Article citation info:
WERBIŃSKA-WOJCIECHOWSKA S. Time resource problem in logistics systems dependability modelling. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2013; 15 (4): 427–433.

Sylwia WERBIŃSKA-WOJCIECHOWSKA

TIME RESOURCE PROBLEM IN LOGISTICS SYSTEMS DEPENDABILITY MODELLING

PROBLEM REZERWOWANIA CZASOWEGO W MODELOWANIU NIEZAWODNOŚCI SYSTEMÓW LOGISTYCZNYCH*

Article presents an overview of some recent developments in the area of mathematical modelling of technical systems' maintenance decisions with the use of delay-time concept. Thus, the literature overview from 1984-2012 in the analysed research area is given. The problem of time relations occurred in logistic systems performance processes is investigated. Later, the example of DT model implementation in the area of logistic system of sixteen forklifts performance analysis is investigated.

Keywords: delay-time concept, dependability, logistic system.

W artykule przedstawiono zagadnienia związane z matematycznym modelowaniem utrzymania systemów technicznych w stanie zdatności z wykorzystaniem koncepcji opóźnień czasowych (DT). Przedstawiono przegląd literatury z badanego obszaru obejmujący okres 1984-2012. Następnie został omówiony problem relacji czasowych w systemach logistycznych. W ostatnim punkcie, został przedstawiony przykład zastosowania modelu DT do oceny niezawodności szesnastu wózków widłowych funkcjonujących w wybranym systemie.

Słowa Kluczowe: koncepcja opóźnień czasowych, niezawodność, system logistyczny.

1. Introduction

In any logistic system operating under an increasingly complex and diverse system environment, there is a need to take into account the possible unreliability of logistic system elements, which may lead to decrease of the system availability level. In the maintenance and reliability theory literature, there are many studies dealing with the problem of designing reliable and available logistic support systems for repairable items performance [61]. However, most of the developed models focus only on spare parts availability (see e.g. [12, 21]) or repair facilities availability (see e.g. [1, 7, 26, 47, 56, 57]), and the problem of possible interactions, which may occur between operational system and its logistic support system is usually not analysed. At the same time, dependability analyses being carried out with the use of known models are incomplete due to the lack of assessment of interactions between both the systems being in cooperation influence on the overall functional reliability.

The article focuses on the problem of logistic support system reliability modelling with the use of Delay Time Analysis (DTA). Consequently, a literature overview, as well as the issues of time relations occurred in logistics systems are presented. In the second part of the article, the focus is on analysis of the case company, which performs maintenance and service operations of forklifts. Moreover, there is used the basic model of system inspections with the use of DTA to evaluate the reliability of operating facilities.

2. Problem of time relations in technical systems performance modelling

In the case of complex systems, where the problem of relations between two consecutive subsystems modelling occurs and influence the overall system availability, many works indicate on operational processes time delays issues.

The problem of time delays occurrence characterises many physical and technical systems and is investigated e.g. in biology, mechanics or economics [29]. In the 70s Twentieth century, time delay concept *Delay Operator* was used in modelling or forecasting processes performance [9]. Later, there were papers which are aimed at time delay concept implementation in other research areas, e.g. in logistics processes performance modelling, or technical systems maintenance modelling. Review of basic research issues related to the operational systems' time relations modelling is presented in [59].

In 1976. Christer (based on [18]) proposed the delay-time concept (DTC), which is used to this day in the theory of renewal processes in order to optimize the technical system downtime connected with not detected in time failures occurrence (time between inspections optimization problem). In the delay time concept, a fault which has developed in the system becoming visible at time u from new, if an inspection is carried out at that time. If the fault is not attended to, the faulty component fails after some further interval h which is called delay time of fault (Fig. 1).

