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Reliability and Availability Analysis of Transport System Composed of Dependent Subsystems

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ABSTRACT: The paper presents reliability and availability analysis of the transport system, taking into account its structure, that is composed of dependent subsystems. The issues introduced are basing on the assumption that one subsystem impacts on functioning of other subsystems, meaning - disruptions occurring within the subsystem can reduce functionality and change level of safety and inoperability of others. By means of multistate approach to analysis, it has been assumed that the deterioration of one subsystem affects the reliability of other subsystems and the entire system. Following this assumption, the transport system reliability function and its basic reliability characteristics were determined. In addition, the system availability function was set out, assuming that its renewal is carried out when its reliability falls below a certain threshold. Furthermore, the reliability and availability analysis of the transport system were conducted, taking into account additional stress on its particular subsystem at certain time points. The summary contains conclusions resulting from the analysis and comparison for various additional stress levels.

1 INTRODUCTION

The transport is one of essential characters of human activities, determining the stability of other systems, that are crucial for social and economic organisms. Ensuring of appropriate quality and continuity of supply chains is of a key importance to maintain the appropriate level of functioning of all activities carried out within the modern economy [41, 22, 21].

One of the base facts confirming unique significance of transport for surrounding systems, is its location within the critical infrastructure, both on international and national levels [10]. A reference can be made to the European Council Directive 2008/114/EC on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection [11], or Polish Act of 26 April 2007 on Crisis Management [33].

The intensive development of modern technologies, that can be observed last years, results in increase of dependency of modern societies, on functioning of systems like transport. One of the most meaningful evidences regarding the dependency, the reference can be made to, is recent Covid-19 pandemic, during which, in its initial phase, the disruption of supply chains caused discontinuance in a number of sectors of the world economy [13, 27, 28]. Reconstruction and reorganization of the supply chains, that was made afterwards, has demonstrated the key importance of proper functioning of transport systems, to quality of functioning of social and economic organisms, including their restoration to the level ensuring their sustainable performance [14, 29, 6].

The intensive development of various technologies, the transport systems base on, results also in increase of complexity of their structure and functionality.

This as well causes extension of influence of dependencies linking particular subsystems, on functioning, reliability and availability of the entire system [35, 17, 8].

The dependencies can be of various nature [40], and emerge on different levels. Their character can be either holistic, appearing within the whole system, or more particular [16], existing in certain sectors or system's components level [38, 37]. For the purpose of the transport system reliability, availability and resilience analysis, it is studied as system of systems [37, 12, 9]. Modeling of dependencies linking subsystems and components building the entire system, is a key issue in its management. Recognizing and distinguishing of the subsystems associations is a key condition to achieve proper functioning and administration of the entire system [4, 34].

There is a number of approaches in the literature, aiming to distinguish particular subsystems of the transport system, and their interconnections and interdependencies. One of the most general perspectives is selecting: individuals and/or products being transported, transport means in which they are moved, and networks through which the transport means are moving [23, 45, 51]. Extended approaches specify: transport infrastructure, transport means, human capital (service providers and recipients), and rules applicable for the whole system functioning [19, 15, 32]. For this article purposes, more detailed studies have been adopted, selecting following subsystems of the transport system [44, 43, 48]: infrastructure (structures through which transport operations are conducted), transport means (carriers transferring goods through the transport network), complementary appliances (equipment operating in a complementary way to infrastructure), power supply (generators of power necessary for operations of transport), provisioning resources (solutions for supplying of provisions essential for functioning of subsystems of the transport system), control (monitoring and communication solutions ensuring operations of transport systems, like safety, traffic control, information provision etc.).

The objective of the paper is to signify, that considering dependencies linking subsystems of the transport system, can be of great meaning for analysis of its reliability and availability, and consequently safety of its functioning. Moreover, article considerations include analysis of deteriorations of the system performance, resulting from additional stress that can appear in one of its subsystems. The additional stress on one or more subsystems, coming from internal or external sources, increases their interdependencies, consequently can result with so called "domino-effect", and significantly reduce safety and operational capabilities of the entire system.

2 RELIABILITY OF THE TRANSPORT SYSTEM COMPOSED OF DEPENDENT SUBSYSTEMS

Relations interconnecting subsystems of the major system, can be identified and described according to different approaches. One of the propositions is to identify nodes and links connecting particular subsystems, then, by taking into account their functional characteristics, the importance and rankings of particular links and nodes can be determined. This can allow to find the significance of particular subsystems, and distinguish the most and the least significant ones [26, 24, 25]. Another approach suggests to represent the whole system as a multilayer structure, built of layers representing particular interconnections linking the subsystems. The layers represent horizontal links within each subsystem showing flow connectivity in that part of system. Layers are interconnected by vertical links, denoting the interdependencies between the subsystems. This leads to specify the relations connecting particular subsystems by a combination of horizontal and vertical links [50, 7, 42]. There are also studies introducing interdependency matrices to analyse relations between interconnected subsystems. By generating various types of the matrices, bidirectional interlinks, joining the subsystems, can be specified, and then the impact of failure of one subsystem, on another one can be determined [39, 49, 31].

