INTEGRATED MODEL OF PORT OIL PIPING TRANSPORTATION SYSTEM SAFETY INCLUDING OPERATING ENVIRONMENT THREATS

MODEL OCENY BEZPIECZEŃSTWA PORTOWEGO SYSTEMU TRANSPORTU PALIWA Z UWZGLĘDNIENIEM ZAGROŻEŃ ŚRODOWISKA EKSPLOATACYJNEGO

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Abstract: *The paper presents an integrated general model of complex technical system, linking its multistate safety model and the model of its operation process including operating environment threats and considering variable at different operation states its safety structures and its components safety parameters. Under the assumption that the system has exponential safety function, the safety characteristics of the port oil piping transportation system are determined.*

Keywords: *safety, operating environment threat, port oil piping transportation system*

Streszczenie: *W pracy przedstawiono zintegrowany ogólny model złożonego systemu technicznego, który łączy model bezpieczeństwa oraz model procesu eksploatacji systemu, uwzględniając wpływ zagrożeń środowiska eksploatacyjnego i biorąc pod uwagę zmienność w czasie struktur bezpieczeństwa tego systemu oraz parametrów bezpieczeństwa jego elementów. Przy założeniu, że system ma wykładniczą funkcję bezpieczeństwa, zostały oszacowane charakterystyki bezpieczeństwa dla portowego systemu transportu paliwa.*

Słowa kluczowe: *bezpieczeństwo, zagrożenia środowiska, portowy system transportu paliwa*

1. Introduction

The general model of the system operation processes and the safety models of various multistate complex technical systems are considered in [6]-[8]. Consequently, the general integrated model linking these system safety models with the model of their operation processes, allowing for the safety analysis of the complex technical systems at the variable conditions with the influence of the operating environment threats are constructed [5]. Using the proposed integrated model, the port oil piping transportation system main safety characteristics including: the conditional and the unconditional expected values and standard deviations of the system lifetimes, the unconditional safety function and the risk function are determined.

2. System operation at variable conditions including operating environment threats

We assume as in [2], that the system during its operation process is taking v' , $v \in N$, different operation states $z'_1, z'_2, \dots, z'_{v'}$. Further, we define the critical infrastructure new operation process $Z(t)$, $t \in \langle 0, +\infty \rangle$ related to the critical infrastructure operating environment threats with discrete operation states from the set $\{z'_1, z'_2, \dots, z'_{v'}\}$. Moreover, we assume that the critical infrastructure operation process $Z(t)$ related to its operating environment threats is a semi-Markov process with the conditional sojourn times θ'_{bl} at the operation states z'_b when its next operation state is z'_l , $b, l = 1, 2, \dots, v'$, $b \neq l$. Under these assumptions, the critical infrastructure operation process may be described by [2]:

- the vector $[p'_b(0)]_{1 \times v'}$ of the initial probabilities $p'_b(0) = P(Z(0) = z'_b)$, $b = 1, 2, \dots, v'$, of the system operation process $Z(t)$ staying at particular operation states at the moment $t = 0$;
- the matrix $[p'_{bl}]_{v' \times v'}$ of probabilities p'_{bl} , $b, l = 1, 2, \dots, v'$, $b \neq l$, of the system operation process $Z(t)$ transitions between the operation states z'_b and z'_l ;
- the matrix $[H'_{bl}(t)]_{v' \times v'}$ of conditional distribution functions $H'_{bl}(t) = P(\theta'_{bl} < t)$, $t \in \langle 0, +\infty \rangle$, $b, l = 1, 2, \dots, v'$, $b \neq l$, of the system operation process $Z(t)$ conditional sojourn times θ'_{bl} at the operation states.

The limit values of the system operation process $Z(t)$ transient probabilities at the particular operation states $p'_b(t) = P(Z(t) = z'_b)$, $t \in \langle 0, +\infty \rangle$, $b = 1, 2, \dots, v'$, can be found using the procedure given in [2]. In the case of a periodic system operation process, the limit transient probabilities p'_b , $b = 1, 2, \dots, v'$, at the operation states, are the long term proportions of the system operation process $Z(t)$ sojourn times at the particular operation states z'_b , $b = 1, 2, \dots, v'$.