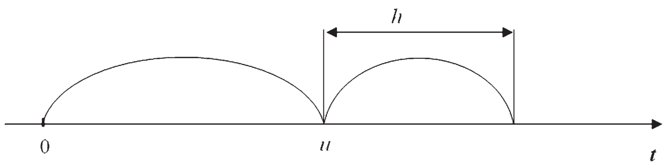

Fig. 1. Time delay conception [18]

There has been increasing effort to encourage the use of the delay-time concept in maintenance modelling of real-life systems. Many works have been carried out on the modelling of this concept to production plants (e.g. [2, 19, 36]). Moreover, well known models base on time-based preventive maintenance (e.g. [43, 53, 63]) or condition-based maintenance (e.g. [20, 40, 41, 55]). Other application areas regard to e.g. maintenance in civil engineering (e.g. [16]), or transport issues (e.g. [24, 37]).

The problem of imperfect inspections performance in technical systems is analysed e.g. in [3, 13, 15, 22, 34, 35, 44, 46, 52].

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

The main questions being investigated in such works are [15]:
- How often vehicles should be maintained preventively or repaired/replaced?
- Is a reliability structure of a system safe?
- How often production plant should be maintained periodically?
- What is an economical and technical effectiveness of a performed maintenance?

Literature review of existing DT models can be found e.g. in [3, 4, 13, 14, 15, 17, 20, 35, 39, 44, 52] or in [31, 32, 33, 39], where the focus is on the possibilities of DT models implementation for multi-unit systems. In [30], there is presented the literature overview of single-unit systems with time delay maintenance processes modelling issues.

A literature review, in which delay-time models are investigated along with other PM models are given in [23, 27, 28, 38, 42, 48, 50].

One of the first publications which strictly investigated recent development in the delay-time modelling is given by Christer & Redmond [17]. Later, in [4] authors discuss the development of delay-time analysis as a means of modelling engineering aspects of maintenance problems. Christer in [15] reviews the recent cumulative knowledge and experience of delay time modelling from 80s and 90s Twentieth century. Author presents the basic delay-time model and discusses the main development directions including e.g. perfect/non-perfect inspection case, steady state and non-steady state conditions, or type of model's parameters estimation process.

Following these considerations, in the Fig. 2, there is presented the main classification of existing delay time models. In the presented scheme, there are defined three main groups of delay-time models according to the maintenance strategy used. First group is devoted to time-based inspection models. There, plenty of studies regard to block-replacement inspection policy, where inspection takes place every T time units. The second group of models which deserve to be mentioned is condition- based maintenance models. There one can find models especially developed for production plant maintenance. The last group of models introduce the delay time concept in reliability cantered maintenance. However, there is only few works regard to this maintenance area.

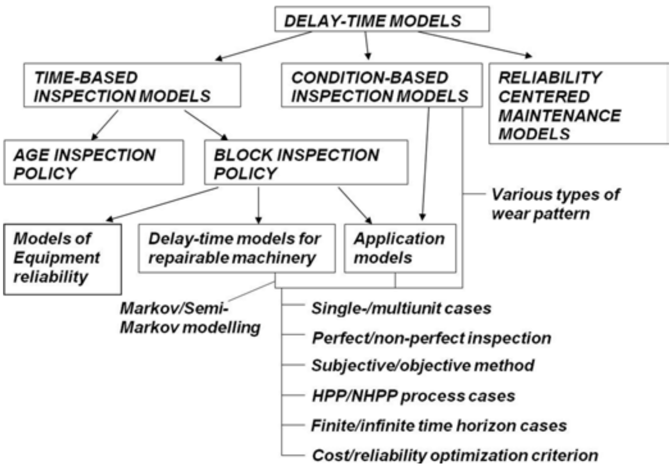

Fig. 2. Classification scheme of delay-time models [39]

Moreover, when analysing the time relations modelling problems, there is also a necessity to investigate the issues of logistics delays occurrence during defence systems operational processes performance [45]. The main problem in this area is connected with definition how logistics processes performance delays affect unreliability (total downtime) of a military system (e.g. maintenance delay time connected with spare parts delivery delays), and as a result, the main system dependability characteristics [60].

