Blokus-Roszkowska Agnieszka

Kołowrocki Krzysztof
Maritime University, Gdynia, Poland

Reliability and availability of a ground ship-rope transporter in variable operation conditions

Keywords

transportation system, reliability, risk, availability, system operation process

Abstract

In the paper the environment and infrastructure influence of the ground ship-rope transporter operating in Naval Shipyard in Gdynia on its operation processes is considered. The results are presented on the basis of a general model of technical systems operation processes related to their environment and infrastructure. The transporter operation process is described and its statistical identification is given. Next, the reliability, risk and availability evaluation of the transporter in variable operation conditions is presented. In addition, the reliability and availability basic characteristics of the system assuming its components' failure dependence are determined. Finally, the obtained results for the ground ship-rope transporter under the assumption that its components are dependent and independent are compared.

1. Description of the ground ship-rope transporter in Naval Shipyard in Gdynia

The ground ship-rope transporter in the Naval Shipyard in Gdynia is used to transfer ships coming to the shipyard for repairs from the platform to the repair post and back from the repair post to the platform.

Figure 1. The ship at the repair post R4

First during ship docking the ship settled in special supporting carriages on the platform is raised to the wharf level and then the ship is transferred from the platform with the rope broaching machine on a traverse. Next the ship with the traverse, on which the ship is settled, is shifted in the repair post direction. Then after stretching the ropes from the ship to the broaching machine through some blocs, the ship is transferred from the traverser to the repair post. After some repair measures, the ship is transferred back to the traverser and then on the platform. Finally, during undocking the ship on the platform is moved down to the water.

There are nine repair posts, denoted by symbols R1-R9. The first repair post R1 can be lengthening to the post R1/B1 for long ships. There are also available two repair depots denoted by symbols B and D. Generally all kind of repairs can be carried out in any repair post. The repair posts R1 and R2 are equipped in crane. The submarines are repaired in the depot. Additionally large vessels are transferred to the repair post R1/B1. The scheme of the plan of repair post placing is given in *Figure 2*.

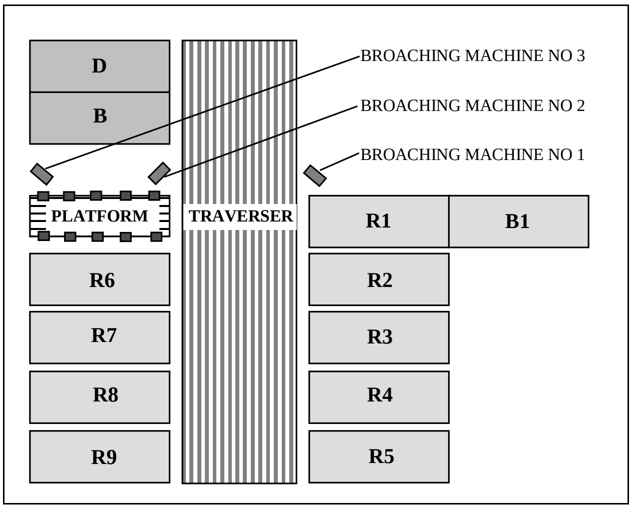

Figure 2. The scheme of the plan repair post placing

The ground ship-rope transporter in the Naval Shipyard in Gdynia is composed of three broaching machines working independently equipped in the steel ropes “Drumet” with the diameter 30 mm. The load of steel ropes in the broaching machines is measured as a power consumption of amperage. The maximum of power consumption of broaching machines is 100 Ampere.

The ground ship-rope transporter reliability depends strongly on the tonnage of transferred ships and the place where the ship should be transferred. The broaching machines in the transportation system are numbered 1, 2, 3. There is used one or there are used two or possibly three broaching machines depending on weight and length of the ship and on which repair post the ship should be transferred. All three broaching machines are working in the extreme situation when large vessel over 1800 tonnes is transferred.

2. Operation process and its statistical identification

We analyze the ground ship-rope transporter in Naval Shipyard in Gdynia taking into account the system operation process and its varying in time reliability structures. Considering the weight and size of the vessel i.e. the system’s loading and the place where the ship is transferred, that has influence on the decision which broaching machines are used we can distinguish following eight operation states:

- an operation state z_1 – the system is without loading, the time of waiting for the ship,
- an operation state z_2 – the ship with a tonnage up to 1300 tonnes is transferred from the platform to the traverser, from the traverser to the repair posts R1-R5 and from the repair posts R6-R9 to the traverser (the broaching machine no. 1 is used),
- an operation state z_3 – the ship with a tonnage up to 1300 tonnes is transferred from the traverser to the repair posts R6-R9, from the repair posts R1-R5 to the traverser and from the traverser to the platform (the broaching machine no. 3 is used),
- an operation state z_4 – the ship with a tonnage up to 1300 tonnes is transferred from the repair posts R1-R5 to the traverser and the access to the broaching machine number 3 is difficult (the broaching machine no. 2 is used),
- an operation state z_5 – the ship with a tonnage over 1300 up to 1800 tonnes is transferred from the platform to the traverser, from the traverser to the repair posts R1-R5 or from the repair posts R6-R9 to the traverser (the broaching machines 1 and 3 are used),
- an operation state z_6 – the ship with a tonnage over 1300 up to 1800 tonnes is transferred from the platform to the traverser, from the traverser to the repair posts R1-R5 or from the repair posts R6-R9 to the traverser and the access to the broaching machine number 3 is difficult (the broaching machines 1 and 2 are used),
- an operation state z_7 – the ship with a tonnage over 1300 up to 1800 tonnes is transferred from the traverser to the repair posts R6-R9, from the repair posts R1-R5 to the traverser or from the traverser to the platform (the broaching machines 2 and 3 are used),
- an operation state z_8 – the ship with a tonnage over 1800 tonnes is transferred (all broaching machines 1, 2 and 3 are used).

On the basis of the statistical data coming from experts using the ground ship-rope transporter in Naval Shipyard in Gdynia [6] the transition probabilities p_{bl} from the operation state z_b into the operation state z_l, $b, l = 1,...,8$, $b \neq l$, were evaluated. Their approximate evaluations are given in the matrix below.

$$[p_{bl}] =$$

$$\begin{bmatrix} 0 & 0.3529 & 0.3529 & 0 & 0.0441 & 0 & 0.1618 & 0.0883 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}.$$

On the basis of statistical data coming from experiment [6] it is possible to evaluate approximately the conditional mean values $M_{bl} = E[\theta_{bl}]$, $b, l = 1,...,8$, $b \neq l$, of the lifetimes in the particular operation states.

