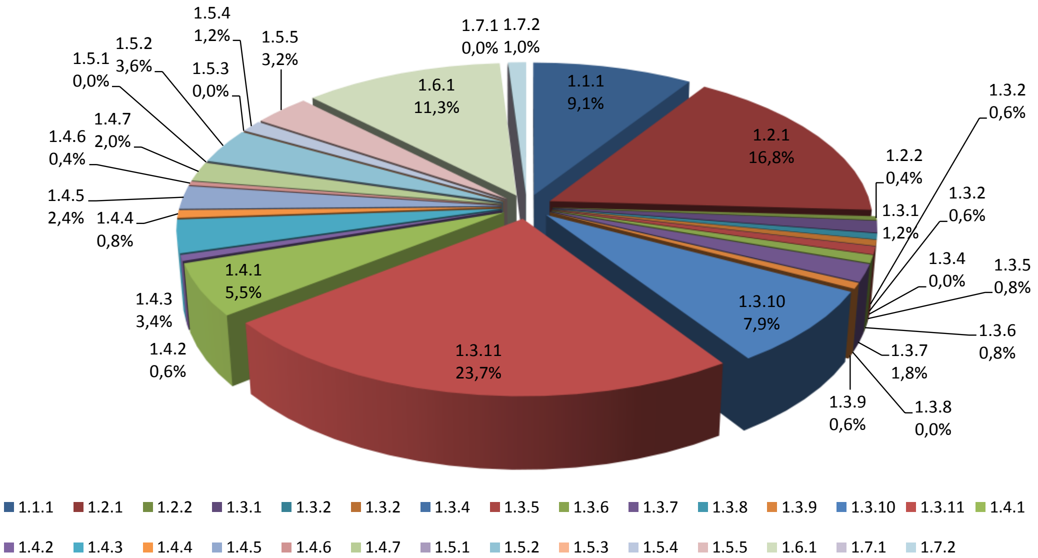

Fig. 3. Structure of 6Dg locomotive failures as divided into components. Notation as in Table 2 (column 1 "Code")

The distribution parameters, including right censored data, together with the computed MTTF (Mean Time To Failure), divided into locomotive's subsystems and components, are presented in Table 2. The table also includes the basic indices for MTTR (Mean Time To Repair) and MLDT (Mean Logistic Delay Time) considered in the reliability and availability analysis.