For this article purposes, methodology assuming the major system as the network of interconnected nodes representing subsystems, has been adopted. Interdependencies between particular subsystems are related to probability of inoperability that one contributes to other one. The approach lets to evaluate engineering resilience and interdependency for subsystems of a networked infrastructure [36, 30, 20].

The subsystems of the transport system, distinguished earlier, have been denoted as below:

- Infrastructure – SUB_1;
- Transport means – SUB_2;
- Complementary appliances – SUB_3;
- Power supply – SUB_4;
- Provisioning resources – SUB_5;
- Control – SUB_6;

The above subsystems, and interdependencies existing in the system, are presented in Figure 1.

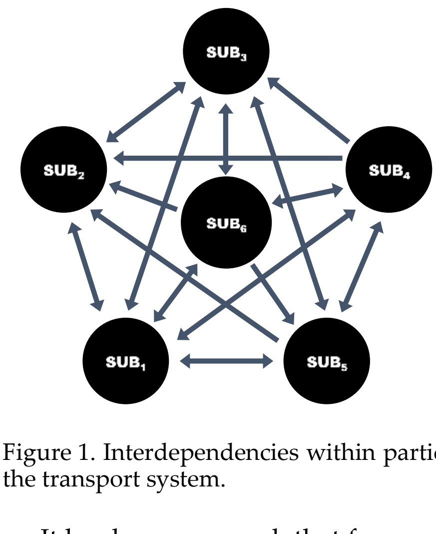

Figure 1. Interdependencies within particular subsystems of the transport system.

It has been assumed, that for proper functioning of the entire system, all the subsystems should be in the appropriate working state. Therefore, reliability and availability analysis of the transport system, is basing on the assumption, that subsystems SUB_i, i = 1, 2,..., 6, the system is built of, are connected in series.

The transport system and its subsystems are analyzed as multistate structures, and their following four reliability states have been specified:

- state 3 of full ability – meaning system is fully operational, and working without any perturbations;
- state 2 of partial reliability – standing for situation when some disruptions in the system appear, but its functionality is still maintained at the appropriate level;
- state 1 of limited reliability – expressing the situation when the disruptions in the system result in falling of its exploitation parameters below allowed limits
- state 0 of complete unreliability – occurring in case of failure stopping system's operation.

It has been also assumed, that reliability functions of subsystems SUB_i, $i = 1, 2,..., 6$, are exponential:

$$R_i(t,\cdot) = [1, R_i(t,1), R_i(t,2), R_i(t,3)], t \geq 0, i = 1,2,\ldots,6, \quad (1)$$

and their coordinates $R_i(t,u)$, $u = 1,2,3$, are defined as the probability of subsystem staying in subset $\{u, u+1,...,3\}$ of reliability states at the moment t, under the assumption that it was at full reliability state (state 3) at the moment $t = 0$, and are given by:

$$R_i(t,u) = \exp[-\lambda_i(u)t], u = 1,2,3, i = 1,2,\ldots,6,, \quad (2)$$

where $\lambda_i(u)$, $u = 1,2,3$, denote the intensities of departure of subsystems SUB_i, $i = 1, 2,\ldots, 6$, from the subset $\{u, u+1,...,3\}$.

Subsystems SUB_i, $i = 1, 2,..., 6$, constituting the transport system, are interdependent. Defects, failures or disruptions in one of the subsystems, do have influence on functioning of others, consequently, on the reliability of entire system. Therefore, reliability analysis of the transport system as a structure of series and dependent subsystems, is carried out. It has been assumed the relationships between the subsystems can be unidirectional or bidirectional. Deterioration of the reliability state of one of subsystems may cause fluctuations of functioning of others, and result in deterioration of their reliability characteristics. To identify layout of interconnections of the subsystems, it is recommended to determine their mutual impact in case of their failure, and specify their behavior before, during and after the appearance of the disruption in one of them [5, 18, 46].

Therefore, by adopting the local load sharing dependency model for a series structure [1 - 3], the expanse of dependencies between subsystems is expressed by the influence coefficients $q(\upsilon, SUB_j, SUB_i)$, $i,j = 1,2,\cdots,6$, $i \neq j$. The influences between the subsystems do not have to be symmetrical. Hence, it has been assumed that $q(\upsilon, SUB_j, SUB_i)$ reflects the effect of changes in reliability state $\{u, u+1,...,3\}$, $u = 1,2,3$, in SUB_j, $j = 1,2,\ldots,6$, on lifetimes in the subset $\{\upsilon, \upsilon+1,...,3\}$, $\upsilon = 1,2$, of SUB_i, $i = 1,2,\cdots,6$, $i \neq j$. Assuming that subsystems SUB_i, $i = 1, 2,\cdots, 6$, have exponential reliability functions, defined by formulas (1)-(2), assuming as described above, the transport system reliability function is defined as follows [2, 3, 47]:

$$\boldsymbol{R}_{dep}(t,\cdot) = [1, \boldsymbol{R}_{dep}(t,1), \boldsymbol{R}_{dep}(t,2), \boldsymbol{R}_{dep}(t,3)], t \geq 0, \quad (3)$$