$$M_{12} = 3613.33, \; M_{13} = 2620.21, \; M_{14} = 0,$$

$$M_{15} = 3405.00, \; M_{16} = 0, \; M_{17} = 2001.36,$$

$$M_{18} = 9229.17,$$

$$M_{21} = 65.25, \; M_{31} = 65.61, \; M_{41} = 0, \; M_{51} = 73.00,$$

$$M_{61} = 0, \; M_{71} = 92.72, \; M_{81} = 120.00.$$

Hence, by [5], [11], [13], the unconditional mean sojourn times in the particular operation states are determined from the formula

$$M_b = E[\theta_b] = \sum_{l=1}^{8} p_{bl} M_{bl}, \; b = 1,...,8,$$

and takes values:

$$M_1 \cong 3494.92, \; M_2 \cong 65.25, \; M_3 \cong 65.61, \; M_4 = 0,$$

$$M_5 \cong 73.00, \; M_6 = 0, \; M_7 \cong 92.72, \; M_8 \cong 120.00.$$

The limit values of the transient probabilities $p_b(t)$ at the operational states z_b, according to results given in [5], [8], [11] are equal to:

$$p_1 = 0.9790, \; p_2 = 0.0064, \; p_3 = 0.0065, \; p_4 = 0,$$

$$p_5 = 0.0009, \; p_6 = 0, \; p_7 = 0.0042, \; p_8 = 0.0030. \quad (1)$$

3. Reliability of the ground ship-rope transporter

According to rope reliability data given in their technical certificates and experts' opinions based on the nature of wire failures the following reliability states have been distinguished:

- a reliability state 3 – a wire is new, without any defects,
- a reliability state 2 – the corrosion of wire is greater than 0% and less than 25%,
- a reliability state 1 – the corrosion of wire is greater than or equal to 25% and less than 50%,
- a reliability state 0 – otherwise (a wire is failed).

The system consists of three broaching machines – subsystems S_1, S_2, S_3 linked in series. Further assuming that the ground ship-rope transporter is in the reliability state subset $\{1,2,3\}, \{2,3\}, \{3\}$, when all its subsystems are in this subset of reliability states, we conclude that the ground ship-rope transporter is a series system of subsystems S_1, S_2, S_3. In our further analysis considering broaching machines we will discuss the reliability of the rope system only, so we say that the broaching machine is in the reliability state subset $\{1,2,3\}, \{2,3\}, \{3\}$, if the rope in this broaching machine is in this state subset.

We assume that the reliability function of the subsystem S_i, $i = 1,2,3$, is given by the vector

$$\boldsymbol{R}_i(t, \cdot) = [\boldsymbol{R}_i(t,0), \boldsymbol{R}_i(t,1), \boldsymbol{R}_i(t,2), \boldsymbol{R}_i(t,3)],$$
$$t \in \langle 0, \infty),$$

with the co-ordinates

$$\boldsymbol{R}_i(t,u) = P(S_i(t) \geq u \mid S_i(0) = 3) = P(T_i(u) > t)$$

for $t \in \langle 0, \infty)$, $u = 0,1,2,3$, $i = 1,2,3$, and $\boldsymbol{R}_i(t,0) = 1$. $T_i(u)$, $i = 1,2,3$ are independent random variables representing the lifetimes of subsystems S_i in the reliability state subset $\{u, u+1,...,3\}$, while they were at the reliability state 3 at the moment $t = 0$ and $S_i(t)$ are the subsystems S_i reliability states at the moment t, $t \in \langle 0, \infty)$.

Then as the system is composed of three broaching machines – subsystems S_1, S_2, S_3 linked in series, according to results given in [4], the reliability of the ground ship-rope transporter is defined by the vector

$$\overline{\boldsymbol{R}}(t, \cdot) = [1, \overline{\boldsymbol{R}}(t,1), \overline{\boldsymbol{R}}(t,2), \overline{\boldsymbol{R}}(t,3)], \; t \in \langle 0, \infty),$$

where

$$\overline{\boldsymbol{R}}(t,u) = \prod_{i=1}^{3} \boldsymbol{R}_i(t,u), \; t \in \langle 0, \infty), \; u = 1,2,3. \quad (2)$$

Each broaching machine S_1, S_2, S_3 is equipped with one rope that is composed of 6 identical strands. Each strand consists of 36 wires with a webbing core. We consider the wires as basic components of the system. The rope is in the reliability state subset $\{1,2,3\}, \{2,3\}, \{3\}$, if all 6 strand are in this subset, so it is a series system. After some consultations with experts we assume that the strand does not satisfy the technical conditions after breaking 6 of its 36 wires. With this assumption we conclude that the rope is in the reliability state subset $\{1,2,3\}, \{2,3\}, \{3\}$, when all six strands of the rope are in this state subset and each of the strand is in the reliability state subset $\{1,2,3\}, \{2,3\}, \{3\}$, if at least 30 out of its 36 wires are in this state subset. Thus, we obtain that the rope is a regular 4-states "30 out of 36"-series system composed of $k_n = 6$ series-linked strands with $l_n = 36$ parallel-linked components (wires). As each broaching machine has only one rope we can say that the broaching machines i.e. subsystems S_1, S_2, S_3, are also regular 4-state "30 out of 36"-series systems. Moreover we assume that the ground ship-rope transporter subsystems S_i, $i = 1,2,3,$ are composed of identical 4-state components (wires), having the multi-state reliability functions

$$R^{(b)}(t,\cdot) = [1, R^{(b)}(t,1), R^{(b)}(t,2), R^{(b)}(t,3)],$$

with exponential co-ordinates $R^{(b)}(t,1)$, $R^{(b)}(t,2)$ and $R^{(b)}(t,3)$ different in various operation states z_b, $b = 1,2,...,8.$

As all three subsystems S_i, $i = 1,2,3,$ are identical "30 out of 36"-series systems in our further analysis we denote their reliability functions by $\overline{\boldsymbol{R}}^{(6)}_{6,36}(t,\cdot)$.

At the system operational state z_1 the system is composed of subsystems S_1, S_2 and S_3 linked in series. Thus, according to (2), the system reliability function is a vector:

$$\overline{\boldsymbol{R}}(t,\cdot) = [1, \overline{\boldsymbol{R}}(t,1), \overline{\boldsymbol{R}}(t,2), \overline{\boldsymbol{R}}(t,3)], \quad t \in <0,\infty),$$

where

$$\overline{\boldsymbol{R}}(t,u) = = \left[\overline{\boldsymbol{R}}^{(6)}_{6,36}(t,u)\right]^3, \; t \in <0,\infty), \; u = 1,2,3. \quad (3)$$

