Reliability and availability assessment of a transport system using Dynamic Fault Tree and Monte Carlo simulation

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Abstract. Ensuring a high level of reliability of the transport system is one of the most important issues related to the proper functioning of this system. It is concerned with the delivery of the transported goods on time and in accordance with recipient’s order specification. The means of transport used in the delivery process are exposed to many external factors that may affect the reliability and safety of supply. Therefore, modelling and assessing the reliability of these systems requires the use of appropriate calculation methods that take into account complex scenarios reflecting the conditions of actual operation and maintenance. The presented paper concerns the application of Dynamic Fault Tree (DFT) together with Monte Carlo simulation to assess the selected reliability and availability indicators for the given transport system. The assessment of reliability was done based on the typical probabilistic models for analysis of the time to failure and the time to repair assigned to the selected components. The proposed approach allows detecting the weakest components of the transport system and is the basis for the development of preventive maintenance tasks. The presented model of the transport system can be further developed and adapted to needs of the specific system.

1. Introduction

One of the most basic aims of the transport system’s proper functioning is providing the highest level of reliability in each phase of a transport process. Conclusion from current scientific research show the mentioned regularity regardless of the profile of an enterprise (figure 1). Reliability is the factor that improves the transport system’s competitiveness. It comprises such delivery parameters as accuracy, completeness, and punctuality [1].

The reliability of a transport system can be evaluated by chosen measurements (indexes). They present the certainty level at which the given service is properly performed. A reliable realization of transport processes depends primarily on the strategy of management and organization of all elements of the transport system [2].

Due to a high level of complexity of real transport systems dynamic changes of technical states between their elements take place. The changes are connected with time relations, such as sequence dependent events, waiting for operation or repairing, and also with the lack of the possibility of taking spare parts and their priorities into account. Considering both the failure and repair characteristics in modelling of logic systems requires choosing the proper method of analysis. Classical methods of the reliability representation of the transport processes include Reliability Block Diagram (RBD) and Fault Tree Analysis (FTA). These techniques are successfully applied in industry. They are widely recognized as the best ones for the evaluation of reliability of technical systems, including transport systems [3, 4].
FTA is a technique of an analytical evaluation of reliability. It presents a set of independent events or processes in a graphical way. A certain combination of those events or processes leads to undesirable events. Based on the Boolean’s gates (AND, OR, VOTING), FTA determines the so-called probability of the top event. Since FTA is a tool for qualitative and quantitative evaluation of reliability it is possible to identify critical events together with the probability of their appearance. Like other analytical tools, FTA has one major fault. It is the application of this method in systems with dynamic redundancy (e.g. load sharing redundancy or standby redundancy). Lack of the possibility for modelling the events whose only a determined sequence of occurrence can lead to the system’s failure is an additional difficulty. A dynamic fault tree analysis (DFTA) method has been created to get rid of these limitations. It is complementary to a classical fault tree (FT) due to a few additional logic gates [6-9]. Several methods have been proposed to solve DFT; two most frequently are Markov models and the Monte Carlo simulation method. The first one can be applied only when the elements of the technical state have the exponential distributions of time through failure and repair time. Moreover, in the case of a complex system with a great number of elements the state space complicates the calculation procedure in a Markov process. Due to these drawbacks in the application of the Markov process, in the following work the Monte Carlo simulation method was used, which seems to meet these constraints. This method is based on a discrete simulation that allows to estimate the values of reliability indicators in the specific time [8, 10-12].

A modelling issue and a transport system reliability evaluation are discussed in numerous academic papers since there is a need of both limiting the occurrence of undesirable events and increasing the efficiency of functioning of these systems. Transport systems are complex systems. Their reliability functional indicators change at each stage of the process of load moving in a dynamic way [5, 11, 13-15].