where

$$R_{dep}(t,1) = \exp\left[-\sum_{i=1}^{6}\lambda_i(2)t\right] + \sum_{j=1}^{6}\frac{\lambda_j(2)-\lambda_j(1)}{\sum_{i=1}^{6}\lambda_i(2)-\sum_{i=1}^{6}\lambda_i(1)}\cdot\left[\exp\left[-\sum_{i=1}^{6}\frac{\lambda_i(1)}{1-q(1,SUB_j,SUB_i)}t\right] - \exp\left[-\left(\sum_{i=1}^{6}\lambda_i(2)-\sum_{i=1}^{6}\lambda_i(1)+\sum_{i=1}^{6}\frac{\lambda_i(1)}{1-q(1,SUB_j,SUB_i)}\right)t\right]\right],\ t \geq 0, \quad (4)$$

$$R_{dep}(t,2) = \exp\left[-\sum_{i=1}^{6}\lambda_i(3)t\right] + \sum_{j=1}^{6}\frac{\lambda_j(3)-\lambda_j(2)}{\sum_{i=1}^{6}\lambda_i(3)-\sum_{i=1}^{6}\lambda_i(2)}\cdot\left[\exp\left[-\sum_{i=1}^{6}\frac{\lambda_i(2)}{1-q(2,SUB_j,SUB_i)}t\right] - \exp\left[-\left(\sum_{i=1}^{6}\lambda_i(3)-\sum_{i=1}^{6}\lambda_i(2)+\sum_{i=1}^{6}\frac{\lambda_i(2)}{1-q(2,SUB_j,SUB_i)}\right)t\right]\right],\ t \geq 0, \quad (5)$$

$$R_{dep}(t,3) = \exp\left[-\sum_{i=1}^{6}\lambda_i(3)t\right],\ t \geq 0, \quad (6)$$

For the article purposes, to demonstrate outcomes of the reliability and availability analysis of the entire transport system, reliability parameters shown in Table 1 have been adopted, and subsystems impact coefficients given in Table 2, have been applied.

Table 1. Intensities $\lambda_i(1)$, $\lambda_i(2)$ and $\lambda_i(3)$ of the SUB_i, $i = 1,2,\ldots,6$, subsystem departure from the safety states subsets {1,2,3}, {2,3}, and {3}, respectively [year^{-1}].

SUB_i	$\lambda_i(1)$	$\lambda_i(2)$	$\lambda_i(3)$
SUB_1	0.06667	0.1	0.28571
SUB_2	0.1	0.13333	0.5
SUB_3	0.13333	0.2	0.4
SUB_4	0.06667	0.1	0.33333
SUB_5	0.13333	0.4	1
SUB_6	0.2	0.5	2

Table 2. Coefficients $q(\upsilon, SUB_j, SUB_i)$, $i,j = 1,2,\ldots,6$, $\upsilon = 1,2$, of the SUB_j subsystem impact on lifetimes and their mean values in the subsets {1,2,3} and {2,3} of the SUB_i subsystem.

$j \mid i$	SUB_1	SUB_2	SUB_3	SUB_4	SUB_5	SUB_6
SUB_1	0	0.7	0.5	0.8	0.6	0.25
SUB_2	0.85	0	0.25	0	0	0
SUB_3	0.55	0.8	0	0	0.75	0.5
SUB_4	0.65	0.25	0.85	0	0.7	0.9
SUB_5	0.7	0.85	0.65	0.35	0	0.2
SUB_6	0.75	0.7	0.6	0.65	0.45	0

Basing on the above given data, basic reliability and availability characteristics of the transport system composed of dependent subsystems have been determined. Table 3 indicates the mean lifetimes in reliability state subsets {1,2,3}, {2,3}, {3}, and standard deviations of the lifetimes, obtained by use of formulae (4)-(6).

Table 3. Mean values and standard deviations of the transport system lifetimes in safety states subsets {1,2,3}, {2,3}, and {3} [year].

Reliability states subset	Mean value μdep	Standard deviation σdep
{1,2,3}	0.880	0.747
{2,3}	0.395	0.349
{3}	0.221	0.221

Reliability function $\boldsymbol{R}_{dep}(t,2)$ of the transport system sojourning in reliability states {2,3}, obtained for the above data, have been shown in Figure 2.

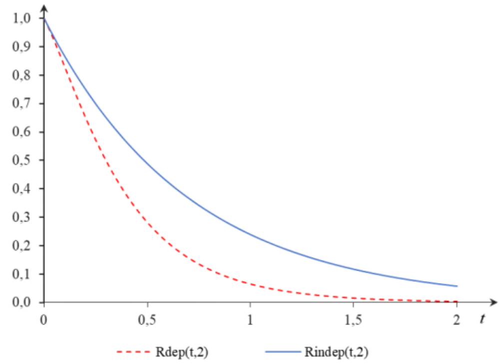

Figure 2. The coordinate of reliability function $\boldsymbol{R}_{dep}(t,2)$, taking into account dependencies between the subsystems, related to coordinate of the function $\boldsymbol{R}_{indep}(t,2)$, assuming the subsystems are independent.