At the system operational state z_1 components of subsystems S_1, S_2 and S_3 (wires in the ropes) have identical following conditional reliability functions co-ordinates:

$$R^{(1)}(t,1) = \exp[-0.0097t],$$

$$R^{(1)}(t,2) = \exp[-0.0147t],$$

$$R^{(1)}(t,3) = \exp[-0.0278t] \text{ for } t \geq 0.$$

Thus, considering (3) and from [5], the conditional multi-state reliability function of the ground ship-rope transporter at the operational state z_1 is given by:

$$[\overline{\boldsymbol{R}}(t,\cdot)]^{(1)} = [1, [\overline{\boldsymbol{R}}(t,1)]^{(1)}, [\overline{\boldsymbol{R}}(t,2)]^{(1)}, [\overline{\boldsymbol{R}}(t,3)]^{(1)}],$$

where

$$[\overline{\boldsymbol{R}}(t,1)]^{(1)} = \left[[\overline{\boldsymbol{R}}^{(6)}_{6,36}(t,1)]^{(1)}\right]^3$$

$$= [\sum_{i=0}^{6} \binom{36}{i} [1 - \exp[-0.0097t]]^i$$

$$\exp[-(36-i)0.0097t]]^{18}, \quad (4)$$

$$[\overline{\boldsymbol{R}}(t,2)]^{(1)} = \left[[\overline{\boldsymbol{R}}^{(6)}_{6,36}(t,2)]^{(1)}\right]^3$$

$$= [\sum_{i=0}^{6} \binom{36}{i} [1 - \exp[-0.0147t]]^i$$

$$\exp[-(36-i)0.0147t]]^{18}, \quad (5)$$

$$[\overline{\boldsymbol{R}}(t,3)]^{(1)} = \left[[\overline{\boldsymbol{R}}^{(6)}_{6,36}(t,3)]^{(1)}\right]^3$$

$$= [\sum_{i=0}^{6} \binom{36}{i} [1 - \exp[-0.0278t]]^i$$

$$\exp[-(36-i)0.0278t]]^{18}, \quad (6)$$

for $t \geq 0$.

The expected values and standard deviations of the ground ship-rope transporter conditional lifetimes in the reliability state subsets calculated from the above result given by (4)-(6), according to results given in [5], [9] at the operation state z_1 are respectively given in years by:

$$\mu_1(1) \cong 9.4539, \; \mu_1(2) \cong 6.3866, \; \mu_1(3) \cong 3.3772, \quad (7)$$

$$\sigma_1(1) \cong 2.0576, \; \sigma_1(2) \cong 1.5939, \; \sigma_1(3) \cong 0.8422, \quad (8)$$

and further, using (7), from [9] it follows that the conditional lifetimes in the particular reliability states at the operation state z_1 in years are:

$$\bar{\mu}_1(1) \cong 3.0673, \; \bar{\mu}_1(2) \cong 3.0094, \; \bar{\mu}_1(3) \cong 3.3772.$$

At the operational state z_2 the ship is transferred using the broaching machine number 1, so the system is composed of subsystem S_1. The scheme of the ground ship-rope transporter at the operational state z_2 is showed in *Figure 3*.

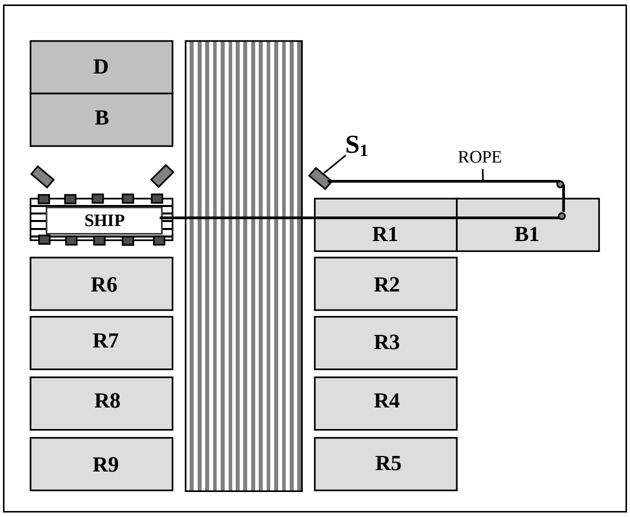

Figure 3. The scheme of the ground ship-rope transporter at the operational state z_2

We assume that at the operational state z_2 wires in the ropes have following exponential conditional reliability functions co-ordinates:

$$R^{(2)}(t,1) = \exp[-0.0158t],$$

$$R^{(2)}(t,2) = \exp[-0.0235t],$$

$$R^{(2)}(t,3) = \exp[-0.0388t], \quad t \geq 0.$$

As the system is composed only of subsystem S_1 the conditional multi-state reliability function of the ground ship-rope transporter at the operational state z_2 is given by:

$$[\overline{\boldsymbol{R}}(t,\cdot)]^{(2)} = [1, [\overline{\boldsymbol{R}}(t,1)]^{(2)}, [\overline{\boldsymbol{R}}(t,2)]^{(2)}, [\overline{\boldsymbol{R}}(t,3)]^{(2)}],$$

where

$$[\overline{\boldsymbol{R}}(t,1)]^{(2)} = [\overline{\boldsymbol{R}}^{(6)}_{6,36}(t,1)]^{(2)}$$

$$= [\sum_{i=0}^{6} \binom{36}{i} [1 - \exp[-0.0158t]]^i$$

$$\exp[-(36-i)0.0158t]]^6, \tag{9}$$

$$[\overline{\boldsymbol{R}}(t,2)]^{(2)} = [\overline{\boldsymbol{R}}^{(6)}_{6,36}(t,2)]^{(2)}$$

$$= [\sum_{i=0}^{6} \binom{36}{i} [1 - \exp[-0.0235t]]^i$$

$$\exp[-(36-i)0.0235t]]^6, \tag{10}$$

$$[\overline{\boldsymbol{R}}(t,3)]^{(2)} = [\overline{\boldsymbol{R}}^{(6)}_{6,36}(t,3)]^{(2)}$$

$$= [\sum_{i=0}^{6} \binom{36}{i} [1 - \exp[-0.0388t]]^i$$

$$\exp[-(36-i)0.0399t]]^6, \tag{11}$$

for $t \geq 0$.

The expected values and standard deviations of the ground ship-rope transporter conditional lifetimes in the reliability state subsets calculated from the above result given by (9)-(11), and from [9] at the operation state z_2 given in years are:

$$\mu_2(1) \cong 7.7309, \mu_2(2) \cong 5.2210,$$
$$\mu_2(3) \cong 3.1622, \tag{12}$$

$$\sigma_2(1) \cong 2.1062, \sigma_2(2) \cong 1.4722,$$
$$\sigma_2(3) \cong 0.8912, \tag{13}$$

and further, using (12), from [9] it follows that the conditional lifetimes in the particular reliability states at the operation state z_2 in years are:

$$\bar{\mu}_2(1) \cong 2.5099, \ \bar{\mu}_2(2) \cong 2.0588, \ \bar{\mu}_2(3) \cong 3.1622.$$

At the system operational state z_3 the system is composed of subsystem S_3. The ship is transferred using the broaching machine number 3 and the scheme is showed in *Figure 4*.

