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The application of a simulation method in the evaluation of the reliability of transport systems

Zastosowanie metody symulacyjnej w ocenie niezawodności systemów transportowych

Abstract

Reliability is the one of the key features that determine the probability of the proper functioning of a transport system. It refers to the degree to which the transported load is delivered on time, according to the client's requirements. However, taking into account the complex relationships between the components of the transport system requires the application of appropriate methods of calculation. The paper presents the application of a method of reliability assessment, based on the Dynamic Fault Tree (DFT) and Monte Carlo (MC) simulation. The investigated approach may be used for the identification of weak components of the transport system and may form the basis for the improvement of reliability.

Keywords: reliability, Dynamic Fault Tree, Monte Carlo simulation

Streszczenie

Niezawodność jest jedną z najistotniejszych cech charakteryzujących funkcjonowanie systemu transportowego. Gwarantuje ona dostarczenie ładunku we właściwym czasie, zgodnie z wymaganiami klienta. Jednak, biorąc pod uwagę złożone relacje między elementami systemu transportowego, należy zastosować odpowiednią metodę obliczeń. Niniejszy artykuł dotyczy zastosowania metody Dynamicznego Drzewa Niezdatności (DFT) i metody symulacyjnej Monte Carlo do oceny niezawodności wybranego systemu transportowego. Zaproponowane rozwiązanie może być wykorzystane do identyfikacji słabych ogniw systemu transportowego, może także stać się podstawą do opracowania przyszłych działań mogących wpłynąć na poprawę niezawodności.

Słowa kluczowe: niezawodność, dynamiczne drzewo niezdatności, symulacja Monte Carlo

1. Introduction

One of the most basic aims of a transport system is the provision of the highest level of reliability in each phase of the transport process. Research results available in professional literature show that such a tendency exists irrespective of the profile of an enterprise (Fig. 1). Reliability is also one of the factors that guarantees the competitiveness of a transport system [5].

The reliability of a transport system can be evaluated by selected measurements (indexes). These present the probability level certainty level at which the given service is properly performed. The reliable realisation of transport processes depends primarily on the strategy of management and the organisation of all elements of the transport system [16]. Due to the high level of structure complexity of real transport systems, dynamic changes to the technical condition of their components occur. These are the sequence-dependent events, such as: waiting for repair, being under repair, waiting for a proper operation.

Taking into consideration failure and repair behaviours in the modelling of logic systems requires the application of adequate analytical methods. Classical methods of representing the reliability of transport processes include the Reliability Block Diagram method and Fault Tree Analysis. These techniques are successfully applied in industry; they are widely recognised as the best approaches for the evaluation of the reliability of technical systems, including transport systems [11].

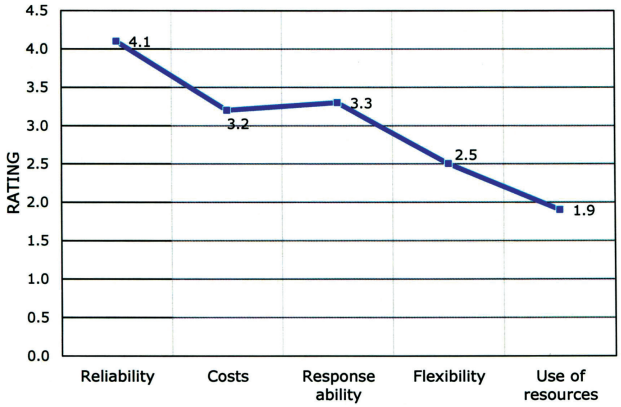

Fig. 1. The main priorities of the logistics industry [10]

FTA is a technique used for the analytical evaluation of reliability. It presents a set of independent events or processes in a graphical way. Certain combinations of these events or processes leads to undesirable events. Based on the Boolean gates 'AND', 'OR', and 'VOTING', FTA determines the probability of the top event. Since FTA is a tool for both the qualitative and the quantitative evaluation of reliability, it is possible to identify critical events and the probability of their occurrence. Like other analytical tools, FTA has one major drawback. There is no possibility to analyse the events that occur only in a specific sequence.