Figure 2 is also indicating $\mathbf{R}_{\mathrm{indep}}(t,2)$ function, determined for the same data, but without considering dependencies linking the subsystems.

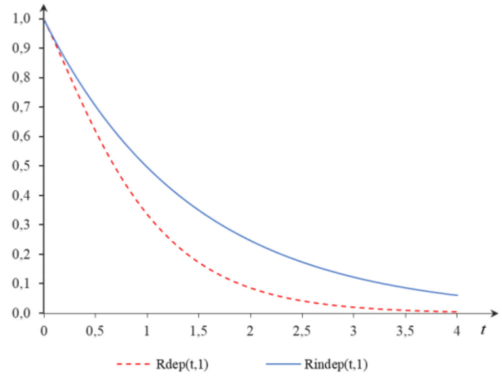

Figure 3. Reliability function $\boldsymbol{R}_{dep}(t,1)$, vs. function $\boldsymbol{R}_{indep}(t,1)$.

Figure 3 illustrates the reliability function $\boldsymbol{R}_{dep}(t,1)$ of the system, remaining in reliability states subset {1,2,3}, determined for the same data. Similarly, the reliability function $R_{indep}(t,1)$, has been demonstrated, related to the same reliability states subset, calculated without taking into account the dependencies between the subsystems.

3 AVAILABILITY OF THE RENEWABLE TRANSPORT SYSTEM

To analyze availability of the renewable system, the key point is to determine the threshold of probability $\boldsymbol{P}_{ren}$, of its staying in certain set of reliability states, which, if reached, results in the renewal of the system. For this paper purposes, the renewals of the transport system are considered within the system sojourning in reliability states subset {2,3}. The $\boldsymbol{P}_{ren}$ probability determines value of the coordinate $\boldsymbol{R}_{dep}(t,2)$, of the reliability function. Therefore, the coordinate of the system availability function $\boldsymbol{AF}_{dep}(t,2)$, is specified as the probability of renewable transport system staying in subset of states {2,3}. That coordinate of availability function, assuming regular renewals of the system after exceeding the $\boldsymbol{P}_{ren}$ threshold, is determined as follows:

$$\boldsymbol{AF}_{dep}(t,2)=\begin{cases}\boldsymbol{R}_{dep}(t,2) & \text{if } \boldsymbol{R}_{dep}(t,2)\geq \boldsymbol{P}_{ren}, t\geq 0\left(\text{if } t\leq \tau_{\boldsymbol{P}_{ren}}(2)\right)\\ \boldsymbol{R}_{dep}\left(t-\omega\cdot\tau_{\boldsymbol{P}_{ren}}(2),2\right) & \text{if } \omega\cdot\tau_{\boldsymbol{P}_{ren}}(2)<t\leq(\omega+1)\cdot\tau_{\boldsymbol{P}_{ren}}(2),\ \omega=1,\dots,N\end{cases} \quad (7)$$

where N is the number of the system renewals and $\tau_{Pren}(2)$ is the moment of the first renewal after exceeding the $\boldsymbol{P}_{ren}$ threshold. The coordinate $\boldsymbol{R}_{dep}(t,2)$ of the system reliability function is given by (5).

The formula (7) allows to determine the availability function $\boldsymbol{AF}_{dep}(t,2)$ coordinate, of the system built of dependent subsystems renewal, after exceeding certain threshold. Figure 4 illustrates the availability function coordinates, determined for the $\boldsymbol{P}_{ren}$ thresholds: 60% (Figure 4a), 40% (Figure 4b), and 20% (Figure 4c). The coordinates have been obtained for the same initial data (given in Tables 1 and 2), that were used to demonstrate $\boldsymbol{R}_{dep}(t,2)$, and $\boldsymbol{R}_{indep}(t,2)$ functions coordinates presented in Figure 3, and under the assumption, that renewals of the system are processed within its sojourning in reliability states subset {2,3}.