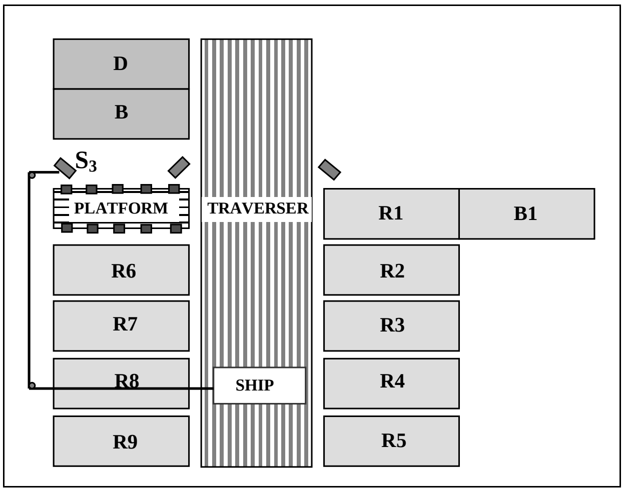

Figure 4. The scheme of the ground ship-rope transporter at the operational state z_3

At the operational state z_4 the ship is transferred using the broaching machine number 2, so the system is composed of subsystem S_2.

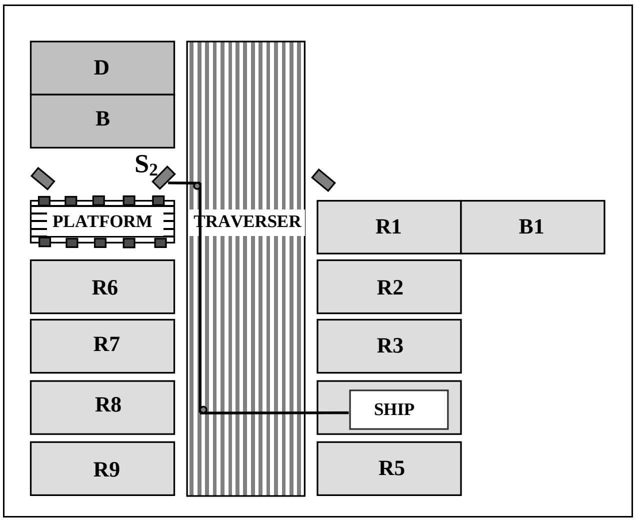

Figure 5. The scheme of the ground ship-rope transporter at the operational state z_4

At the operation states z_3 and z_4 the system similarly as at the operation state z_2 is composed of one rope. As all ropes are composed of identical wires the conditional reliability function of the ground ship-rope transporter at the operation states z_3 and z_4 are the same as at the operation state z_2.
At the system operational state z_5 the system is composed of subsystems S_1 and S_3 linked in series. At the operational state z_5 the ship is transferred using the broaching machines number 1 and 3 and the scheme of the ground ship-rope transporter at the operational state z_5 is showed in *Figure 6*. Thus the system is a series system composed of identical two subsystems S_i, $i = 1,3,$ and its reliability function is a vector:

$$\overline{\boldsymbol{R}}(t,\cdot) = [1, \overline{\boldsymbol{R}}(t,1), \overline{\boldsymbol{R}}(t,2), \overline{\boldsymbol{R}}(t,3)], \quad t \in <0,\infty),$$

where

$$\overline{\boldsymbol{R}}(t,u) = \left[\overline{\boldsymbol{R}}^{(6)}_{6,36}(t,u)\right]^2, \; t \in <0,\infty), \; u = 1,2,3. \quad (14)$$

The subsystems S_1 and S_3 are 4-state "30 out of 36"-series systems, in which components (wires in the ropes) have identical following conditional reliability functions co-ordinates:

$$R^{(5)}(t,1) = \exp[-0.0175t],$$

$$R^{(5)}(t,2) = \exp[-0.0361t],$$

$$R^{(5)}(t,3) = \exp[-0.0551t] \text{ for } t \geq 0.$$

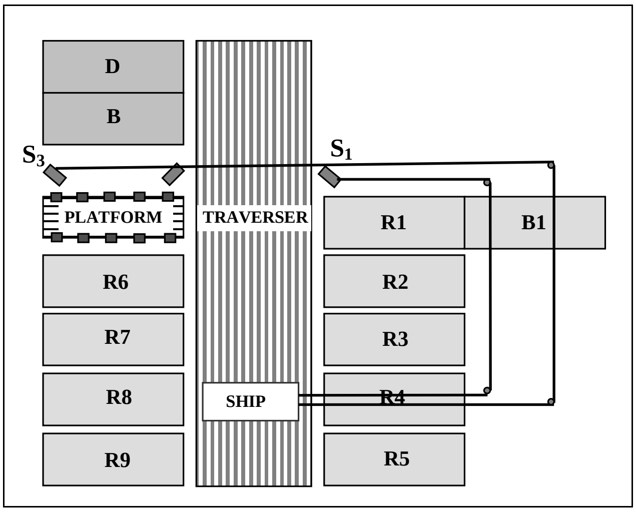

Figure 6. The scheme of the ground ship-rope transporter at the operational state z_5

Thus, considering (14) and from [5], the conditional multi-state reliability function of the ground ship-rope transporter at the operational state z_5 is given by:

$$[\overline{\boldsymbol{R}}(t,\cdot)]^{(5)} = [1, [\overline{\boldsymbol{R}}(t,1)]^{(5)}, [\overline{\boldsymbol{R}}(t,2)]^{(5)}, [\overline{\boldsymbol{R}}(t,3)]^{(5)}],$$

where

$$[\overline{\boldsymbol{R}}(t,1)]^{(5)} = \left[[\overline{\boldsymbol{R}}^{(6)}_{6,36}(t,1)]^{(5)}\right]^2$$

$$= [\sum_{i=0}^{6} \binom{36}{i} [1 - \exp[-0.0175t]]^i$$

$$\exp[-(36-i)0.0175t]]^{12}, \quad (15)$$

$$[\overline{\boldsymbol{R}}(t,2)]^{(5)} = \left[[\overline{\boldsymbol{R}}^{(6)}_{6,36}(t,2)]^{(5)}\right]^2$$

$$= [\sum_{i=0}^{6} \binom{36}{i} [1 - \exp[-0.0361t]]^i$$

$$\exp[-(36-i)0.0361]]^{12}, \quad (16)$$

$$[\overline{\boldsymbol{R}}(t,3)]^{(5)} = \left[[\overline{\boldsymbol{R}}^{(6)}_{6,36}(t,3)]^{(5)}\right]^2$$

$$= [\sum_{i=0}^{6} \binom{36}{i} [1 - \exp[-0.0551t]]^i$$

$$\exp[-(36-i)0.0551t]]^{12}, \quad (17)$$

for $t \geq 0$.

The expected values and standard deviations, from results in [9], of the ground ship-rope transporter conditional lifetimes in the reliability state subsets at the operation state z_5 counted in years are:

$$\mu_5(1) \cong 5.8962, \mu_5(2) \cong 2.8583,$$
$$\mu_5(3) \cong 1.8727, \tag{18}$$

$$\sigma_5(1) \cong 1.5326, \sigma_5(2) \cong 0.7421,$$
$$\sigma_5(3) \cong 0.4852. \tag{19}$$

Hence the conditional lifetimes in the particular reliability states at the operation state z_5 in years are:

$$\bar{\mu}_5(1) \cong 3.0379,\ \bar{\mu}_5(2) \cong 0.9856,\ \bar{\mu}_5(3) \cong 1.8727.$$

At the operation states z_6 and z_7 the system similarly as at the operation state z_5 is composed of two ropes, thus the conditional reliability function of the ground ship-rope transporter at the operation states z_6 and z_7 are the same as at the operation state z_5.