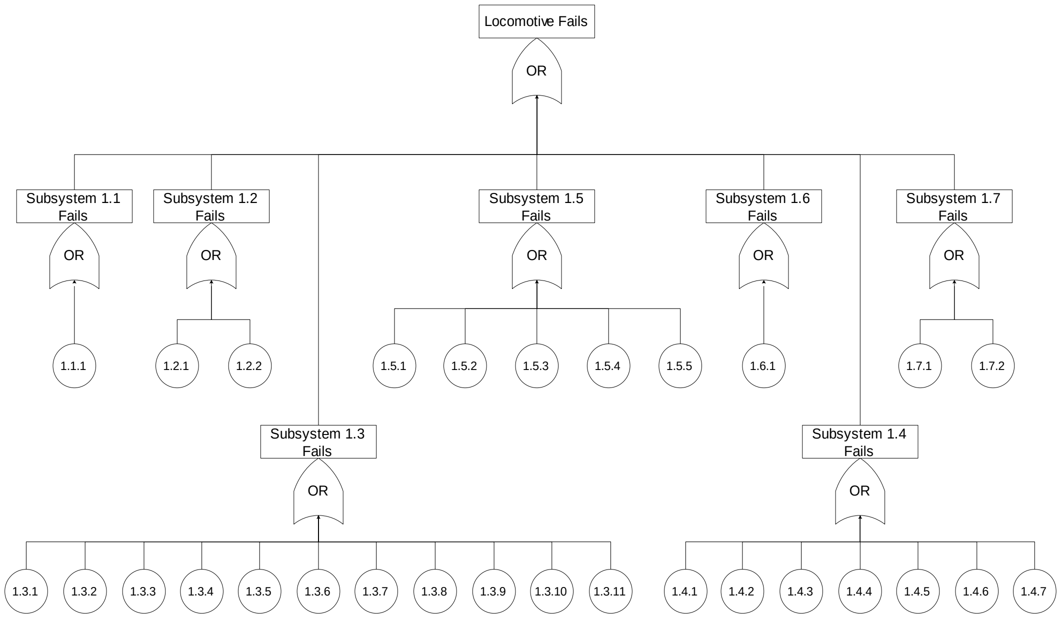

Fig. 4. 6Dg locomotive fault tree model

Table 2. Distribution parameters of TTF and TTR of 6Dg locomotive components

Code	System/Subsystem/Elements	Number of failures	Parameters of Weibull distribution (β, η)		MTTF [hrs]	MTTR [hrs]	MLDT [hrs]
			β	η			
1.	2.	3.	4.	5.	6.	7.	8.
1	**6Dg locomotive**						
1.1	**Locomotive's operator**						
1.1.1	Failures caused by improper service	45	1,5242	1.531,04	1.379,5	2,0	1,0
1.2	**Locomotive's power transmission system**						
1.2.1	IC engine (including fuel system, cooling system with fan and pump, lubrication system, heat exchanger)	83	1,7098	2.811,91	2.507,9	12,5	24,0
1.2.2	Engine speed governor	2	2,1447	14.613,3	12.941,7	3,0	24,0
1.3	**Locomotive's electrical system**						
1.3.1	Railway motors	6	1,0975	3.567,00	3.444,5	14,0	8,0
1.3.2	Master generator	3	2,8388	11.167,4	9.949,3	16,0	24,0
1.3.3	Auxiliary generator	3	6,5558	4.395,82	4.097,8	10,5	12,0
1.3.4	Converter	0	no data	no data	no data	no data	no data
1.3.5	Contactor	4	1,8212	15.556,2	13.826,3	2,0	1,0
1.3.6	Other connectors (running controller, disconnecting switch, circuit breaker, etc itp.)	4	1,6539	17.253,2	15.425,2	4,0	1,0
1.3.7	Relay (protective or control)	9	0,9006	30.012,5	31.567,2	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	10.916,9	9.668,4	2,0	2,0
1.3.10	Storage batteries	39	1,2462	6.619,19	6.169,3	2,5	1,0
1.3.11	Other components of electrical circuits	117	1,9503	2.275,13	2.017,4	1,5	1,0

Table 2. Distribution parameters of TTF and TTR of 6Dg locomotive components (cont.)

Code	System/Subsystem/Elements	Number of failures	Parameters of Weibull distribution (β, η)		MTTF [hrs]	MTTR [hrs]	MLDT [hrs]
			β	η			
1.	2.	3.	4.	5.	6.	7.	8.
1.4	**Locomotive's pneumatic and braking systems**						
1.4.1	Master or auxiliary compressor	27	1,1252	9.607,99	9.203,9	12,0	24,0
1.4.2	Master or auxiliary compressor driving motor	3	1,2142	41.034,1	38.483,2	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	6.010,36	5.357,3	4,0	2,0
1.4.4	Freeze protection	4	0,7204	186.192,0	229.515,0	3,0	1,0
1.4.5	Pneumatic conductors	12	1,0096	22.993,4	22.901,9	3,5	1,0
1.4.6	Servo-motor in braking system	2	1,0221	115.243,0	114.214,0	6,0	2,0
1.4.7	Other elements in pneumatic circuit	10	1,7743	5.867,30	5.221,5	2,5	1,5
1.5	**Locomotive's running gear mechanical system**						
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	6.336,1	5.711,2	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	8.806,18	7.809,6	12,0	8,0
1.5.5	Other elements of running gear	16	2,0962	5.820,74	5.155,5	8,0	8,0
1.6	**Vehicle motion safety automatic control devices**						
1.6.1	Sensors, Measurement instruments (speedometer, ammeter), radio-telephone	56	1,0042	6.909,63	6.897,3	8,0	2,5
1.7	**Other systems of vehicle**						
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	77.751,20	85.083,7	8,0	1,0

5. Analysis of locomotive's reliability and availability

5.1. Reliability ratios applied in the analysis

Rail means of transport can be analysed at various complexity levels. As refers to the 6Dg locomotive investigated in the present study the reliability and availability indices are characterised in what follows in items a ÷ c.

a) Instantaneous technical availability A(t)