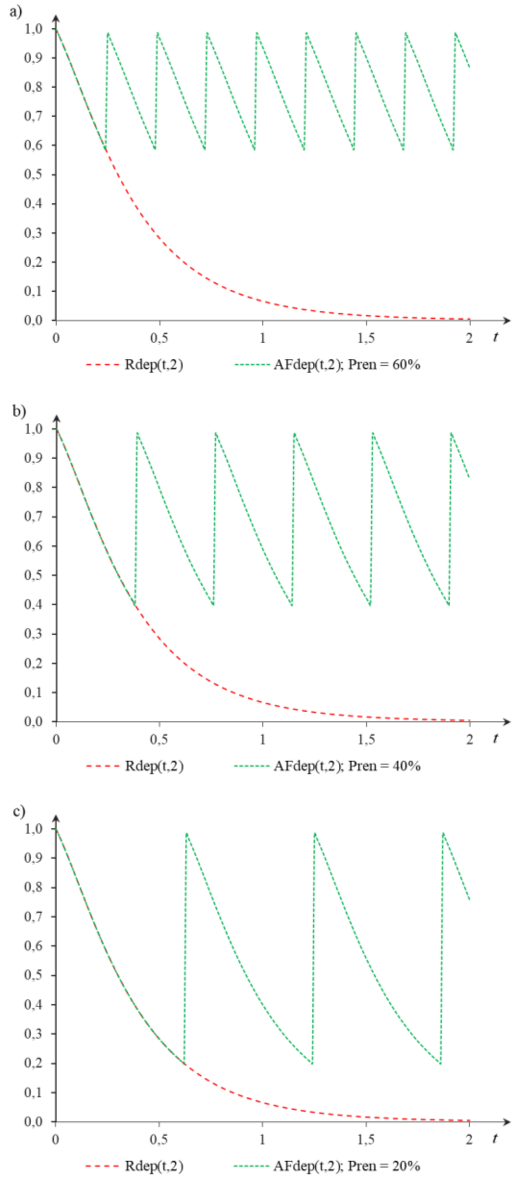

Figure 4. The coordinates of availability function $\boldsymbol{AF}_{dep}(t,2)$, of the transport system built of dependent subsystems, obtained for: a) the $\boldsymbol{P}_{ren}$ threshold 60% ($\tau_{0.6}(2)$), b) 40% ($\tau_{0.4}(2)$), and c) 20% ($\tau_{0.2}(2)$), in relation to $\boldsymbol{R}_{dep}(t,2)$ reliability function, determined for not renewable system.

The coordinates shown in Figure 4 allow to determine, that the system renewals, for threshold $\boldsymbol{P}_{ren}$ = 60% take place every 0.24 years, for $\boldsymbol{P}_{ren}$ = 40% every 0.38 years, and for $\boldsymbol{P}_{ren}$ = 20% every 0.62 years. The data indicated in Figure 4 let to conduct various types of analysis. Basing on the system $\boldsymbol{P}_{ren}$ threshold determination, costs of system renewal related to the $\boldsymbol{P}_{ren}$ threshold, additional costs associated with performance of not fully efficient system or its malfunction, and costs of technical inspections, optimal cost strategies of system maintenance and repairs can be planned. This however is not covered by the paper considerations, but will be subject of future research works.

4 AVAILABILITY OF THE TRANSPORT SYSTEM REFLECTING ADDITIONAL STRESS ON ITS SUBSYSTEMS

The reliability of the transport system may be reduced by unforeseen external elements, resulting with additional negative impact on one or more of its subsystems. To analyze the reliability and availability of the system, affected by the external negative impact on its subsystems, the impact is interpreted as appearance of additional stress within them. Reduced system's reliability results in abridging of its sojourn time in certain subset of reliability states. Moreover, additional stress concerning one of the subsystems, affects functionality and reliability of other dependent subsystems.

To figure out the analysis of reliability and availability it is assumed, that the additional stress appears in one of the subsystems at certain moment T_L. The T_L moment is the initial point of increase of the entire system's intensity of departure from intended reliability states subset.

The coordinate of the transport system reliability function, influenced by the additional stress, in case the system is not renewed, is then specified as follows:

$$\boldsymbol{R}_{dep}^{SUB_i-L}(t,T_L,2)=\begin{cases}\boldsymbol{R}_{dep}(t,2) & if\ 0\le t\le T_L\\ \boldsymbol{R}_{dep}^{SUB_i-L}(t,2) & if\ t>T_L\end{cases} \qquad (8)$$

where $\boldsymbol{R}_{dep}^{SUB_i-L}(t,2)$ is the transport system, composed of dependent subsystems SUB_i, i = 1, 2,..., 6, reliability function coordinate, reflecting its increased departure intensity from the subset of states {2,3}, while T_L is the moment of appearance of the additional stress within the system. $\boldsymbol{R}_{dep}^{SUB_i-L}(t,2)$ is determined correspondingly to the coordinate $\boldsymbol{R}_{dep}(t,2)$ specified by (5), where the intensity $\lambda_i(2)$ of sojourn of the i-th subsystem SUB_i, i = 1, 2,..., 6, in the subset of states {2,3}, is amended with the new value $\lambda_i^L(2)$, raised due to the additional stress L.

To determine the availability function of the transport system in the case the system is renewable, similar assumption, that the additional stress in one of the subsystems at certain moment T_L, results in increase of intensity of the entire system departure from intended subset of reliability states, has been adopted. However, when considering the renewals, it must be emphasized, that after the system renewal, its reliability parameters, i.e. intensity of departure from intended subsets of reliability states are the same as at the initial moment.

To conduct the analysis, it has been assumed that at the initial moment t = 0, the transport system stays in the reliability state 3. It has been also assumed, the renewal of the system takes place when the probability of its sojourning in the subset of reliability states {2,3}, assuming that subsystems are dependent, decreases below certain threshold $\boldsymbol{P}_{ren}$.