At the system operational state z_6 the system is composed of subsystems S_1 and S_2 linked in series. The ship is transferred using the broaching machines number 1 and 2 and the scheme of the ground ship-rope transporter at the operational state z_6 is presented in *Figure 7*.

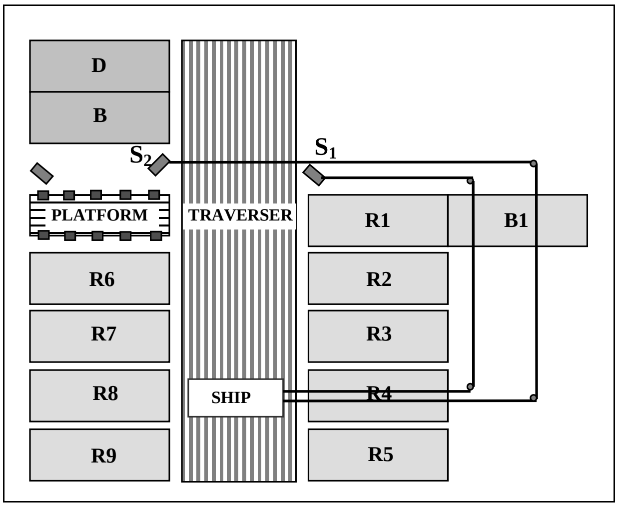

Figure 7. The scheme of the ground ship-rope transporter at the operational state z_6

Whereas at the system operational state z_7 the system is composed of subsystems S_2 and S_3 linked in series. Then the ship is transferred using the broaching machines number 2 and 3 and the scheme of this situation is showed in *Figure 8*.

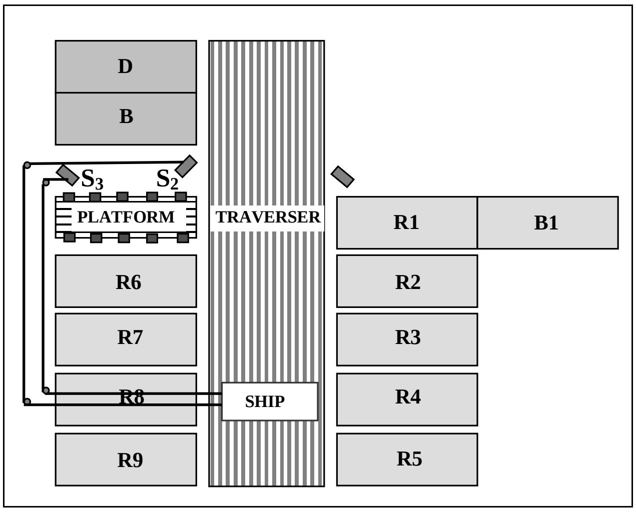

Figure 8. The scheme of the ground ship-rope transporter at the operational state z_7

At the operational state z_8 the system is composed of subsystems S_1, S_2 and S_3 linked in series. At the operational state z_8 the ship is transferred using all three broaching machines 1,2 and 3 (*Figure 9*). Thus the system is a series system composed of three identical subsystems S_i, $i = 1,2,3,$ and its reliability function, according to (3), is a vector:

$$\overline{\boldsymbol{R}}(t,\cdot) = [1, \overline{\boldsymbol{R}}(t,1), \overline{\boldsymbol{R}}(t,2), \overline{\boldsymbol{R}}(t,3)],\ \ t \in <0,\infty),$$

where

$$\overline{\boldsymbol{R}}(t,u) = \left[\overline{\boldsymbol{R}}^{(6)}_{6,36}(t,u)\right]^3,\ t \in <0,\infty),\ u = 1,2,3. \tag{20}$$

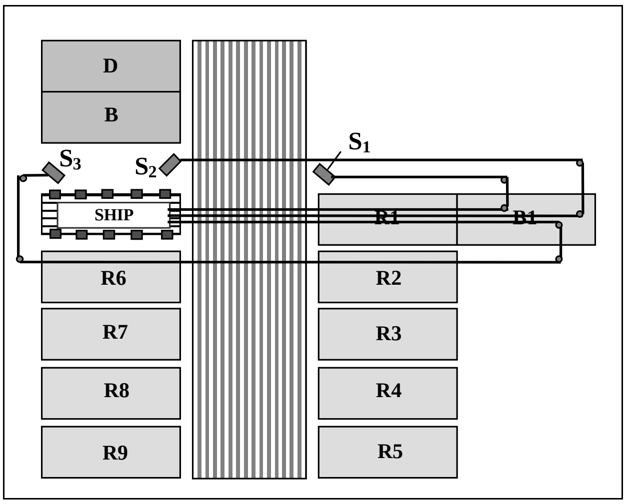

Figure 9. The scheme of the ground ship-rope transporter at the operational state z_8

The subsystems S_1, S_2 and S_3 are 4-state "30 out of 36"-series systems, in which components (wires in the ropes) have identical following conditional reliability functions co-ordinates:

$$R^{(8)}(t,1) = \exp[-0.0215t],$$

$$R^{(8)}(t,2) = \exp[-0.0394t],$$

$$R^{(8)}(t,3) = \exp[-0.0607t] \text{ for } t \geq 0.$$

Thus, considering (20) and from [5], the conditional multi-state reliability function of the ground ship-rope transporter at the operational state z_8 is given by:

$$[\overline{\boldsymbol{R}}(t,\cdot)]^{(8)} = [1, [\overline{\boldsymbol{R}}(t,1)]^{(8)}, [\overline{\boldsymbol{R}}(t,2)]^{(8)}, [\overline{\boldsymbol{R}}(t,3)]^{(8)}],$$

where

$$[\overline{\boldsymbol{R}}(t,1)]^{(8)} = \left[[\overline{\boldsymbol{R}}^{(6)}_{6,36}(t,1)]^{(8)}\right]^3$$

$$= [\sum_{i=0}^{6} \binom{36}{i} [1 - \exp[-0.0215t]]^i,$$

$$\exp[-(36-i)0.0215t]]^{18}, \quad (21)$$

$$[\overline{\boldsymbol{R}}(t,2)]^{(8)} = \left[[\overline{\boldsymbol{R}}^{(6)}_{6,36}(t,2)]^{(8)}\right]^3$$

$$= [\sum_{i=0}^{6} \binom{36}{i} [1 - \exp[-0.0394t]]^i$$

$$\exp[-(36-i)0.0.394t]]^{18}, \quad (22)$$

$$[\overline{\boldsymbol{R}}(t,3)]^{(8)} = \left[[\overline{\boldsymbol{R}}^{(6)}_{6,36}(t,3)]^{(8)}\right]^3$$

$$= [\sum_{i=0}^{6} \binom{36}{i} [1 - \exp[-0.0607t]]^i$$

$$\exp[-(36-i)0.0607t]]^{18}, \text{ for } t \geq 0. \quad (23)$$

The expected values and standard deviations of the ground ship-rope transporter conditional lifetimes in the reliability state subsets calculated from the above result, according to results given in [9] at the operation state z_8, in years, are respectively given by:

$$\mu_8(1) \cong 4.3668, \mu_8(2) \cong 2.3829,$$
$$\mu_8(3) \cong 1.5467, \quad (24)$$

$$\sigma_8(1) \cong 0.8427, \sigma_8(2) \cong 0.5935,$$
$$\sigma_8(3) \cong 0.3841. \quad (25)$$

and further, using (24) and from [9], the conditional lifetimes in the particular reliability states at the operation state z_8 in years are:

$$\bar{\mu}_8(1) \cong 1.9839, \ \bar{\mu}_8(2) \cong 0.8362, \ \bar{\mu}_8(3) \cong 1.5467.$$