The presented defence approach may also be used in time analyses of production and technical systems performance, connected with [60]:
- delays occurred during operational processes performance (between consecutive operations),
- random lead times,
- spare parts availability.

The convenient example, which serves to illustrate the complexity of such problems is given in [60], where the system of systems with time resource model is developed. The model takes into account the possibility of logistic support system functional unreliability and allows for assessing the impact of logistic system failures on the overall system of systems dependability and economic characteristics.

2.1. Basic model of inspection based on the DTA implementation

One of the main inspection policy models, which are based on the DTA approach implementation, is given in [18]. The investigated simplest possible case of an inspection policy is characterized by the following assumptions:

a) there is a constant time T between successive inspections which require d time units,
b) inspection costs I units,
c) inspections are perfect in that any defect present within the plant will be identified,
d) inspections are independent of each other,
e) faults are independent and arise within the technical system at a constant rate k for any inspection period,
f) defects identified at an inspection will be repaired within the inspection period,
g) breakdowns impose a small amount of downtime, d_b, compared to the inspection interval T and d,
h) the delay time of a fault is independent of the arrival time and has known pdf $f_h(h)$ and cdf $F_h(h)$.

For such assumptions there is possible to estimate the probability of a fault arising as a breakdown $P_b(T)$ [18]:

$$P_b(T) = \frac{1}{T}\int_0^T (T-h) f_h(h)dh \tag{1}$$

The expected downtime per unit time to be incurred operating an inspection policy of period T is given by $E_d(T)$, where[18]:

$$E_d(T) = \frac{kTd_bP_b(T)+d}{T+d} \tag{2}$$

Moreover, with average breakdown and inspection repair costs c_b and c_i respectively, the expected cost per unit time of maintaining the plant on an inspection system of period T is $C(T)$, where [18]:

$$C(T) = \frac{1}{(T+d)}\left\{kT\left[c_bP_b(T)+c_i\left(1-P_b(T)\right)\right]+1\right\} \tag{3}$$

Let's consider the second case, when the inspections are non-perfect. Thus, there is introduced a probability β that a specific defect will be identified at nth inspection, and a corresponding probability (1- β) that it will not. For such an assumption the modified form of $P_b(T)$ is given by [18]:

$$P_b(T) = 1 - \left\{ \int_{y=0}^{T} \sum_{n=1}^{\infty} \frac{\beta}{T[(1-\beta)^{n-1} R(nT-y)]dy} \right\} \quad (4)$$

There exist many variations of the presented model, being investigated in known literature from reliability theory. Moreover, one can find few works in which the described model is used to real-life systems' reliability analysis performance. For example see [39].

3. Time relations in logistic systems performance

At the present time, in the era of competition, there is a problem of fully integration of the logistics systems in cooperation. Moreover, there is a necessity to eliminate any time delays which may influence the added value of a product [8]. Treating the supply chain disruptions as unexpected events occurrence, we can describe them as having uncertainty in supply chain operations. Uncertainty in the supply chain can be seen from different aspects, such as [51]:

- time (in the sense of duration of activity/process, starting/ending moment of activity realization, frequency of activity/demand occurrence),
- quantity (of supply, demand or physical transfer of goods),
- location/place (where activity starts/ends),
- quality (of service/products),
- cost (fluctuation, occurrence).

However, not every disruption occurrence leads to logistic system failure appearance. The critical factor which determines the logistic system failures is time. In a situation, when disruption (connected with e.g. improper delivery quality/quantity, improper location) occurs, there is a necessity to find out if we have enough time to correct the problem. When the spare time let us to remove the disruption – logistic system is not defined as failed. In other words, time redundant system has the ability to tolerate interruptions in their basic function for a specific period of time without having the negative impact on the system task performance.