Basing on the above assumptions, the coordinate of the transport system availability function, influenced by the additional stress at the moment $T_L^{(1)}$, is drawn out as follows:

$$\boldsymbol{AF}_{dep}^{SUB_i-L}\left(t,T_L^{(1)},2\right)=$$
$$\begin{cases}\boldsymbol{R}_{dep}(t,2) & if\ 0\le t\le \min\left\{T_L^{(1)};\tau_{\boldsymbol{P}_{ren}}(2)\right\}\\ \boldsymbol{R}_{dep}^{SUB_i-L}(t,2) & if\ T_L^{(1)}<t<\tau_{\boldsymbol{P}_{ren}}(2)\\ \boldsymbol{R}_{dep}\left(t-\omega\cdot\tau_{\boldsymbol{P}_{ren}}(2),2\right) & \begin{aligned}&if\ \omega\cdot\tau_{\boldsymbol{P}_{ren}}(2)<t<(\omega+1)\cdot\tau_{\boldsymbol{P}_{ren}}(2)\ and\ t\le T_L^{(1)}\ or\\ &t>T_L^{(1)}\ and\ T_L^{(1)}\le\omega\cdot\tau_{\boldsymbol{P}_{ren}}(2),\ \omega=1,\dots,N\end{aligned}\\ \boldsymbol{R}_{dep}^{SUB_i-L}\left(t-\omega\cdot\tau_{\boldsymbol{P}_{ren}}(2),2\right) & \begin{aligned}&if\ \omega\cdot\tau_{\boldsymbol{P}_{ren}}(2)<t<(\omega+1)\cdot\tau_{\boldsymbol{P}_{ren}}(2)\ and\ t>T_L^{(1)}\ and\\ &T_L^{(1)}>\omega\cdot\tau_{\boldsymbol{P}_{ren}},\ \omega=1,\dots,N\end{aligned}\end{cases} \qquad (9)$$

where N is the number of the transport system renewals, and $\tau_{Pren}(2)$ is the moment of the first renewal, after the probability of the system sojourn in subset of states {2,3} goes down below $\boldsymbol{P}_{ren}$.

The stress affecting certain subsystem of the transport system can appear several times. It can be assumed, that particular subsystem, within certain time period, is affected by M successive stresses, at $T_L^{(k)}$ moments, k = 1, ... , M, causing increased strain in the entire system. The coordinate of the availability function of the system, taking into account its renewals, is then determined as below:

$$\boldsymbol{AF}_{dep}^{SUB_i-L}(t,2)=$$
$$\begin{cases}\boldsymbol{AF}_{dep}^{SUB_i-L}\left(t,T_L^{(1)},2\right) & for\ t\ge 0\ if\ M=1\\ \boldsymbol{AF}_{dep}^{SUB_i-L}\left(t,T_L^{(1)},2\right) & if\ 0\le t\le(\omega+1)\cdot\tau_{\boldsymbol{P}_{ren}}(2)\ and\ T_L^{(1)}>\omega\cdot\tau_{\boldsymbol{P}_{ren}}(2),\ for\ \omega=0,1,\dots,N,M>1\\ \boldsymbol{AF}_{dep}^{SUB_i-L}\left(t,T_L^{(k+1)},2\right) & \begin{aligned}&if\ \omega\cdot\tau_{\boldsymbol{P}_{ren}}(2)<t<(\omega+1)\cdot\tau_{\boldsymbol{P}_{ren}}(2)\ and\ T_L^{(k)}\le\omega\cdot\tau_{\boldsymbol{P}_{ren}}(2)\le T_L^{(k+1)},\\ &for\ \omega=0,1,\dots,N,k=1,\dots,M-2\end{aligned}\\ \boldsymbol{AF}_{dep}^{SUB_i-L}\left(t,T_L^{(k+1)},2\right) & \begin{aligned}&if\ t>\omega\cdot\tau_{\boldsymbol{P}_{ren}}(2)\ and\ T_L^{(k)}\le\omega\cdot\tau_{\boldsymbol{P}_{ren}}(2)\\ &for\ \omega=1,\dots,N,k=M-1,M>1\end{aligned}\end{cases} \qquad (10)$$

where $\boldsymbol{AF}_{dep}^{SUBi\_L}(t,T_L^{(1)},2)$ is given by (9) and

$$\boldsymbol{AF}_{dep}^{SUB_i-L}\left(t,T_L^{(k)},2\right)=$$
$$\begin{cases}\boldsymbol{R}_{dep}\left(t-\omega\cdot\tau_{\boldsymbol{P}_{ren}}(2),2\right) & \begin{aligned}&if\ \omega\cdot\tau_{\boldsymbol{P}_{ren}}(2)<t\le(\omega+1)\cdot\tau_{\boldsymbol{P}_{ren}}(2)\ and\ t\le T_L^{(k)}\ or\\ &t>T_L^{(k)}\ and\ T_L^{(k)}\le\omega\cdot\tau_{\boldsymbol{P}_{ren}}(2),\ \omega=1,\dots,N\end{aligned}\\ \boldsymbol{R}_{dep}^{SUB_i-L}\left(t-\omega\cdot\tau_{\boldsymbol{P}_{ren}}(2),2\right) & \begin{aligned}&if\ \omega\cdot\tau_{\boldsymbol{P}_{ren}}(2)<t<(\omega+1)\cdot\tau_{\boldsymbol{P}_{ren}}(2)\ and\ t>T_L^{(k)}\ and\\ &T_L^{(k)}>\omega\cdot\tau_{\boldsymbol{P}_{ren}}(2),\ \omega=1,\dots,N\end{aligned}\end{cases} \qquad (11)$$

for k = 2, ... , M.