In the case when the operation time is large enough its unconditional multi-state reliability function of the ground ship-rope transporter is given by the vector

$$\overline{\boldsymbol{R}}(t,\cdot) = [1, \overline{\boldsymbol{R}}(t,1), \overline{\boldsymbol{R}}(t,2), \overline{\boldsymbol{R}}(t,3)], \ t \in <0,\infty),$$

where according to [5], [13], the vector co-ordinates are given respectively by:

$$\overline{\boldsymbol{R}}(t,u) = \sum_{i=1}^{8} p_i [\overline{\boldsymbol{R}}(t,u)]^{(i)} \text{ for } t \geq 0, \ u = 1,2,3, \quad (26)$$

where $[\overline{\boldsymbol{R}}(t,u)]^{(i)}$, $i = 1,\ldots,8$, are given by (4)-(6), (9)-(11), (15)-(17), (21)-(23).

The mean values and the standard deviations of the ground ship-rope transporter unconditional lifetimes in the reliability state subsets, according to [5] and after considering (7)-(8), (12)-(13), (18)-(19), (24)-(25) and (1), respectively are:

$$\mu(1) = \sum_{i=1}^{8} p_i \mu_i(1) \cong 9.3996, \quad (27)$$

$$\sigma(1) \cong 2.0901,$$

$$\mu(2) = \sum_{i=1}^{8} p_i \mu_i(2) \cong 6.3424, \quad (28)$$

$$\sigma(2) \cong 1.6234,$$

$$\mu(3) = \sum_{i=1}^{8} p_i \mu_i(3) \cong 3.3613, \quad (29)$$

$$\sigma(3) \cong 0.8532.$$

Next, the unconditional mean values of the ground ship-rope transporter lifetimes in the particular reliability states, by [9] and considering (27)-(29), in years are:

$$\bar{\mu}(1) = \mu(1) - \mu(2) = 3.0572,$$

$$\bar{\mu}(2) = \mu(2) - \mu(3) = 2.9811,$$

$$\bar{\mu}(3) = \mu(3) = 3.3613.$$

If the critical reliability state is $r = 2$, then according to [5], [9], the system risk function takes the form

$$\boldsymbol{r}(t) = 1 - \overline{\boldsymbol{R}}(t,2) = 1 - \sum_{i=1}^{8} p_i [\overline{\boldsymbol{R}}(t,2)]^{(i)}, \ t \geq 0.$$

where $\overline{\boldsymbol{R}}(t,2)$ is the unconditional reliability function of the ground ship-rope transporter at the critical state.
Hence, the moment when the system risk function exceeds a permitted level, for instance $\delta = 0.05$, from [4], [9], is

$$\tau = \boldsymbol{r}^{-1}(\delta) \cong 3.685 \text{ years} \cong 3 \text{ years } 250 \text{ days}.$$

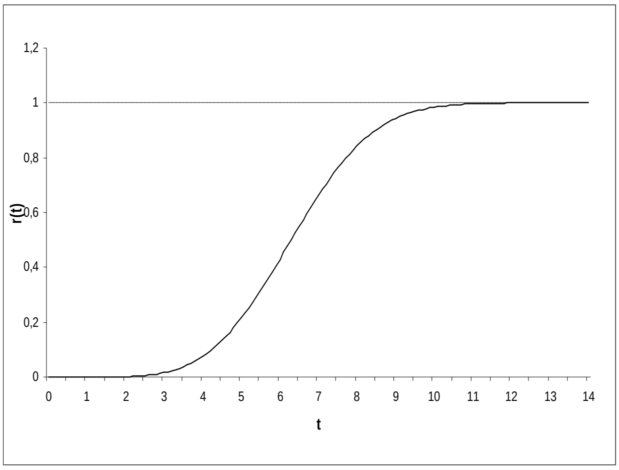

Figure 10. The graph of the ground ship-rope transporter risk function $r(t)$

4. Availability of the ground ship-rope transporter

In this point the asymptotic evaluation of the basic reliability and availability characteristics of renewal systems with non-ignored time of renovation are determined in an example of the ground ship-rope transporter.
Assuming that the ground ship-rope transporter is repaired after its failure and that the time of the system renovation is not ignored and it has the mean value $\mu_0(2) = 0.0014 \cong 12$ hours and the standard deviation $\sigma_0(2) = 0.0002 \cong 2$ hours, applying theoretical results presented in [4], we obtain the following results:

i) the distribution function of the time $\overline{\overline{S}}_N(2)$ until the *Nth* system's renovation, for sufficiently large *N*, has approximately normal distribution $N(6.3438N, 1.6234\sqrt{N})$, i.e.,

$$\overline{\overline{F}}^{(N)}(t,2) = P(\overline{\overline{S}}_N(2) < t) \cong F_{N(0,1)}(\frac{t - 6.3438N}{1.6234\sqrt{N}}),$$
$$t \in (-\infty, \infty), \ N = 1,2,...,$$

ii) the expected value and the variance of the time $\overline{\overline{S}}_N(2)$ until the *Nth* system's renovation take respectively forms

$$E[\overline{\overline{S}}_N(2)] \cong 6.3438N, \ D[\overline{\overline{S}}_N(2)] \cong 2.6354N,$$

iii) the distribution function of the time $\overline{S}_N(2)$ until the *Nth* exceeding the reliability critical state 2 of this system takes form

$$\overline{F}^{(N)}(t,2) =$$
$$P(\overline{S}_N(2) < t) = F_{N(0,1)}(\frac{t - 6.3438N + 0.0014}{1.6234\sqrt{N}}),$$
$$t \in (-\infty, \infty), \ N = 1,2,...,$$

iv) the expected value and the variance of the time $\overline{S}_N(2)$ until the *Nth* exceeding the reliability critical state 2 of this system take respectively forms

$$E[\overline{S}_N(2)] \cong 6.3424N + 0.0014(N-1),$$

$$D[\overline{S}_N(2)] \cong 2.6354N,$$

v) the distribution of the number $\overline{\overline{N}}(t,2)$ of system's renovations up to the moment t, $t \geq 0$, is of the form