Availability has to do with two separate events - failure and repair. Assuming that all the components working in a locomotive are described by identical distribution functions of probability of time to failure and time to repair, instantaneous availability A(t) can be described by the function (Manzini et al., 2010):

$$A(t) = 1 - F(t) + \int_0^t \left[1 - F(t-\tau)\right] h(\tau) d\tau \tag{2}$$

where:

$F(t)$ – distribution function of time to failure,

$h(\tau)$ – probability density function of repair.

b) Mean technical availability A

Formula (2) in practice is used infrequently because of a considerable degree of calculation complexity. What is commonly used instead is the so-called index of mean availability A, defined as a mean contribution of time in which the investigated vehicle remains in the state of serviceability (Szkoda, 2014). For an individual object the availability index is defined as:

$$A = \frac{\sum_{i=1}^{N} TZ_i}{\sum_{i=1}^{N} TZ_i + \sum_{i=1}^{N} TUB_i + \sum_{i=1}^{N} TUP_i} \tag{3}$$

where:
TZi – time of vehicle "i" in serviceability state,
$TUBi$ – time of vehicle "i" in unavailability state due to corrective repairs,
$TUPi$ – time of vehicle "i" in unavailability state due to preventive repairs,
N – sample size of vehicles taken for tests.

c) Reliability function R(t)

$$R(t) = \int_t^{\infty} f(t)dt, \quad t \geq 0 \tag{4}$$

where:
$f(t)$ – probability density function of time to failure, i.e. $f(t)\Delta t$ is approximately the probability that the vehicle failure event will occur in time interval (t, $t+\Delta t$).

d) RS DECI (ReliaSoft's Downing Event Criticality Index)

This is a relative index showing the percentage of times that a downing event of the block caused the vehicle to go down (i.e., the number of vehicle downing events caused by the component divided by the total number of vehicle downing events). This is obtained from (Reliasoft Corporation, 2009):

$$RS\ DECI = \frac{C_{NSDE}}{N_{ALLdown}} \tag{5}$$

where:
C_{NSDE} – Number of System Downing Events, this is the number of downing events for the vehicles caused by component "i",
$N_{ALLdown}$ – total number of downing events.

5.2. Results of calculations

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

The Monte Carlo simulation applied in ReliaSoft package lies in generating random values of TTF on the basis of 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 (Reliasoft Corporation, 2009):

$$R(T) = \exp - \left(\frac{T}{\eta} \right)^{\beta} \tag{6}$$

Then, to generate a random time from Weibull distribution with given β and η, a uniform random number from 0 to 1, $U_R[0,1]$, is first obtained. The random time from Weibull distribution is then obtained from:

$$T_R = \eta \cdot \left\{ -\ln \left[U_R [0,1] \right] \right\}^{\frac{1}{\beta}} \tag{7}$$

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, owing to which it ensures more realistic representation of the stochastic nature of these failures.

The Monte Carlo simulation performed with the use of ReliaSoft package required the introduction of input data:

- Simulation End Time: 3916,5 h,
- Point Results Every: 1,0 h,
  Number of Simulations: 100000,0.

The parameters thus adopted ensure the representation of the behaviour of the analysed locomotive in real operation conditions. The results of obtained indices for time = 3916,5 h, which corresponds to the mean performance time of 6Dg locomotive at PKP Cargo S.A., are presented in table 3.

Figures 5a and 5b present some other significant results obtained by the simulation analysis. Figure 5a compares the value of point reliability $R(t)$ by assuming non-repairable components and point availability $A(t)$ of the system made of repairable components. In particular, $A(t)$ is the probability that the vehicle is up at time t.

Table 3. Results of reliability and availability indices for 6Dg locomotive

No.	Specification	
1.	**General**	
1.1	Mean Availability (All Events):	0,9689
1.2	Mean Availability (w/o PM, OC % Inspection:	0,9749
1.3	Point Availability (All Events) at 3916,5 h:	0,9676
1.4	Expected Number of Failures:	8,4
1.5	MTTFF (Hr):	604,5
1.6	MTBF (Total Time) (Hr):	467,0
1.7	MTBF (Uptime) (Hr):	452,4
1.8	MTBE (Total Time) (Hr):	345,5
1.9	MTBE (Uptime) (Hr):	334,8
2.	**Locomotive's Uptime/Downtime**	
2.1	Uptime (Hr):	3.794,5
2.2	Corrective Maintenance Downtime (Hr):	98,5
2.3	Preventive Maintenance Downtime (Hr):	23,5
2.4	Total Downtime (Hr):	122,0
3	**Locomotive's Downing Events**	
3.1	Number of Failures:	8,4
3.2	Number of Corrective Maintenance Events:	8,4
3.3	Number of Preventive Maintenance Events:	2,9
3.4	Total Events:	11,3