The dynamic fault tree analysis (DFTA) method has been was created to eliminate these limitation. It is complementary to a classical fault tree (FT) due to the inclusion of a few additional logic gates [1, 2, 4, 7].

Several methods have been proposed to solve DFT; two most frequently used are Markov models and the Monte Carlo simulation method. The first of these can only be applied when the components have a lifetime and repair time that are exponentially distributed. Moreover, in the case of a complex system with a large number of elements, the state space complicates the calculation procedure in the Markov process. Therefore, the Monte Carlo simulation method, capable of overcoming many difficulties in different scenarios, is used. This method allows the evaluation of reliability indices through a discrete simulation of the system behaviour at a specific times [3, 8].

2. Solving dft with the use of monte carlo simulation

Modelling issues and transport system reliability evaluation have been discussed in numerous academic papers since there is a need to both limit the occurrence of undesirable events and increase the efficiency of the functioning of these systems. Transport systems are complex systems; their reliability indicators change at each phase of their operation [6, 12, 18].

The analysis of a classical fault tree involves the creation of a set of Boolean equations. The equations are connected with the occurrence of undesirable events in the system. Despite many limitations of this method, e.g. the lack of the possibility of modelling dynamic scenarios for the system's components, the method is still used in a lot of cases. The quantitative and qualitative evaluation of a power system's reliability is an example of its application [17]. In paper [3], the authors carried out a case study on the reactor regulation system (RRS) of a nuclear power plant. The solving of the dynamic fault tree was accomplished with the use of the Monte Carlo simulation.

In some works, the FTA method is used for the evaluation of risk connected with the occurrence of hazards in the proper functioning of technical systems. There are examples of the application of the Monte Carlo simulation in the evaluation of accident risk in aviation. The method has been used to generate alerts for air traffic controllers about a likely collision of a taxiing aircraft on a runway with an aircraft taking off on the same runway [15].

New techniques which extend traditional fault trees are developed in order to eliminate the FTA limitations. One of these, the so-called timed fault trees (TFTs), allows the identification of faults that should be immediately eliminated. This technique also allows the determination of the time needed for maintenance activities. The example of the TFTs application in [13] refers to a case study on a simple railway transport system.

We can also use Petri nets to build transport systems. One example of the application of this method is an analysis of the reliability and efficiency of a real tram system. The performed research shows that models based on the Petri nets can also include time dependencies [13].

3. Description of the system

The scheme of the transport system under consideration in this paper is presented in Fig. 2. This is an inter-modal transport system that consists of a few subsystems in which various vehicles perform other transport tasks. The required reliability level of the transport system is achieved by calculating the number of redundant elements. It has been assumed that each subsystem consists of two identical means of transport arranged in a *cold-standby*. These are repairable objects which undergo strictly determined maintenance activities.

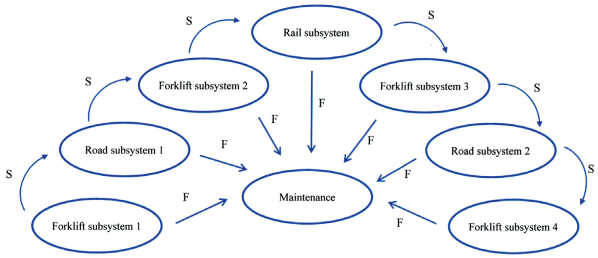

Fig. 2. Scheme of transport system functioning: S – suspended, F – failed

Analyses of transport system reliability should include not only the repair time of damaged elements but also the delay time that is connected with waiting for a standby object. The successful operation of the system requires all of its individual partial processes to be performed, these are:

a) Loading: formation of a unit load and preparation for road transport,
b) Road transport 1: transport of a unit load to the rail terminal,
c) Rail transport: transport of a unit load to the consignee's nearest terminal ,
d) Reloading: reloading of a unit load onto a means of road transport,
e) Road transport 2: transport of a unit load to the delivery point,
f) Unloading: unloading of a unit load and finishing the transport process.