3. Safety of multistate exponential systems at variable operation conditions including operating environment threats

In the safety analysis of multistate systems at the variable operation conditions, to define the system with degrading components we assume that the changes of the system operation process $Z'(t)$ states have an impact on the system's components and its structure [7]. Moreover, in this section we assume that the system components at the system operation states have the exponential safety functions. According to [5], the conditional system safety function is defined by the vector

$$[S'_i(t, \cdot)]^{(b)} = [1, [S'_i(t, 1)]^{(b)}, \dots, [S'_i(t, z)]^{(b)}], \quad t \in <0, +\infty), \quad b = 1, 2, \dots, v', \quad i = 1, 2, \dots, n, \quad (1)$$

with the coordinates

$$[S'_i(t, u)]^{(b)} = P(T_i^{(b)}(u) > t | Z'(t) = z'_b) = \exp[-[\lambda'_i(u)]^{(b)} t], \quad t \in <0, +\infty), \\ b = 1, 2, \dots, v', \quad i = 1, 2, \dots, n, \quad (2)$$

where the intensities of ageing of the system components E_i , $i = 1, 2, \dots, n$, related to operation impact, existing in (2), are given by

$$[\lambda'_i(u)]^{(b)} = \rho_i^{(b)}(u) \cdot \lambda_i(u), \quad u = 1, 2, \dots, z, \quad b = 1, 2, \dots, v', \quad i = 1, 2, \dots, n, \quad (3)$$

and $\lambda_i(u)$ are the intensities of ageing of the system components E_i , $i = 1, 2, \dots, n$, without operation impact and

$$[\rho'_i(u)]^{(b)}, \quad u = 1, 2, \dots, z, \quad b = 1, 2, \dots, v', \quad i = 1, 2, \dots, n, \quad (4)$$

are the coefficients of operation impact on the system components E_i , $i = 1, 2, \dots, n$, intensities of ageing without operation impact.

Further, we denote the system unconditional lifetime in the safety state subset $\{u, u+1, \dots, z\}$ by $T(u)$ and the system unconditional safety function by the vector

$$S'(t, \cdot) = [1, S'(t, 1), \dots, S'(t, z)], \quad (5)$$

with the coordinates defined by

$$S'(t, u) = P(T(u) > t), \quad t \in <0, +\infty), \quad u = 1, 2, \dots, z. \quad (6)$$

In the case when the system operation time θ' is large enough, the coordinates of the unconditional safety function of the system defined by (5) are given by

$$S'(t, u) \cong \sum_{b=1}^{v'} p'_b [S'(t, u)]^{(b)} \quad \text{for } t \in <0, +\infty), \quad u = 1, 2, \dots, z, \quad (7)$$

where $[S'(t, u)]^{(b)}$, $u = 1, 2, \dots, z$, $b = 1, 2, \dots, v'$, are the coordinates of the system conditional safety functions defined by (2)-(3) and p'_b , $b = 1, 2, \dots, v'$, are the system operation process limit transient probabilities.

For the exponential complex technical systems [7], we determine the mean values $\mu'(u)$ and the standard deviations $\sigma'(u)$ of the unconditional lifetimes of the system in the safety state subsets $\{u, u+1, \dots, z\}$, $u = 1, 2, \dots, z$, the mean values $\bar{\mu}'(u)$ of the unconditional lifetimes of the system in the particular safety states u , $u = 1, 2, \dots, z$, the system risk function $r'(t)$ and the moment τ' when the system risk function exceeds a permitted level δ , after substituting for $S'(t, u)$, $u = 1, 2, \dots, z$, the coordinates of the unconditional safety functions given by (6).

4. Port oil piping transportation system operation process related to operating environment threats

The port oil pipeline transportation system is a series system composed of:

- the subsystem S_1 , which is composed of two identical pipelines, each has 176 pipe segments of length 12m and two valves,
- the subsystem S_2 , which is composed of two identical pipelines, each has 717 pipe segments of length 12m and two valves,
- the subsystem S_3 , which is composed of two identical and one different pipelines, each has 360 pipe segments of either 10m or 7,5m length and two valves.