5 APPLICATION

The formulae and indications introduced in the article allow to conduct various analyses concerning reliability and availability of the transport system, taking into account it is built of interdependent subsystems. The analyses allow to consider influence of additional stress appearing in one of subsystems, on the entire system. Basing on the formulae (8) and (10), and with use of data given in Chapter 2, the reliability function $\boldsymbol{R}_{dep}^{SUB_i-L}(t,T_L,2)$, and availability function $\boldsymbol{AF}_{dep}^{SUB_i-L}(t,T_L,2)$), of the system, reflecting additional stress in subsystem i, taking place at certain time TL, can be determined. Figure 5 demonstrates reliability (taking into account system is not renewed), and availability (for renewable system) function coordinates, calculated for the $\boldsymbol{P}_{ren}$ = 60% threshold, assuming additional stress *L* as triple increase of intensities of *i* subsystem departure from the safety states subsets {2,3} appearing in subsystem SUB_2 (Figure 5a), and in subsystem SUB_5 (Figure 5b), at time TL = 0.5 years.

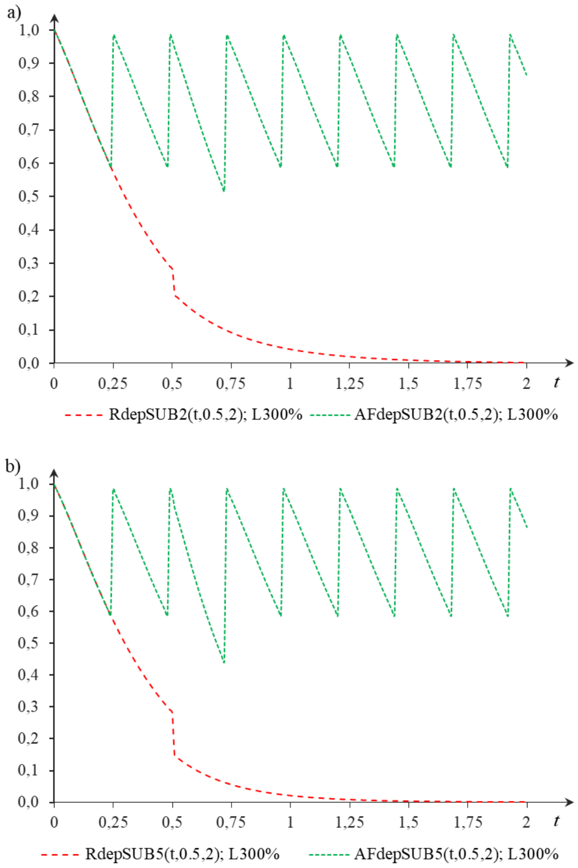

Figure 5. The coordinates of reliability function $\boldsymbol{R}_{dep}^{SUBi\_L}(t,0.5,2)$, and availability function $\boldsymbol{AF}_{dep}^{SUBi\_L}(t,0.5,2)$, of the transport system, determined for Pren threshold 60%, and assuming: a) the stress appears in SUB_2 subsystem, and b) the stress appears in SUB_5 subsystem.

Moreover, it is possible to analyse impact of different levels of stress appearing in one of the subsystems, on the entire system reliability and availability. The different levels of the stress are represented by appropriate increase of intensities of particular subsystem departure $\lambda_i(2)$, from the subset of reliability states {2,3}, given in Table 2.

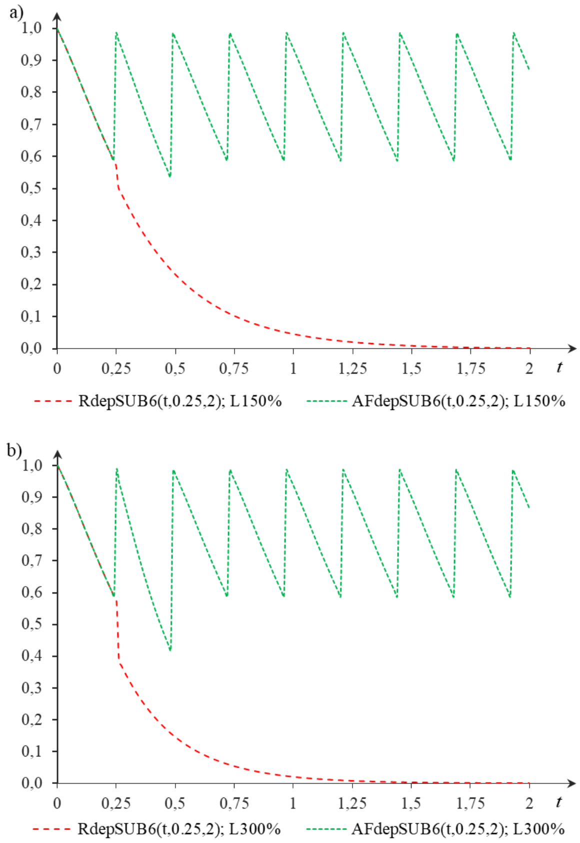

Figure 6. The coordinates of reliability function $R_{dep}^{SUB6\_L}(t,0.25,2)$, and availability function $\boldsymbol{AF}_{dep}^{SUB6\_L}(t,0.25,2)$, of the transport system, determined for Pren threshold 60%, obtained for the stress: a) 150% increase, and b) 300% increase of intensities of the subsystem departure from the safety states subset {2,3}.