$$P(\overline{\overline{N}}(t,2) = N) \cong F_{N(0,1)}(\frac{6.3438 - t}{0.6445\sqrt{t}})$$

$$- F_{N(0,1)}(\frac{6.3438(N+1) - t}{0.6445\sqrt{t}}), \ N = 1,2,...,$$

vi) the expected value and the variance of the number $\overline{\overline{N}}(t,2)$ of system's renovations up to the moment t, $t \geq 0$, take respectively forms

$$\overline{\overline{H}}(t,2) \cong 0.1576t, \quad \overline{\overline{D}}(t,2) \cong 0.0103t,$$

vii) the distribution of the number $\overline{N}(t,2)$ of exceeding the reliability critical state 2 of this system up to the moment $t, t \geq 0,$ is of the form

$$P(\overline{N}(t,2) = N) \cong F_{N(0,1)}(\frac{6.3438N - t - 0.0014}{0.6445\sqrt{t + 0.0014}})$$

$$- F_{N(0,1)}(\frac{6.3438(N+1) - t - 00014}{0.6445\sqrt{t + 0.0014}}), \; N = 1,2,...,$$

viii) the expected value and the variance of the number $\overline{N}(t,2)$ of exceeding the reliability critical state 2 of this system up to the moment $t, t \geq 0,$ are respectively given by

$$\overline{H}(t,2) \cong 0.1576(t + 0.0014),$$

$$\overline{D}(t,1) \cong 0.0103(t + 0.0014),$$

ix) the availability coefficient of the system at the moment t is given by the formula

$$K(t,2) \cong 0.9998, \; t \geq 0,$$

x) the availability coefficient of the system in the time interval $< t, t+\tau), \tau > 0,$ is given by the formula

$$K(t,\tau,2) \cong 0.1576 \int_{\tau}^{\infty} \overline{\boldsymbol{R}}(t,2)dt, \; t \geq 0, \; \tau > 0,$$

where the reliability function of a system at the critical state $\overline{\boldsymbol{R}}(t,2)$ is given by the formula (26).

5. The ground ship-rope transporter with dependent failures of components

From practical point of view it seems reasonable to consider the ground ship-rope transporter assuming component failures' dependence [7]. Indeed, failures of some wires in ropes have influence on the remaining wires and may cause their reliability characteristics worsening. Thus, the assumption about dependence of wires seems to be natural and justified.
The increased load caused by one or several components' failures may cause the increase of the failure rates of the rest components. We consider an equal load sharing model that is widely described in [2], [3].

A multi-state "m out of n"-series system with dependent components is considered as a system of linked independently in series multi-state "m out of n" subsystems composed of components with failure dependency. In each of these subsystems we assume the following model of failure dependency. After getting out v components in a subsystem, of the reliability state subset $\{u,u+1,\ldots,z\}$, $u = 1,2,\ldots,z$, the increased load is shared equally among others. The number of components v, that are getting out of the reliability state subset can be equal to $v = 0,1,2,\ldots,l_i - 1$, where l_i, $i = 1,2,\ldots,k$, is number of components in the i-th subsystem.
We denote by $T_{ij}(u)$, $i = 1,2,\ldots,k$, $j = 1,2,\ldots,l_i$, $u = 1,2,\ldots,z$, the random variables representing the lifetimes of components E_{ij} in the state subset $\{u, u+1,..., z\}$, and $T(u)$, $u = 1,2,\ldots,z$, is a random variable representing the lifetime of a system in this reliability state subset. Then the reliability of remaining not failed components is getting worse so that the mean values of the i-th, $i = 1,2,\ldots,k$, subsystem component lifetimes in the state subset $\{u,u+1,\ldots,z\}$, are of the form

$$E[T_{ij}'(u)] = E[T_{ij}(u)] - \frac{v}{l_i} E[T_{ij}(u)]$$

$$= \frac{l_i - v}{l_i} E[T_{ij}(u)],$$

$$j = 1,2,\ldots,l_i, \; v = 0,1,2,\ldots,l_i - 1, \; i = 1,2,\ldots,k,$$
$$u = 1,2,\ldots,z.$$

The ground ship-rope transporter as a system with dependent failures of components is described in [7]. In this paper there are quoted only some final values of reliability characteristics to compare them with results obtained in the previous point. Additionally the availability analysis of the ground ship-rope transporter in Naval Shipyard in Gdynia assuming the wires' failure dependence is presented.
The mean values and the standard deviations of the ground ship-rope transporter unconditional lifetimes in the reliability state subsets, according to results given in [5], [13], counted in years respectively are:

$$\mu(1) = \sum_{i=1}^{8} p_i \mu_i \; (1) \cong 8.7940, \tag{30}$$

$$\sigma(1) \cong 2.2355,$$

$$\mu(2) = \sum_{i=1}^{8} p_i \mu_i \; (2) \cong 5.7981, \tag{31}$$

$$\sigma(2) \cong 1.4867,$$

$$\mu(3) = \sum_{i=1}^{8} p_i \mu_i(3) \cong 3.0731, \qquad (32)$$

$$\sigma(3) \cong 0.7797.$$

Next, the unconditional mean values of the ground ship-rope transporter lifetimes in the particular reliability states, by [9] and considering (30)-(32), in years are:

$$\bar{\mu}(1) = \mu(1) - \mu(2) = 2.9959,$$

$$\bar{\mu}(2) = \mu(2) - \mu(3) = 2.725,$$

$$\bar{\mu}(3) = \mu(3) = 3.0731.$$

Next, assuming that the ground ship-rope transporter is repaired after its failure and that the time of the system renovation is not ignored and it has the mean value $\mu_0(2) = 0.0014 \cong 12$ hours and the standard deviation $\sigma_0(2) = 0.0002 \cong 2$ hours, applying results given in [4], we obtain the following results:

i) the distribution function of the time $\bar{\bar{S}}_N(2)$ until the *Nth* system's renovation, for sufficiently large *N*, has approximately normal distribution $N(5.7995N, 1.4867\sqrt{N})$, i.e.,

$$\bar{\bar{F}}^{(N)}(t,2) = P(\bar{\bar{S}}_N(2) < t) \cong F_{N(0,1)}\left(\frac{t - 5.7995N}{1.4867\sqrt{N}}\right),$$
$$t \in (-\infty, \infty), \; N = 1,2,...,$$

ii) the expected value and the variance of the time $\bar{\bar{S}}_N(2)$ until the *Nth* system's renovation take respectively forms

$$E[\bar{\bar{S}}_N(2)] \cong 5.7995N, \; D[\bar{\bar{S}}_N(2)] \cong 2.2103N,$$

iii) the distribution function of the time $\bar{S}_N(2)$ until the *Nth* exceeding the reliability critical state 2 of this system takes form

$$\bar{F}^{(N)}(t,2) =$$
$$P(\bar{S}_N(2) < t) = F_{N(0,1)}\left(\frac{t - 5.7995N + 0.0014}{1.4867\sqrt{N}}\right),$$
$$t \in (-\infty, \infty), \; N = 1,2,...,$$