The typical approach to fault tree analysis involves the use of Boolean algebra to present the relationship between undesirable events and their impact on system operation. Fault tree method is still widely used despite many limitations resulting from its idea. The most important limitation is the inability to take into account dynamic and complex time dependencies between the basic events. An evaluation of reliability of the power system using quantitative and qualitative approach underlines its valuable and application [16]. In the paper [10] the authors conducted a study related to the reactor regulation system (RRS) for the selected power plant. Solving a dynamic fault tree was accomplished by a numerical simulation.

In the selected papers, the application of FTA method was addressed to assess the risk of a hazard occurrence on the proper operation of a transport system. The possibility of using the Monte Carlo simulation to perform the necessary calculations in the air transport system was also considered. By combining both the methods, it was possible to generate alerts for air traffic controllers about the possibility of collisions in the air traffic [17]. This approach allowed to extend the use of the FTA method in transport-related issues.
New techniques which extend traditional fault trees are developed in order to eliminate the FTA limitations. One of them, the so-called timed fault trees (TFTs), allows an identification of faults that should be immediately eliminated. This technique also allows the determination of time needed for maintenance activities. One of the possibilities of using TFTs was the application referring to the selected rail transport system [18].

To build transport systems also the Petri nets can be used. One of the examples of this method’s application 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 [19].

2. Description of the analysed system

The transport system analysed in this paper is presented in figure 2. It is an inter-modal transport system that consists of a few subsystems in which various means of transport (materials handling, road transport and rail transport) perform other transport tasks. The required reliability level of the transport system is achieved by assuming the number of backup elements. It has been assumed that each subsystem consists of two identical means of transport arranged in a cold standby redundant configuration. They are repairable objects which undergo strictly determined maintenance activities.

![Figure 2. Scheme of transport system functioning: S – suspended, F – failed.](image)

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

- a) Loading: formation of a unit load and preparation for road transport;
- b) Road transport 1: moving the cargo to the desired railway terminal transport of a unit load to the rail terminal;
- c) Reloading: changing the road transport to a railway transport;
- d) Rail transport: moving the cargo to the nearest road terminal;
- e) Reloading: changing the railway transport to a rail transport;
- f) Road transport 2: moving the cargo to the final destination place;
- g) Unloading: discharging the cargo and completing whole to process.

Inability to perform any of the elementary tasks is considered as incorrect operation 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. They are, e.g. sequence enforcing gate (SEQ), spare gate (SPARE), priority AND (PAND) and functional dependency (FDEP), shown in figure 3. The rules for the gates are as follows [9]:

- a) SEQ gate: it goes into a failure state only when all the assigned components occur in a given sequence. Every other combination of the input events cannot take place;
- b) SPARE gate: it is associated with both active and spare components. The correct operation of the system described by this gate occurs if the required number of components is working correctly.
- c) FDEP gate: it is used to show that all the components are functionally dependent on an additional factor, called the trigger;
d) PAND gate: the gate indicates the failure of a system when all the input components will fail in a pre-assigned order. Unlike the SEQ gate, the PAND gate allows for other than pre-assigned sequence of events.

![Figure 3. Dynamic gates: a) SEQ, b) SPARE, c) FDEP, d) PAND.](image)

Fault tree model of the transport system taking into account in the presented study is presented in figure 4. The OR gate represents a top event. This event occurs if any of the partial process of transport is failed. Each process uses certain transport means. The case in which the primary vehicle is failed will result in a stop the operation and the need to take a corrective task. The damaged vehicle is under corrective maintenance at that time. After the corrective maintenance, the vehicle goes into a standby stage. If the standby vehicle gets damaged during repair activities of the primary vehicle, the whole partial process is regarded undone. Corrective maintenance is accomplished when the vehicle is back again in the as good as a new condition.