In this report, we assume that the port oil piping transportation system operation process and safety may depend on its operating environment threats and we distinguish the following 3 unnatural threats: ut_1 – a human error, ut_2 – a terrorist attack and ut_3 – an act of vandalism and/or theft.

Taking into account expert opinions on the operation process without of separation of the operating environment threats of the considered piping system, in [1], there were distinguished seven operation states. In this case, according to (2.7) in [1], the maximum value of the number of operation states v' of the port oil piping transportation system operation process $Z(t)$ related to its operating environment threats is 56 [2]. Taking into account expert opinions on the varying in time operation process $Z(t)$ of the considered piping system and assuming that the threats are disjoint, according to (2.8)-(2.11) in [2], we distinguish the following as its 28 operation states, respectively marked by:

$$z'_b = z_1, \text{ for } b = 1, z'_b = z_2, \text{ for } b = 5, \dots, z'_b = z_7, \text{ for } b = 25; \quad (8)$$

where z'_b , $b = 1, 5, \dots, 25$, are the operation states without including operating environment threats ut_1 , ut_2 , ut_3 and

$$z'_b, \text{ for } b = 2, 3, 4, 6, 7, 8, \dots, 26, 27, 28. \quad (9)$$

are the operation states including state z_b , $b = 1, 2, \dots, 7$, and successively the threats ut_1 , ut_2 , ut_3 .

The influence of the above system operation states changing on the changes of the pipeline system safety structure is similar to that described in Section 2.2 of [1].

For the new operation states numeration), we have the following system structures:

- at the system operation states z'_b , $b = 1, 2, 3, 4, 9, 10, \dots, 28$, the system is composed of two series-parallel subsystems S_1 , S_2 and one series-“2 out of 3” subsystem S_3 ;
- at the system operation states z'_b , $b = 5, 6, 7, 8$, the system is composed of two series-parallel subsystems S_1 , S_2 and one series-parallel subsystem S_3 .

Considering expert opinions coming from Baltic Oil Terminal in Dębogórze that at all operation states z_b , $b = 1, 2, \dots, 7$, of the port oil piping system, the probability of a human error, a terrorist attack and an act of vandalism and/or theft can be approximately and respectively evaluated as [2]

$$\begin{aligned} P_b(ut_1) = P(ut_1) = 1/1158h = 0.00086, \quad P_b(ut_2) = P(ut_2) = 0, \\ P_b(ut_3) = P(ut_3) = 1/13100h = 0.000076. \end{aligned} \quad (10)$$

According to [2], it was possible to predict the limit transient probabilities of the port oil piping transportation system operation process $Z(t)$ including operating environment threats at particular states:

$$\begin{aligned} p'_{11} = 0.394064, \quad p'_{15} = 0.059064, \quad p'_{19} = 0.002064, \quad p'_{13} = 0.001064, \\ p'_{17} = 0.199064, \quad p'_{21} = 0.057064, \quad p'_{25} = 0.281064, \\ p'_b = 0.00086, \text{ for } b = 2, 6, 10, 14, 18, 22, 26, \\ p'_b = 0, \text{ for } b = 3, 7, 11, 15, 19, 23, 27, \\ p'_b = 0.000076, \text{ for } b = 4, 8, 12, 16, 20, 24, 28. \end{aligned} \quad (11)$$

5. Safety of port oil piping transportation system related to its operating process including operating environment threats

Port oil piping transportation system safety parameters

After considering the comments and opinions coming from experts, taking into account the effectiveness and safety aspects of the operation of the oil pipeline transportation system, we fix the number of pipeline system safety states 3 ($z = 2$) and we distinguish the following three safety states:

- a safety state 2 – piping operation is fully safe,
- a safety state 1 – piping operation is less safe and more dangerous because of the possibility of environment pollution,
- a safety state 0 – piping is destroyed.

Moreover, by the expert opinions, we assume that there are possible the transitions between the components safety states only from better to worse ones.