If any of the elementary tasks are not performed, the transport process is assumed to be incomplete.

4. DFT of the system

In order to make a model of the presented transport system by using a fault tree and to take into consideration the described assumptions, one has to use gates with a dynamic dependency. Examples of such gates are' sequence enforcing gates (SEQ), spare gates (SPARE), priority AND (PAND) and functional dependency (FDEP); these are shown in Fig. 3. The rules for the gates are as follows [4]:

a) SEQ gate: this goes into a failure state only when all the input events occur in a specific sequence. No other combination of input events can take place.
b) SPARE gate: this includes active and spare components. If the number of active components is less than the minimum required, the gate fails.
c) FDEP gate: this is used when all the events are functionally dependent on an additional event called the trigger event.

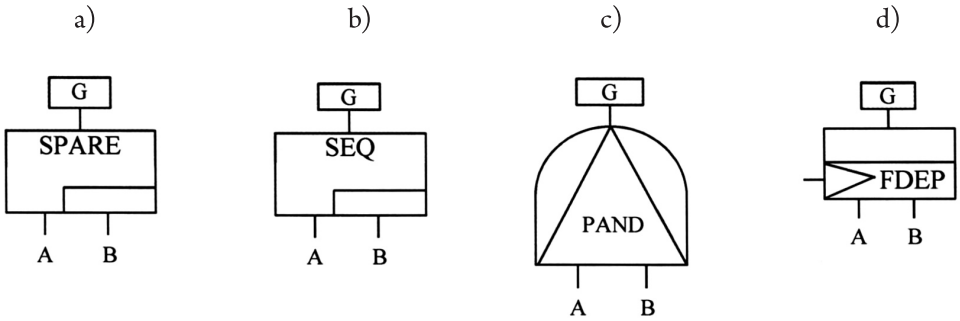

Fig. 3. Dynamic gates: a) SEQ, b) SPARE, c) FDEP, d) PAND

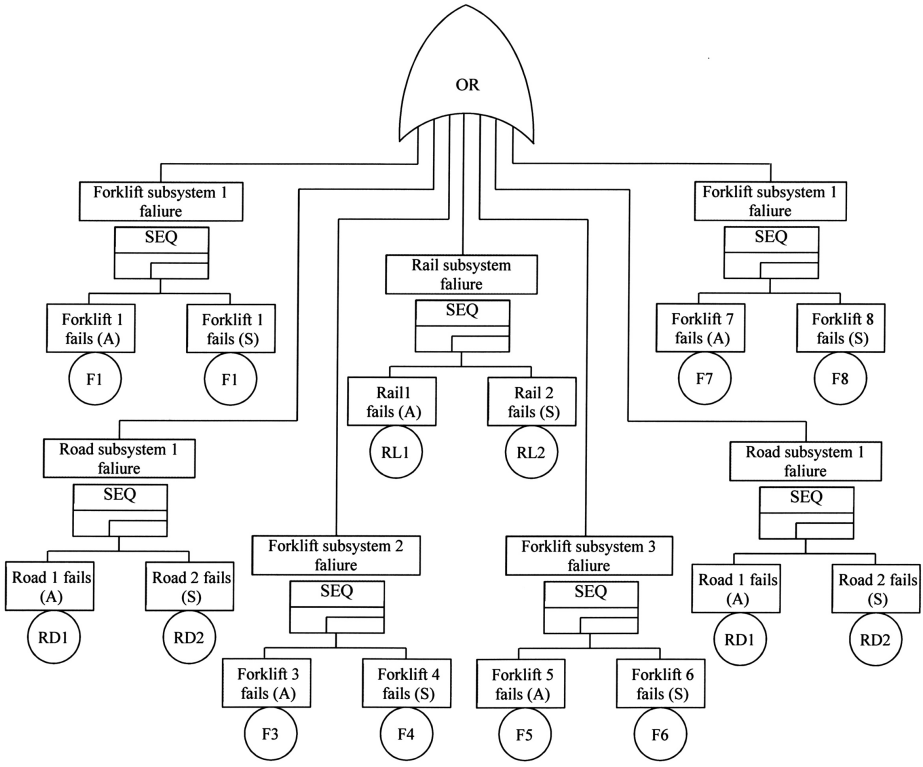

Fig. 4. Dynamic gates: a) SEQ, b) SPARE, c) FDEP, d) PAND

d) PAND gate: this gate goes into a failed state when all the inputs are in a pre-assigned order. Unlike the SEQ gate, PAND gate allows to occur the events out of the desired sequence.

A model of the fault tree of the considered transport system is presented in Fig. 4. The OR gate has been used to assign a top event. This event takes place when an optional partial transport process is. Each process uses specific means of transport. The moment the primary vehicle is damaged, the transport process is stopped and one has to wait until a substitute vehicle arrives. The damaged vehicle is under repair at that time. After the repair the vehicle goes into a standby stage. If the standby vehicle gets failed during repair activities of the primary vehicle, the whole partial process is regarded as being undone. Repair is accomplished when the vehicle is back again in as good as a new condition.

5. Case study

The study presented in the following sections aims to demonstrate the reliability and availability analysis by solving DFT with the use of the Monte Carlo simulation. The analysis was conducted based on hypothetical input data (Table 1).

5.1. Assumptions