![Figure 4. The fault tree model of the analysed system.](image)

3. Reliability and availability analysis of the transport system
In the analysed transport system, the system elements have a normal distribution of time over failure (TTF) and a lognormal distribution of the repair time (TTR). The mean delay time (MDT), which is related to the substitution of spare components, is also taken into account. The detailed data are in table 1.
Table 1. Failure and repair data used for the analysis.

| Component | Distribution | Failure Parameters | Repair Parameter | Delay Parameter |
|-----------|--------------|--------------------|------------------|-----------------|
|           |              | Mean | 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              |

The ReliaSoft’s software, which allows to simulate of a discrete event, has been used to perform the Monte Carlo simulation. This specialized tool is widely applied in the different application of the industrial areas. The simulation performed in the following study is based on the Random Number Generator with Bays-Durham shuffle algorithm. The simulation requires an introduction of some input parameters, such as [20]:

a) Simulation End Time (SET);
b) Point Results Every (PRE);
c) Number of Simulations (NoF).

4. Results

The results were obtained using one hundred thousand simulations in the specified period: 0 to 1825 days. The PRE was assumed as 100000. When the simulation was ended the results were gathered in the System Overview table (table 2). The information in the table relies on the mean values.

Table 2. The simulated results for the 1825 days of operation.

| System Overview, General |        |
|--------------------------|--------|
| Mean Availability (All Events): | 0.9996 |
| Std 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 |
| Std Deviation (Number of Failures): | 0.5940 |
| MTTFF, Day: | 1148.7 |
| MTBF, Total Time, Day: | 770.3 |
| MTBE, Total Time, Day: | 543.3 |

| System Uptime/Downtime |        |
|------------------------|--------|
| Uptime, Day: | 1824.4 |
| CM Downtime, Day: | 0.5992 |
| MTTFF, Day: | 1148.7 |
| MTBF, Total Time, Day: | 770.3 |
| MTBE, Total Time, Day: | 543.3 |

Mean availability $A$, is defined as a mean contribution of time in which the investigated vehicle remains in the state of serviceability. For an individual object the availability index is defined as [2]:

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

where $TZ_i$ – time of vehicle $i$ in serviceability 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 a considered transport system a significant decrease in the system’s availability occurs at certain intervals.

By analysing the participation of downing events and the number of failures of the system’s elements 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 do that [20].

RS DECI is a relative index. It shows the amount of time of which the component contributed to the system downing event. (i.e. the number of the system downing events caused by the block divided by the total amount of the system downing events).

$$RS \ DECI = \frac{C_{NSDE}}{N_{AllDown}},$$

where $C_{NSDE}$ is the Number of System Downing Events, this is the number of time when this component’s downing causes the system to be down; $N_{AllDown}$ – the number of downing events.

In the simulation results (figure 5), it can be observed that for the F1 element the RS DECI = 59%. This implies that 59% of the time when the system was down were due to the component F1 being down. Besides, the conducted analysis allows for noticing that the greatest influence on the system’s downtime have two elements: F1 and F2 (forklift 1 and forklift 2). It is connected with an assumed reliability structure together with an unloaded standby. If the primary element gets damaged then its functions are taken by the standby element.

![Figure 5](image)

**Figure 5.** Simulation Results: (a) Point Availability chart; (b) Component Up/Down chart.

RS FCI is a relative index that shows the percentage of time when a failure of this 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’s failures not included in $C_{NSDF}$. This counter is not directly included in the calculations but it is used by the software. The reason for the presence of this counter is that failures with zero duration time are not contained in $C_{NSDF}$ since they really do not down the system. However, these failures are required to be taken into account when we are calculating the RS FCI; $N_F$ – the number of system’s failures.

An RS FCI chart for the selected components is shown in figure 6. For the RD1 component, RS FCI = 43.5%. This implies that the component RD1 failure was responsible for 43.5% of the time 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.
Figure 6. Simulation Results for the selected components: (a) RS DECI chart; (b) RS FCI chart.

It is worth to mention that for both RS DECI and RS FCI, with the overlapping events present, the component that contributed to the system downing event gets credited with this system event. Subsequent components that do not cause the system to go down (because the system might be already down) is not included in this metric [20].