Typically, the time redundant systems have a defined time resource that is larger than the time needed to perform the system total task [58]. *Time redundancy is to take additional time to complete the task (in relation to the time necessary for its execution), which can be used to restore the state of the system or improve its technical characteristics* [49, 58]. This means that the system with time resource tolerate faults with a short (usually specified) duration.

In the known literature, there is many works which investigate the problem of time redundancy (see e.g. [10, 11, 49, 58]). Moreover, taking into account the following issues [49, 58]:

- type of failure tolerance,
- type of time resource usage,
- type of time resource replenishment,

one can define the main types of time resource, which are described e.g. in [62].

The proper type of time resource choice depends on the type of modelled system, type of operational task, efficiency definition, and system's reliability structure. The main models classification of systems with time resource is given in [62].

4. Implementation of basic model of inspection based on DTA – case study

The basic DTA model implementation is analysed based on the information about operational and maintenance processes of forklifts, which are operated by considered case company [25]. The company specializes in servicing and carrying out a comprehensive overhaul of motor, diesel, gas, and electric lift trucks. It also prepares the necessary documentation for Office of Technical Inspection and supervises the maintenance processes of trucks subjected to technical inspection. It also provides services for both, individual and businesses customers. These services encompass a full range of internal transport facilities providing and spare parts and tires supplying.

The necessary data, used in reliability analysis regard to eight years of trucks performance time period, since 2000 till 2008. The performance data include operational processes realization, repair and preventive maintenance times, types of replaced elements, and types of occurred failures. The shortest mileage of analysed forklifts is 2 800 working hours and the longest mileage is equal to 13 300 working hours.

4.1. Maintenance tasks being performed during analysed time period

In the first step of performed reliability and maintenance analysis, author gathered the data about maintenance tasks (replacing of elements, spare parts, repairs), being performed during analysed time period. The gathered information is classified into seven working groups: track frame and body, installation and electrical equipment, hydraulic circuit, lifting circuit, transmission, steering system, and brake system. In the table 1, there are presented the main maintenance tasks performed in lifting circuit during analysed time period.

The trucks inspection actions are performed according to the given operators manuals. During the inspection performance, there should be checked out if all circuits and transmission perform satisfactory, especially:

- security systems,
- forks and carriage,
- steering system,
- transmission,
- lighting system,
- signalling system,
- properness of performed maintenance actions,
- frame (in every 12 months).

Preventive maintenance actions are performed according to the trucks mileage indications. Moreover, inspections are performed after every 1000 working hours (e.g. mast, forks and axle maintenance), after every 2000 working hours (e.g. lifting system maintenance), or after every 3000 working hours (e.g. hydraulic system maintenance).

4.2. Main reliability characteristics of analysed system's elements

Electrical forklift is a repairable object, thus, it is repaired after its failure occurrence[1]. Reliability analysis of forklifts has been per-

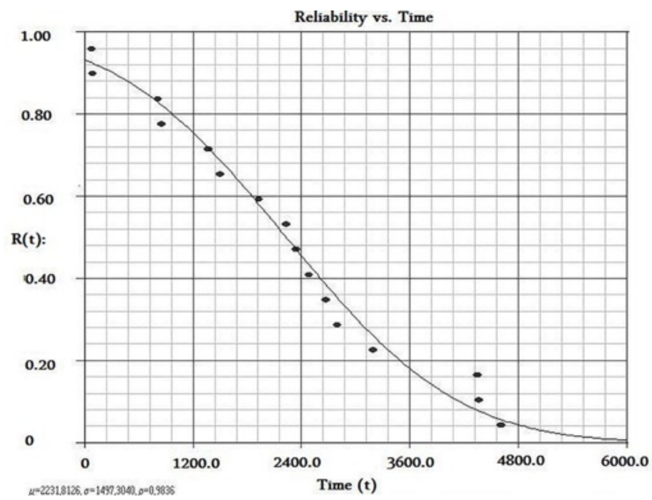

Fig. 3. The probability density fu nction $R_1(t)$ of time to first failures for chosen trucks