Considering the assumptions and agreements from Section 4, similarly to Section 3, we assume that the components $E_{ij}^{(v)}$, $i = 1, 2, \dots, k, j = 1, 2, \dots, l_i$, of the subsystem S_v , $v = 1, 2, 3$, at the system operation states z'_b , $b = 1, 2, \dots, 28$, have the exponential safety functions, i.e. the coordinates of the vector

$$[S_{ij}^{(v)}(t, \cdot)]^{(b)} = [1, [S_{ij}^{(v)}(t, 1)]^{(b)}, [S_{ij}^{(v)}(t, 2)]^{(b)}], \quad t \in <0, +\infty), \quad i = 1, 2, \dots, k, \\ j = 1, 2, \dots, l_i, \quad v = 1, 2, 3, \quad b = 1, 2, \dots, 28, \quad (12)$$

are given by

$$[S_{ij}^{(v)}(t, u)]^{(b)} = P([T_{ij}^{(v)}]^{(b)}(u) > t | Z'(t) = z'_b) = \exp[-[\lambda_{ij}^{(v)}(u)]^{(b)} t], \\ t \in <0, +\infty), \quad u = 1, 2, \quad i = 1, 2, \dots, k, \quad j = 1, 2, \dots, l_i, \quad v = 1, 2, 3, \quad b = 1, 2, \dots, 28. \quad (13)$$

Existing in the above formula the intensities of ageing of the components $E_{ij}^{(v)}$, $i = 1, 2, \dots, k, j = 1, 2, \dots, l_i$, of the subsystem S_v , $v = 1, 2, 3$, at the system operation process states z'_b , $b = 1, 2, \dots, 28$, i.e. the coordinates of the vector of intensities

$$[\lambda_{ij}^{(v)}(\cdot)]^{(b)} = [0, [\lambda_{ij}^{(v)}(1)]^{(b)}, [\lambda_{ij}^{(v)}(2)]^{(b)}], \quad i = 1, 2, \dots, k, \quad j = 1, 2, \dots, l_i, \quad v = 1, 2, 3, \\ b = 1, 2, \dots, 28, \quad (14)$$

are given by

$$[\lambda_{ij}^{(v)}(u)]^{(b)} = [\rho_{ij}^{(v)}(u)]^{(b)} \lambda_{ij}^{(v)}(u), \quad u = 1, 2, \quad i = 1, 2, \dots, k, \quad j = 1, 2, \dots, l_i, \\ v = 1, 2, 3, \quad b = 1, 2, \dots, 28, \quad (15)$$

where $\lambda_{ij}^{(v)}(u)$, $u = 1, 2, i = 1, 2, \dots, k, j = 1, 2, \dots, l_i$, are the intensities of ageing of the components $E_{ij}^{(v)}$, $i = 1, 2, \dots, k, j = 1, 2, \dots, l_i$, of the subsystems S_v , $v = 1, 2, 3$, without of operation impact, i.e. the coordinates of the vector of intensities

$$\lambda_{ij}^{(v)}(\cdot) = [0, \lambda_{ij}^{(v)}(1), \lambda_{ij}^{(v)}(2)], \quad i = 1, 2, \dots, k, \quad j = 1, 2, \dots, l_i, \quad v = 1, 2, 3, \quad (16)$$

and

$$[\rho_{ij}^{(v)}(u)]^{(b)}, \quad u = 1, 2, \quad i = 1, 2, \dots, k, \quad j = 1, 2, \dots, l_i, \quad v = 1, 2, 3, \quad b = 1, 2, \dots, 28, \quad (17)$$

are the coefficients of the operation impact on the components $E_{ij}^{(v)}$, $i = 1, 2, \dots, k, j = 1, 2, \dots, l_i$, of the subsystems S_v , $v = 1, 2, 3$, intensities of ageing at the system operation process states z'_b , $b = 1, 2, \dots, 28$, i.e. the coordinates of the vector coefficients of operation impact

$$[\rho_{ij}^{(v)}(\cdot)]^{(b)} = [0, [\rho_{ij}^{(v)}(1)]^{(b)}, [\rho_{ij}^{(v)}(2)]^{(b)}], \quad i = 1, 2, \dots, k, \quad j = 1, 2, \dots, l_i, \\ v = 1, 2, 3, \quad b = 1, 2, \dots, 28. \quad (18)$$