In the analysed transport system, it was assumed that the system components have the times to failure that are normally distributed and the repair times that follow the lognormal distribution. The mean delay time (MDT), which is connected with the usage of standby elements, has also been considered. The detailed data is shown in Table 1.

Table 1. Failure and repair data used for the analysis

Component	Failure			Repair	Delay
	Distribution	Parameters		Parameter	Parameter
		Mean (days)	Std (days)	MTTR (hours)	MDT (hours)
F1, F2	NORMAL	60	5	2	2
RD1, RD2	NORMAL	95	5	4	4
F3, F4	NORMAL	70	6	2	2
RL1, RL2	NORMAL	187	11	6	6
F5, F6	NORMAL	65	5	2	2
RD3, RD4	NORMAL	100	10	4	4
F7, F8	NORMAL	55	7	2	2

5.2. Monte Carlo Simulation

The ReliaSoft software package, which provides the simulation of discrete events, was used for the Monte Carlo simulation. This software is commonly used in many industrial applications. The Monte Carlo simulation used in the calculation process is based on a random number generator with the Bays-Durham shuffle algorithm. The simulation requires the introduction of certain input parameters, such as [14]:

- Simulation End Time
- Point Results Every
- Number of Simulations

6. RESULTS

To obtain the results, one hundred thousand simulations were run over the specified period: 0 to 1,825 days. The point results every was assumed as 100,000.0. At the end of the simulation, the results were gathered in the system overview table (Table 2).

Table 2. The simulated results for the 1,825 days of operation

System Overview	
General	
mean availability (all events):	0.9996
standard deviation (mean availability):	0.000147
mean availability (w/o PM, OC & inspection):	0.9996
point availability (all events) at 1825:	0.9964
expected number of failures:	2.3691
standard deviation (number of failures):	0.5940
MTTFF (day):	1,148.7
MTBF (total time) (day):	770.3
MTBE (total time) (day):	543.3
System Uptime/Downtime	
uptime (day):	1,824.4
CM downtime (day):	0.5992
MTTFF (day):	1,148.7
MTBF (total time) (day):	770.3
MTBE (total time) (day):	543.3
System Uptime/Downtime	
uptime (day):	1,824.4
CM downtime (day):	0.5992

Mean availability A, is defined as the mean amount of the time in which the investigated vehicle remains in a state of operability. For an individual object, the availability index is defined as [16]:

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

where:
TZ_i – time of vehicle i in operability 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.