1 According to the definition given in dictionary of Operation by PNTTE, http://www.eksploatacja.waw.pl/indexphp.php?s=4000

Table 1. Types and number of maintenance tasks being performed to provide lifting service [25]

Maintenance task	Maintenance actions' object	Number of performed maintenance actions	Maintenance task	Maintenance actions' object	Number of performed maintenance actions
replacement	mast rollers	22	repair	tilt cylinder	21
	mast support bearing	18		broken lifting chain	17
	lifting chain	18		mast rollers	14
	forks lock	14		lifting cylinder (sealing)	13
	lifting chain safety device	14		truck mast (welding, grinding)	10
	forks	12		lifting chain regulation	8
	mast roller	8		regulation of lifting and tilting functions	8
	tilt cylinder's pins	4		lifting chain's rollers cover	4
	tensioning screw	3			
	mast fixing screw	2			
	tilt cylinder	2			
	lifting cylinder	1			

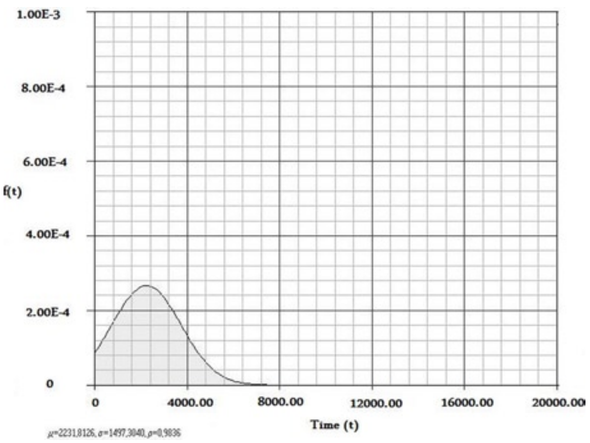

Fig. 4. The probability function f(t) of time between failures

formed based on the data from service manual where the information about trucks actual mileage, types and times of performed maintenance actions can be found. Thus, the obtained data of sixteen forklifts operational processes performance let author estimate the main reliability characteristics, e.g. probability distribution function of times to first failure of the chosen trucks. Moreover, there has been also the possibility to define the cumulative distribution function $F(t)$, or probability distribution function $f(t)$.The data analysis has been carried out with the use of Weibull ++ v. 6 software (distributed by ReliaSoft Co. USA), what gives the possibility to estimate e.g. probability functions of time to failure or repair time. The defined functions are a normal probability functions. The chosen reliability characteristics of analysed forklifts are given in Fig. 3–4.

4.3. Possibility of basic model of inspection implementation

The implementation of basic model of inspection based on DTA implementation and investigated in Section 2.1 needs estimation of the main model parameters:

- inspections time d is equal to 2 hours,
- downtime d_b connected with breakdowns removing equals 5.18 h (estimated as a mean repair time of all sixteen trucks in a given time period),
- total operational time of all trucks in a given time period is 131700 working hours,
- the constant rate k of fault occurrence is estimated at the level k = 0.006363 per hour (838 failures during analysed time period),
- MTBF equals 157 working hours, with standard deviation being equal to 381 working hours.

Taking into account the defined model parameters, the formula given in (2), when using formula (1), may be defined as:

$$E_d(T) = \frac{kT\left[\frac{1}{T}\int_0^T (T-h)\,f_h(h)dh\right]d_b + d}{T+d} \tag{5}$$

Substituting obtained values of model parameters into Equation (5) gives the following:

$$E_d(T) = \frac{(0{,}006363T)\left[\frac{1}{T}\int_0^T (T-h)\,f_h(h)dh\right]5{,}18 + 2}{T+2} \tag{6}$$

In the analysed model, there is also a necessity for delay time h distribution definition. This distribution function is independent on the system's elements failures occurrence and is defined by $f_h(h)$ and $F_h(h)$.