According to expert opinions, changing the port oil piping transportation operation process states including operating environment threats have influence on changing the system safety structures and its selected components' safety parameters as well. For this system, the coefficients and the intensities of components departure from the safety states subset $\{1,2\}$, $\{2\}$ without of operation impact are given in [3], whereas the coefficients and the intensities related to the operation process influence on its safety are given in [4]. The coefficients related to the operating environment threats influence on its safety are given in [5]. Thus, the new intensities of components departure from the safety states subset $\{1,2\}$, $\{2\}$ related to the operating threats influence on the pipeline system safety are as follows:

– for subsystem S_1 :

- $[\lambda_{ij}^{(1)}(1)]^{(b)} = 0.00002$, $[\lambda_{ij}^{(1)}(2)]^{(b)} = 0.00003$, $i = 1,2$, $j = 1,122$, $b = 1,5,25$,
- $[\lambda_{ij}^{(1)}(1)]^{(b)} = 0.002$, $[\lambda_{ij}^{(1)}(2)]^{(b)} = 0.003$, $i = 1,2$, $j = 1,122$, $b = 2,3,6,7,26,27$,
- $[\lambda_{ij}^{(1)}(1)]^{(b)} = 0.000022$, $[\lambda_{ij}^{(1)}(2)]^{(b)} = 0.000033$, $i = 1,2$, $j = 1,122$, $b = 4,8,28$,
- $[\lambda_{ij}^{(1)}(1)]^{(b)} = 0.000024$, $[\lambda_{ij}^{(1)}(2)]^{(b)} = 0.000036$, $i = 1,2$, $j = 1,122$, $b = 9,13,17,21$,
- $[\lambda_{ij}^{(1)}(1)]^{(b)} = 0.0024$, $[\lambda_{ij}^{(1)}(2)]^{(b)} = 0.0036$, $i = 1,2$, $j = 1,122$, $b = 10,11,14,15,18,19,22,23$,
- $[\lambda_{ij}^{(1)}(1)]^{(b)} = 0.0000264$, $[\lambda_{ij}^{(1)}(2)]^{(b)} = 0.0000396$, $i = 1,2$, $j = 1,122$, $b = 12,16,20,24$,
- $[\lambda_{ij}^{(1)}(1)]^{(b)} = 0.00002$, $[\lambda_{ij}^{(1)}(2)]^{(b)} = 0.00003$, $i = 1,2$, $j = 2, \dots, 121, 123, \dots, 176$, $b = 1,2, \dots, 8, 25, 26, 27, 28$,
- $[\lambda_{ij}^{(1)}(1)]^{(b)} = 0.000024$, $[\lambda_{ij}^{(1)}(2)]^{(b)} = 0.000036$, $i = 1,2$, $j = 2, \dots, 121, 123, \dots, 176$, $b = 9, 10, \dots, 24$,
- $[\lambda_{ij}^{(1)}(1)]^{(b)} = 0.00005$, $[\lambda_{ij}^{(1)}(2)]^{(b)} = 0.00006$, $i = 1,2$, $j = 177, 178$, $b = 1,2, \dots, 8, 25, 26, 27, 28$,
- $[\lambda_{ij}^{(1)}(1)]^{(b)} = 0.000060$, $[\lambda_{ij}^{(1)}(2)]^{(b)} = 0.000072$, $i = 1,2$, $j = 177, 178$, $b = 9, 10, \dots, 24$, (19)

– for subsystem S_2 :