It can be stated on the basis of the obtained results that for the considered transport system, a significant decrease in the system's availability occurs at certain intervals; this is shown in Fig. 5. In order to identify the causes of the decreases in point availability, a block up/down chart may be used (Fig. 6). The timeline shows the moments at which the failures of the primary and secondary component occurs. The expected downtime periods relating to the repair activities are also shown.

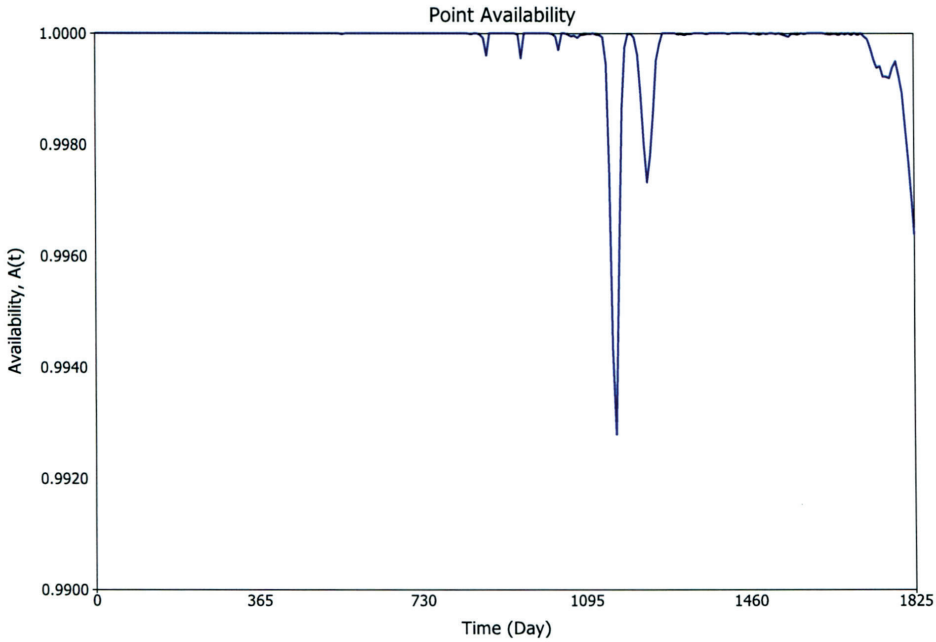

Fig. 5. Point availability vs. time plot

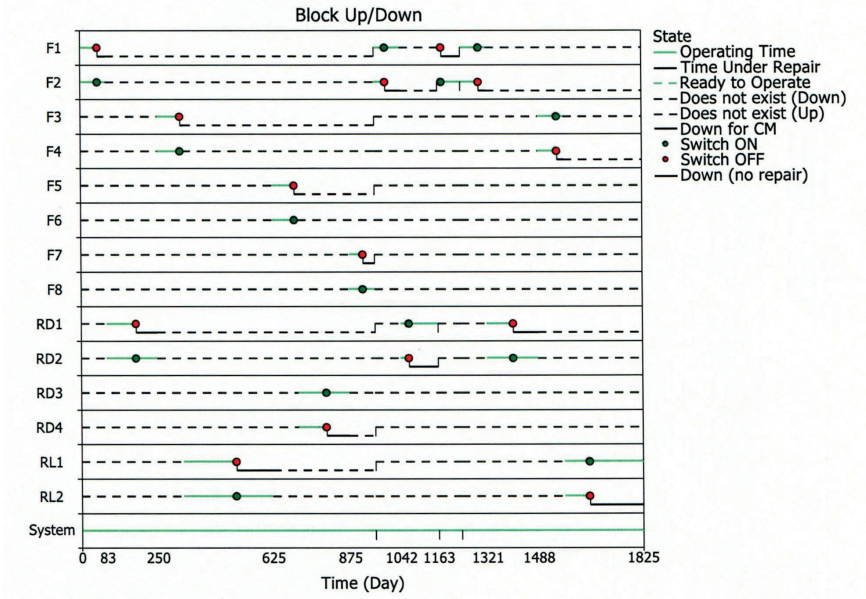

Fig. 6. The system up/down analysis

By analysing the proportion of downing events and the number of failures of the system's components, the weakest component of the system for the simulated end time can be determined. The ReliaSoft Downing Event Criticality Index (RS DECI) and ReliaSoft Failure Criticality Index (RS FCI) are used to achieve this [14].