In the calculations, apart from corrective maintenance performed after a failure has occurred, preventive maintenance P2, which following the locomotive's maintenance procedures is conducted every 1000,0 motohours, has also been taken into account. The preventive maintenance plan does not include the locomotive's operator (element 1.1.1). For preventive maintenance the recovery index was adopted as 0.7. Figure 5b presents the mean availability defined by Eq. 2.

Figure 6, also obtained with the application of the Monte Carlo simulation analysis, illustrates the state diagram, i.e., the up/down diagram, reporting the state of the components and of the locomotive for different values over time from 0 to 3916,5 h. The locomotive fails when a generic component fails, i. e., it passes from the state of function to the state of failure.

RS DECI considers all downing events (failures and preventive maintenance) that cause an interruption in the locomotive's operation. Figure 7 shows the values obtained by the application of the simulation analysis.

The results indicate that for component 1.1.1 (operator's faults), RS DECI = 21.75%. This implies that 21.75% of the time that the vehicle was down was due to improper servicing of the vehicle. Following the simulation it can be stated that the combined RS DECI for four locomotive components: 1.1.1, 1.3.11, 1.3.1 and 1.2.1 is 50.6 %. This means that 14% of the components making up the structure of the locomotive in question contributed more than 50% of the vehicle downtime. From the point of view of the technical availability, these are the weakest elements of the locomotive. This is very useful information in the evaluation of the reliability and availability of railway vehicles. The components should be the first to take into account in downtime minimization and unavailability costs reduction. The analysis indicates, moreover, that components 1.3.7, 1.4.4, 1.7.2 fail at a decreasing failure rate. In their case the preventive maintenance in the form of periodical inspection may result in unintended downtime and costs that may not benefit the locomotive system.

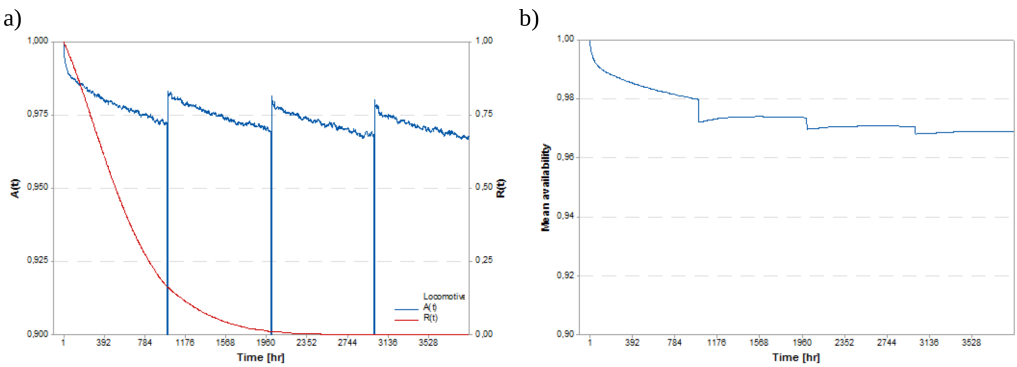

Fig. 5. a) Availability $A(t)$ and Reliability $R(t)$ in function of time b) Mean availability over the period of one year operation