- $[\lambda_{ij}^{(2)}(1)]^{(b)} = 0.00002$, $[\lambda_{ij}^{(2)}(2)]^{(b)} = 0.00003$, $i = 1,2$, $j = 1,122$, $b = 1,5,25$,
- $[\lambda_{ij}^{(2)}(1)]^{(b)} = 0.002$, $[\lambda_{ij}^{(2)}(2)]^{(b)} = 0.003$, $i = 1,2$, $j = 1,122$, $b = 2,3,6,7,26,27$,
- $[\lambda_{ij}^{(2)}(1)]^{(b)} = 0.000022$, $[\lambda_{ij}^{(2)}(2)]^{(b)} = 0.000033$, $i = 1,2$, $j = 1,122$, $b = 4,8,28$,
- $[\lambda_{ij}^{(2)}(1)]^{(b)} = 0.000024$, $[\lambda_{ij}^{(2)}(2)]^{(b)} = 0.000036$, $i = 1,2$, $j = 1,122$, $b = 9,13,17,21$,
- $[\lambda_{ij}^{(2)}(1)]^{(b)} = 0.0024$, $[\lambda_{ij}^{(2)}(2)]^{(b)} = 0.0036$, $i = 1,2$, $j = 1,122$, $b = 10,11,14,15,18,19,22,23$,
- $[\lambda_{ij}^{(2)}(1)]^{(b)} = 0.0000264$, $[\lambda_{ij}^{(2)}(2)]^{(b)} = 0.0000396$, $i = 1,2$, $j = 1,122$, $b = 12,16,20,24$,
- $[\lambda_{ij}^{(2)}(1)]^{(b)} = 0.00002$, $[\lambda_{ij}^{(2)}(2)]^{(b)} = 0.00003$, $i = 1,2$, $j = 2, \dots, 121, 123, \dots, 176$, $b = 1,2, \dots, 8, 25, 26, 27, 28$,
- $[\lambda_{ij}^{(2)}(1)]^{(b)} = 0.000024$, $[\lambda_{ij}^{(2)}(2)]^{(b)} = 0.000036$, $i = 1,2$, $j = 2, \dots, 121, 123, \dots, 176$, $b = 9, 10, \dots, 24$,
- $[\lambda_{ij}^{(2)}(1)]^{(b)} = 0.00005$, $[\lambda_{ij}^{(2)}(2)]^{(b)} = 0.00006$, $i = 1,2$, $j = 177, 178$, $b = 1,2, \dots, 8, 25, 26, 27, 28$,
- $[\lambda_{ij}^{(2)}(1)]^{(b)} = 0.000060$, $[\lambda_{ij}^{(2)}(2)]^{(b)} = 0.000072$, $i = 1,2$, $j = 177, 178$, $b = 9, 10, \dots, 24$, (20)

– for subsystem S_3 :

- in the pipelines of the first type:

- $[\lambda_{ij}^{(3)}(1)]^{(b)} = 0.000020, [\lambda_{ij}^{(3)}(2)]^{(b)} = 0.000025, i=1,2, j=1,2,...,360, b=9,10,11,12,17,18,19,20,$
- $[\lambda_{ij}^{(3)}(1)]^{(b)} = 0.000005, [\lambda_{ij}^{(3)}(2)]^{(b)} = 0.000006, i=1,2, j=361,362, b=9,10,11,12,17,18,19,20,$
- $[\lambda_{ij}^{(3)}(1)]^{(b)} = 0.000024, [\lambda_{ij}^{(3)}(2)]^{(b)} = 0.000030, i=1,2, j=1,2,...,360,$
 $b=1,2,...,8,13,...,16,21,...,28,$
- $[\lambda_{ij}^{(3)}(1)]^{(b)} = 0.000060, [\lambda_{ij}^{(3)}(2)]^{(b)} = 0.000072, i=1,2, j=361,362, b=1,2,...,8,13,...,16,21,...,28,$
(21)

- in the pipeline of the second type there are:

- $[\lambda_{ij}^{(3)}(1)]^{(b)} = 0.000024, [\lambda_{ij}^{(3)}(2)]^{(b)} = 0.000027, i=3, j=1,2,...,360, b=9,10,11,12,17,18,19,20,$
- $[\lambda_{ij}^{(3)}(1)]^{(b)} = 0.000005, [\lambda_{ij}^{(3)}(2)]^{(b)} = 0.000006, i=3, j=361,362, b=9,10,11,12,17,18,19,20,$
- $[\lambda_{ij}^{(3)}(1)]^{(b)} = 0.0000288, [\lambda_{ij}^{(3)}(2)]^{(b)} = 0.0000324, i=3, j=1,2,...,360, b=1,2,...,8,13,...,16,21,...,28,$
- $[\lambda_{ij}^{(3)}(1)]^{(b)} = 0.000060, [\lambda_{ij}^{(3)}(2)]^{(b)} = 0.000072, i=3, j=361,362, b=1,2,...,8,13,...,16,21,...,28,$
(22)