Figure 6 shows reliability (taking into account system is not renewed), and availability (for renewable system) function coordinates, calculated for the $\boldsymbol{P}_{ren}$ = 60% threshold, assuming additional stress appears in subsystem SUB_6, at time T_L = 0.25 years, obtained under the assumption the stress *L* is 150% (Figure 6a) increase of intensities of the subsystem departure from the safety states subset {2,3}, and 300% (Figure 6b) increase.

Furthermore, the considerations presented, allow to take into account successive stresses emerging in one of the subsystems at certain time moments $T_L^{(k)}$. The impact of two successive stresses, on the reliability and availability of the system, determined for the $\boldsymbol{P}_{ren}$ = 60% threshold, assuming the first additional stress appears in subsystem SUB_3, at time T_L = 0.30 years, and the second one appears in the same subsystem, at time T_L = 0.60 years, has been presented in Figure 7. The reliability (taking into account system is not renewed), and availability (for renewable system) function coordinates have been determined under the assumption the stress *L* is 300% increase of intensities of the subsystem departure from the safety states subset {2,3}.

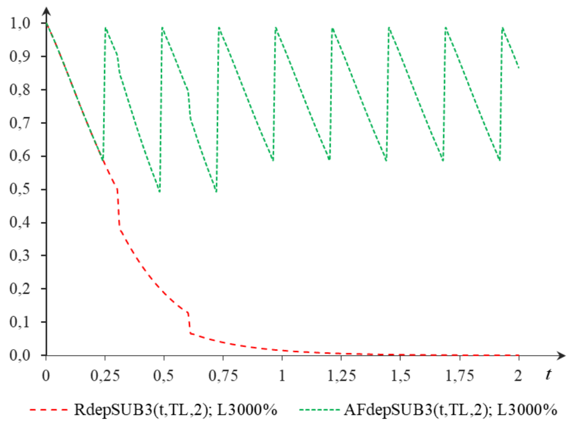

Figure 7. The coordinates of reliability function $\boldsymbol{R}_{dep}{}^{SUB3\_L}(t,T_L,2)$, and availability function $\boldsymbol{AF}_{dep}{}^{SUB3\_L}(t,T_L,2)$, of the transport system, determined for $\boldsymbol{P}_{ren}$ threshold 60%, obtained for stress L 300% increase of intensities of the subsystem departure from the safety states subset {2,3}, appearing in subsystem SUB_3 twice, at $T_L = 0.30$ years, and at $T_L = 0.60$ years.

6 CONCLUSIONS

The paper presents analysis of reliability of the transport system consisting of dependent subsystems. The availability analysis of the system has been also conducted, assuming renewal of the system takes place at the moment $\tau_{Pren}(2)$, reflecting the probability of its sojourn in the subset of reliability states {2,3} goes down below the certain threshold $\boldsymbol{P}_{ren}$. Furthermore, reliability and availability analyses have taken into account degradation of their parameters, caused by the appearance of additional stress, in one of subsystems forming the entire system, at the certain moment T_L. The stress can be result both of internal or external disruptions. The stress can be as well of different level, and can also be repeatable, taking place at successive time moments $T_L^{(k)}$. The results introduced in Chapter 5, prove that worsening and degradation of reliability state of one of subsystems, can significantly affect the safety parameters of the entire transport system. Negative effects are getting more significant meanings, if the subsystems forming the complete system are interdependent.

Results shown in Chapter 5 do also indicate remarkable value of considering interactions and interdependencies linking the subsystems, and taking into account internal and external disturbances degrading their reliability parameters, for reliability and availability analyses of the entire system. The outcomes of the paper allow to analyze and deduce, which of the subsystems are of the key importance for the whole system functioning. The diagrams shown in Chapter 5 indicate clearly, that the same additional stress level, taking place in different subsystems, results with different impact on the entire system reliability parameters.

Moreover, the paper content and results prove, considering interdependencies connecting the subsystems, and their impact on safety parameters of the complete system, are of the key importance in case of activities aiming to ensure respective levels of its safety and efficiency. By analyzing of system reliability and availability, considering various exploitation data, optimal strategies of system renewals, maintenance and repairs can be built.

The impact of additional stresses, on functioning and reliability of the transport system, depends as well on the time slots the stress takes place. By investigating the influence of the moment the stress takes place, in relation to interdependencies linking the subsystems and the system renewals, on the safety parameters of the entire system, the proper resistance of the system can be projected, and appropriate safety management activities can be conducted.

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