These distribution functions of delay time parameter h can be estimated using two methods, namely subjective and objective ones. In the known literature few models have been developed for these two approaches, for more information see e.g. [5, 6, 54]. The use of objective models requires a large amount of data in comparison with survey questionnaires which should reflect the operations of the analysed system over a considerable period of time.

When dealing with the analysed forklift system, there is no possibility to identify time moments *u* occurrence. Thus, there is no reliable information about the most appropriate distribution function for *h* parameter. As a result, there is a necessity to study different *pdf* functions of delay-time. In the article, author focuses on the exponential case, for which the distribution for the delay time is given by:

$$f_h(h) = ke^{-kh} \tag{7}$$

Substituting formula (7) into Equation (6) to obtain an expression for the downtime will give:

$$E_d(T) = \frac{(0,006363T)\left[\frac{1}{T}\int_0^T (T-h)ke^{-kh}dh\right]5,18+2}{T+2} \tag{8}$$

Taking into account the average failure rate *k* (in analysed case *k* = 0.006363) in the equation (8), there was possible to obtain results shown in Figure 5.

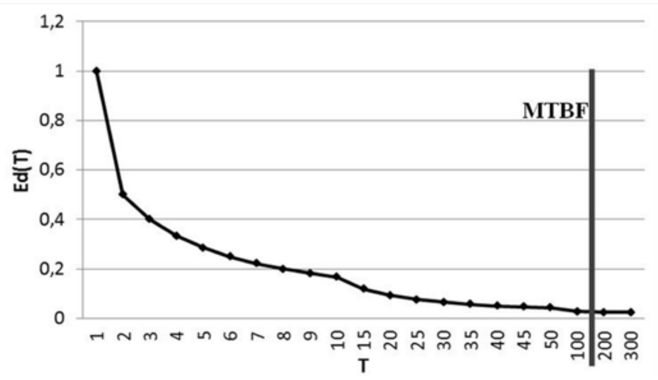

Fig. 5. Function $E_d(T)$ when using exponential distribution for delay time h

According to the Fig. 5, clearly can be seen that the function of the expected downtime stabilizes around the estimated value of MTBF. At the same time, the question arises which model parameters and how they affect the research results. Thus, there should be carried out the model sensitivity analysis. Moreover, it should be analysed the influence of various probability distribution functions of random variable *h* on the function $E_d(T)$. These issues will be also the subject of author's further research.

5. Summary

The use of inspection models based on DTA implementation and proper preventive maintenance system can be used to minimize the technical system downtime connected with undetected defects or damage occurrence. The article focuses on the application of one of the first inspection models based on DTA to analyse the system of forklifts performance. However, unfortunately the used model requires consideration of a number of simplifying assumptions that cannot always be met in practice. Firstly, the inspection actions are not always perfect, which means that not all occurred defects are identified during the inspection process performance. The second assumption, which is usually not fulfilled in practice regards to constant failure rate *k*.

Last and the most important problem is connected with the time delay *h* parameter estimation process. Usually, there is no relevant data that allow, with the use of mathematical functions, to estimate this random variable. This means, that there is no possibility to unambiguously determine the period *T* between system inspection actions performance. At the same time, it is expected that the combination of modeling based on DTA implementation and preventive maintenance tasks investigation may guarantee the expected number of undetected faults at the level of 5 – 10% (depending on the chosen probability distribution).

In order to determine whether the analysed inspection model which bases on DTA implementation is suitable for analysed system of sixteen forklifts dependability characteristics estimation, the input data should be complemented. The additional data gathering process should allow to define the time delay parameter and its probabilistic characteristics in more precise way.

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Sylwia WERBIŃSKA-WOJCIECHOWSKA, Ph.D. (Eng.)
Faculty of Mechanical Engineering
Institute of Machine Design and Operation
Wroclaw University of Technology
Wybrzeze Wyspianskiego 27, 50-370, Wroclaw, Poland
e-mail: sylwia.werbinska@pwr.wroc.pl