Port oil piping transportation system safety characteristics

In [7], it is fixed that the port oil piping transportation system safety structure and its subsystems and components safety depend on its changing in time operation states. The influence of the system operation states changing on the changes of the system safety structure and its components safety functions is given in [2], [5]. Thus, in the case when the operation time is large enough, according to (5) the port oil transportation system unconditional safety function is given by the vector

$$S'(t, \cdot) = [1, S'(t,1), S'(t,2)], t \in <0, +\infty), \quad (23)$$

where according to (7) and considering the pipeline system operation process transient probabilities at the operation states given by (11), the vector coordinates are given respectively by

$$\begin{aligned} S'(t,u) = & 0.394064 [S'(t,u)]^{(1)} + 0.00086 [S'(t,u)]^{(2)} + 0.000076 [S'(t,u)]^{(4)} \\ & + 0.059064 [S'(t,u)]^{(5)} + 0.00086 [S'(t,u)]^{(6)} + 0.000076 [S'(t,u)]^{(8)} \\ & + 0.002064 [S'(t,u)]^{(9)} + 0.00086 [S'(t,u)]^{(10)} + 0.000076 [S'(t,u)]^{(12)} \\ & + 0.001064 [S'(t,u)]^{(13)} + 0.00086 [S'(t,u)]^{(14)} + 0.000076 [S'(t,u)]^{(16)} \\ & + 0.199064 [S'(t,u)]^{(17)} + 0.00086 [S'(t,u)]^{(18)} + 0.000076 [S'(t,u)]^{(20)} \\ & + 0.057064 [S'(t,u)]^{(21)} + 0.00086 [S'(t,u)]^{(22)} + 0.000076 [S'(t,u)]^{(24)} \end{aligned} \quad (24)$$

$$+ 0.281064 [S'(t,u)]^{(25)} + 0.00086 [S'(t,u)]^{(26)} + 0.000076 [S'(t,u)]^{(28)},$$

$t \in <0, +\infty), u = 1, 2,$

where $[S'(t,u)]^{(b)}, u = 1, 2, b = 1, 2, \dots, 28,$ are given in [5].

The graph of the three-state port oil piping transportation system safety function is presented in Figure 1.

Fig. 1 The graph of the pipeline system safety function $S'(t, \cdot)$ coordinates

The expected values and standard deviations (in years) of the system unconditional lifetimes in the safety state subsets $\{1, 2\}, \{2\}$, calculated from the above results given by (24), respectively are:

$$\mu'(1) \cong 58.23, \sigma'(1) \cong 39.49, \mu'(2) \cong 42.74, \sigma'(2) \cong 28.95, \quad (25)$$

and further, considering (25), the mean values (in years) of the unconditional lifetimes in the particular safety states 1, 2, respectively are:

$$\bar{\mu}'(1) = \mu'(1) - \mu'(2) = 15.49, \quad \bar{\mu}'(2) = \mu'(2) = 42.74. \quad (26)$$

Since the critical safety state is $r = 1$, then the system risk function is given by

$$r'(t) = 1 - S'(t,1), \text{ for } t \in <0, +\infty), \quad (27)$$

where $S'(t,1)$ is given by (24). Hence, the moment when the system risk function exceeds a permitted level, for instance $\delta = 0.05$, is

$$\tau = r'^{-1}(\delta) \cong 11.19 \text{ year.} \quad (28)$$

The graph (the fragility curve) of the port oil piping transportation system risk function $r'(t)$ is presented in Figure 2.

Fig. 2 The graph of the pipeline system risk function $r'(t)$

6. Conclusions

The proposed integrated general model of complex technical system is applied to the port oil piping transportation system safety evaluation. The predicted safety characteristics of this system operating at the variable conditions including operating environment threats are different from those determined for the considered system without of considering the impact of operating environment threats on the system safety [4]. This fact justifies the sensibility of considering real systems at the variable operation conditions that is appearing out in a natural way from practice.

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