5. Conclusion
As a result of the conducted analysis of the transport system’s 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 this system’s elements failures during operation. This approach allows for a qualitative and quantitative evaluation of reliability and an identification of weak components of the system. It can also constitute the basis for a preventive maintenance strategy. Such created model of the transport system can be further developed until it achieves a required level of detail. The applied ReliaSoft software package undoubtedly makes the usage of simulation techniques easier, especially in systems with a high level of complexity.

References
[1] Gajewska T and Kaczor G 2014 Analiza niezawodności dostaw w transporcie chłodniczym Logistyka 5 453–62
[2] Szkoda M 2014 Assessment of reliability, availability and maintainability of rail gauge change systems Eksplatacja i Niezawodność – Maintenance and Reliability 16 422–32
[3] Jacyna M and Merkisz J 2014 Proecological approach to modelling traffic organization in national transport system Archives of Transport 30 31–41
[4] Nowakowski T 2004 Reliability model of combined transport system. Probabilistic safety assessment and management Proc. Europ. Safety and Reliability Conference PSAM7-ESREL 2004 (London: Springer)
[5] Nowakowski T 2011 Niezawodność Systemow Logistycznych (Wroclaw: Oficyna Wydawnicza Politechniki Wroclawskiej)
[6] Amari S, Dill G and Howald E 2003 A new approach to solve dynamic fault trees Annual IEEE reliability and maintainability symposium 374–89
[7] Cepin M and Mavko B 2002 A dynamic fault tree Reliab. Eng. Syst. Safe. 75 83–91
[8] Manno G, Chiacchio F, Compagno L, D’Urso D and Trapani N 2012 An integrated FT and Monte Carlo Simulink tool for the reliability assessment of dynamic fault tree Expert. Syst. Appl. 39 10334–42
[9] Faulin J, Juan A A, Matrorell S and Remirez-Marquez J E 2010 Simulation Methods for Reliability and Availability of Complex Systems (London: Springer-Verlag)
[10] Durga Rao K, Gopika V, Sanyasi Rao V V S, Kushwaha H S, Verma A K and Srividya A 2009 Dynamic fault tree analysis using Monte Carlo simulation in probabilistic safety assessment *Reliab. Eng. Syst. Safe.* **94** 872–83

[11] Marseguerra M and Zio E 2004 Monte Carlo estimation of differential importance measure: application to the protection system of a nuclear reactor *Reliab. Eng. Syst. Safe.* **86** 11–24

[12] Szkoda M and Kaczor G 2016 Reliability and availability assessment of diesel locomotive using Fault Tree Analysis *Archives of Transport* **40** 65–75

[13] Jacyna-Golda I, Żak J and Gołębiowski P 2014 Models of traffic flow distribution for various scenarios of the development of proecological transport system *Archives of Transport* **32** 17–28

[14] Kaczor G 2015 Modelowanie i ocena niezawodności systemu transportu intermodalnego *Logistyka* **3** 2047–54

[15] Nowakowski T and Zając M 2005 Analysis of reliability model of combined transport system *Advances in Safety and Reliability – Proc. Europ. Safety and Reliability Conference (ESREL 2005)* 147–51

[16] Volkanowski A, Cepin M and Mavko B 2009 Application of the fault tree analysis for assessment of power system reliability *Reliab. Eng. Syst. Safe.* **94** 1116–27

[17] Stroeve S H, Blom H A P and Bakker G J 2009 Systematic accident risk assessment in air traffic by Monte Carlo simulation *Safety Science* **47** 238–49

[18] Peng A, Lu Y, Miller A, Johnson C and Zhao T 2014 Risk assessment of railway transportation system using timed fault tree *Qual. Reliab. Eng. Int.* **32** 181–94

[19] Kowalski M, Magott J, Nowakowski T and Werbińska-Wojciechowska S 2011 Analysis of transport system with the use of Petri nets *Eksplotacja i Niezawodność – Maintenance and Reliability* **13** 48–62

[20] Reliasoft Corp. 2010 *System Analysis Reference* (Tucson, USA: ReliaSoft Publishing)