RS DECI is a relative index which shows the percentage of times when a downing event of a given component causes the system to go down.

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

where:

C_{NSDE} – the number of system downing events; this is the number of times when the given component's downing causes the system to go down,

$N_{ALLdown}$ – the number of downing events.

In the simulation results (Fig. 7), it can be observed that for the F1 component, the RS DECI = 59%. This implies that 59% of the times when the system was down were due to the F1 component being down. Furthermore, the conducted analysis enables the identification that the greatest influence on the system's downtime has two elements: F1 and F2 (forklift 1 and forklift 2). It is related to the reliability-wise configuration (standby redundancy). If the primary element gets failed, its functions are taken by the standby element.

RS FCI is a relative index that shows the percentage of times when a failure of a given component caused the system's failure. This is obtained from:

$$RS\ FCI = \frac{C_{NSDF} + F_{ZD}}{N_F}$$

where:

F_{ZD} – a special counter of the system failures not included in C_{NSDF}. This counter is not explicitly shown in the results but is maintained by the software. The reason for this counter is the fact that zero duration failures are not counted in C_{NSDF} because they do not cause the system to go down. However, these zero duration failures need to be included in computing *RS FCI*,

N_F – number of system failures.

An RS FCI chart for the selected components is shown in Fig. 8. For the RD1 component, RS FCI = 43.5%. This implies that the RD1 component failure was responsible for 43.5% of the times when the system failed. It should be noted that the combined RS FCI of RD1 and F2 is almost 80%. In other words, RD1 and F2 contributed to about 80% of the system's total downing failures.

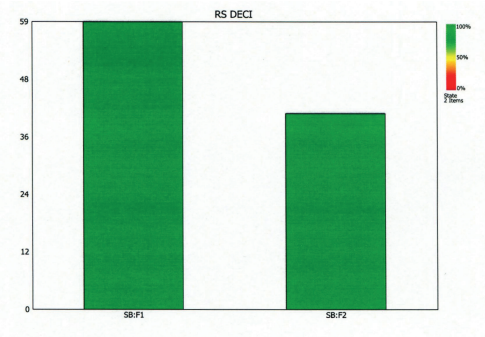

Fig. 7. RS DECI chart for the selected components

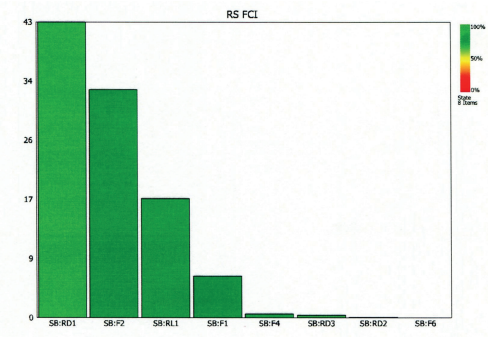

Fig. 8. RS FCI chart for the selected components

It is important to note that RS DECI relates to all the events that cause the system to go down (e. g. waiting for repair, logistic delay), whereas the RS FCI includes only the failures of the analyzed system [14].

7. Conclusion

As a result of the conducted analysis of transport system reliability with the use of a fault tree and the Monte Carlo simulation, the authors obtained the values of the selected indexes that may be used for the determination of the probability of failures of the system elements during operation. This approach allows for a qualitative and quantitative evaluation of reliability and the identification of weak components of the system. It can also constitute the basis for a preventative maintenance strategy. A model thus created of the transport system

can be further developed to achieve the required level of detail. The applied ReliaSoft software package undoubtedly makes usage of the simulation techniques easier, especially in systems with a high level of complexity.

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