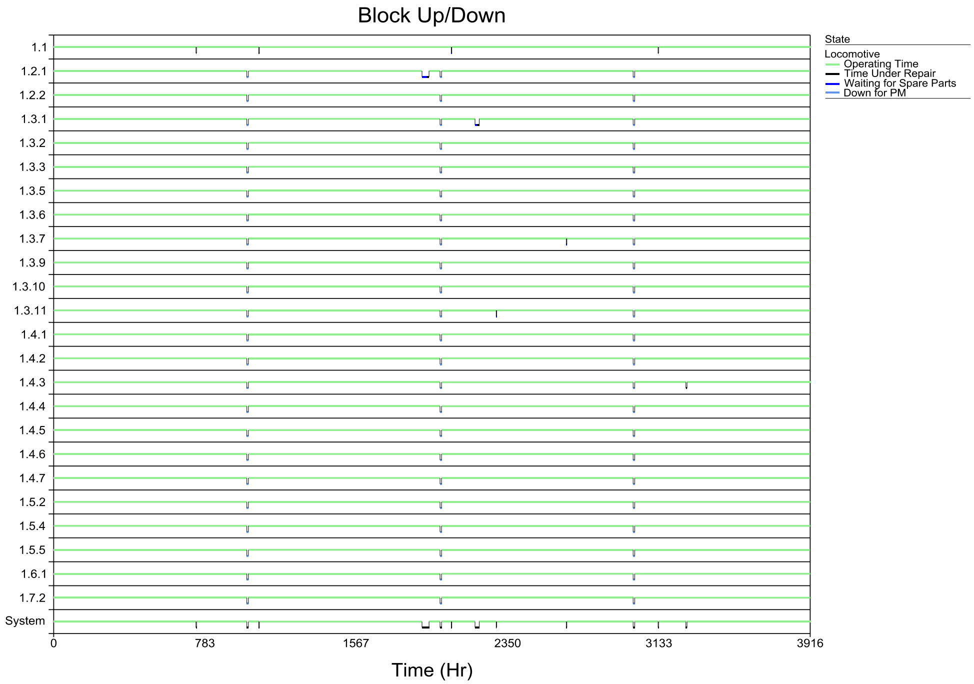

Fig. 6. State diagram (up/down) of the components and locomotive

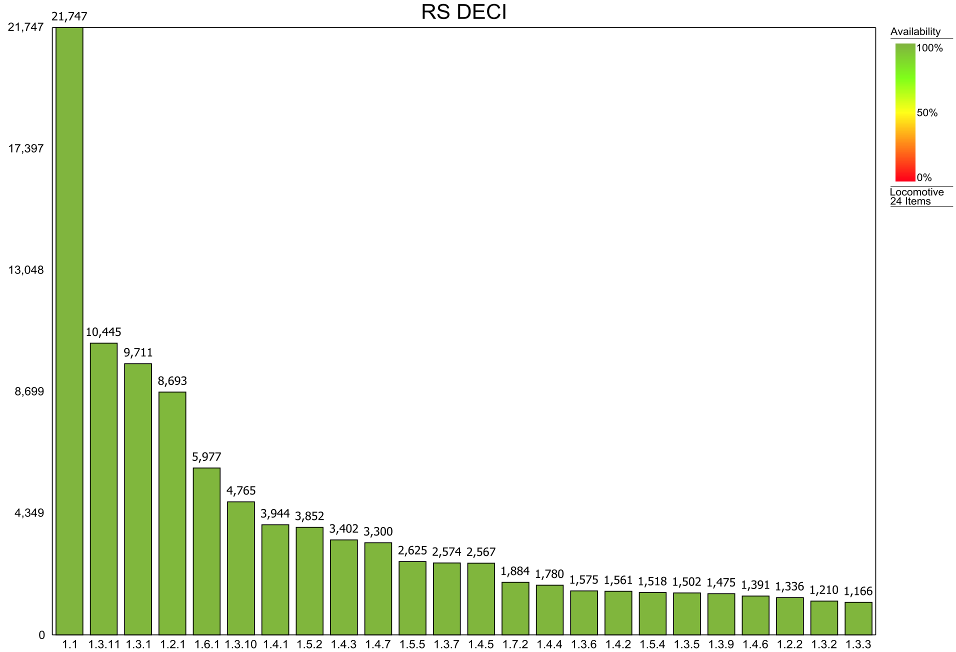

Fig. 7. Downing Event Criticality Index (RS DECI)

6. Conclusion

In the research project presented in the paper the 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 components failures on the locomotive operation. Discrete simulation was conducted to estimate selected characteristics and indices for the assessment of rail vehicles reliability and availability. 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 preventive tasks development to improve the reliability, availability and costs of the analysed locomotive. Preliminary activities indicate that locomotive's mean availability can be improved by 4.94% 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 in the amount of 387 thousand EUR/year.

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