iv) the expected value and the variance of the time $\bar{S}_N(2)$ until the *Nth* exceeding the reliability critical state 2 of this system take respectively forms

$$E[\bar{S}_N(2)] \cong 5.7981N + 0.0014(N-1),$$

$$D[\bar{S}_N(2)] \cong 2.2103N,$$

v) the distribution of the number $\bar{\bar{N}}(t,2)$ of system's renovations up to the moment $t, \; t \geq 0,$ is of the form

$$P(\bar{\bar{N}}(t,2) = N) \cong F_{N(0,1)}\left(\frac{5.7995 - t}{0.6173\sqrt{t}}\right)$$

$$- F_{N(0,1)}\left(\frac{5.7995(N+1) - t}{0.6173\sqrt{t}}\right), \; N = 1,2,...,$$

vi) the expected value and the variance of the number $\bar{\bar{N}}(t,2)$ of system's renovations up to the moment $t, \; t \geq 0,$ take respectively forms

$$\bar{\bar{H}}(t,2) \cong 0.1724t, \; \bar{\bar{D}}(t,2) \cong 0.0113t,$$

vii) the distribution of the number $\bar{N}(t,2)$ of exceeding the reliability critical state 2 of this system up to the moment $t, \; t \geq 0,$ is of the form

$$P(\bar{N}(t,2) = N) \cong F_{N(0,1)}\left(\frac{5.7995N - t - 0.0014}{0.6173\sqrt{t + 0.0014}}\right)$$

$$- F_{N(0,1)}\left(\frac{5.7995(N+1) - t - 00014}{0.6173\sqrt{t + 0.0014}}\right), \; N = 1,2,...,$$

viii) the expected value and the variance of the number $\bar{N}(t,2)$ of exceeding the reliability critical state 2 of this system up to the moment $t, \; t \geq 0,$ are respectively given by

$$\bar{H}(t,2) \cong 0.1724(t + 0.0014),$$

$$\bar{D}(t,1) \cong 0.0113(t + 0.0014),$$

ix) the availability coefficient of the system at the moment *t* is given by the formula

$$K(t,2) \cong 0.9998, \quad t \geq 0,$$

x) the availability coefficient of the system in the time interval $< t, t + \tau), \tau > 0,$ is given by the formula

$$K(t,\tau,2) \cong 0.1724 \int_{\tau}^{\infty} \overline{\boldsymbol{R}}(t,2)dt, \; t \ge 0, \; \tau > 0,$$

where the reliability function of a system at the critical state $\overline{\boldsymbol{R}}(t,2)$ is given by the formula

$$\overline{\boldsymbol{R}}(t,2) = \sum_{i=1}^{8} p_i [\overline{\boldsymbol{R}}(t,2)]^{(i)}, \quad t \ge 0,$$

where

$$[\overline{\boldsymbol{R}}(t,2)]^{(1)} = [\sum_{j=0}^{6} \frac{(0.5292t)^j}{j!} \exp[-0.5292t]]^{18}$$

$$[\overline{\boldsymbol{R}}(t,2)]^{(i)} = [\sum_{j=0}^{6} \frac{(0.846t)^j}{j!} \exp[-0.846t]]^{6},$$

for $i = 2,3,4$,

$$[\overline{\boldsymbol{R}}(t,2)]^{(i)} = [\sum_{j=0}^{6} \frac{(1.2996t)^j}{j!} \exp[-1.2996t]]^{12}$$

for $i = 5,6,7$,

$$[\overline{\boldsymbol{R}}(t,2)]^{(8)} = [\sum_{j=0}^{6} \frac{(1.4184t)^j}{j!} \exp[-1.4184t]]^{18}$$

for $t \ge 0$.

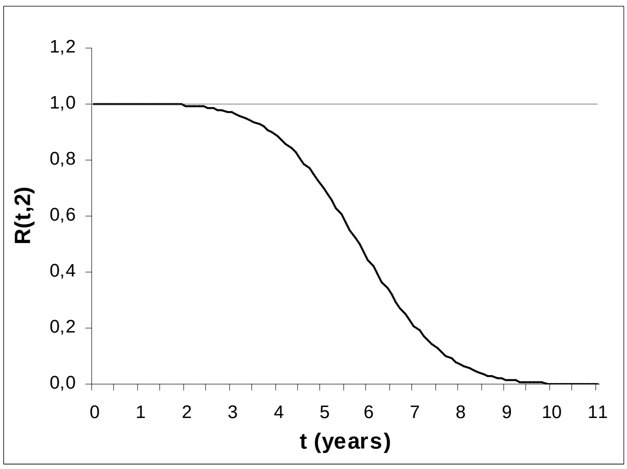

Figure 11. The graph of the unconditional reliability function of the ground ship-rope transporter with dependent failures of components

Now we can compare the expected values of the ground ship-rope transporter unconditional lifetimes in the reliability state subsets in the case when wires failure in dependent and independent way. We can notice that these values under the assumption that wires failure in dependent way in the reliability state subset {1,2,3} are shorten for about 6.4% and in the reliability state subsets {2,3}, {3} are shorten for about 8.6% than in the case when wires are independent. Comparing also the expected values of the time until the *Nth* system's renovation we also conclude that there are lower for about 8.6% in the case the wires failure in dependent way than independently.

The obtained results illustrate that the increased load of remaining un-failed components causes shortening the lifetime of these components. That fact can be interpreted as a decrease of their reliability faster than for the systems with independent components.

5. Conclusion

In the paper a practical application of the theoretical results of reliability, risk and availability evaluation of industrial systems in variable operation conditions is presented. The ground ship-rope transporter in Naval Shipyard in Gdynia is considered in varying in time operation conditions with its different reliability structure and its components' reliability functions in different operation states. The results presented in the paper can suggest that it seems reasonable to continue the investigations focusing on the methods of reliability, risk and availability analysis of complex multi-state systems and the methods of safety evaluation related to the multi-state systems in variable operation processes and their applications to the ground ship-rope transporters used in shipyards.

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References

[1] Blokus, A., Kołowrotki, K. & Soszyńska, J. (2005). Reliability of port transportation systems related to their operation processes. *Proc. 12-th International Congress of the International Maritime Association of the Mediterranean - IMAM 2005.* Maritime Transportation and Exploitation of Ocean and Coastal Resources, A. A. Balkema, Lisbon, 1487-1495.

[2] Blokus-Roszkowska, A. (2007). *Reliability analysis of homogenous large systems with component dependent failures* (*in Polish*). Ph.D. Thesis, Maritime University, Gdynia – System Research Institute, Warsaw.

[3] Blokus-Roszkowska, A. (2007). On component failures' dependency influence on system's lifetime. *International Journal of Reliability, Quality and Safety Engineering. Special Issue: System Reliability and Safety*. 14(6), 1-19.

[4] Blokus-Roszkowska, A., Guze, S., Kołowrocki, K., Kwiatuszewska-Sarnecka, B. & Soszyńska, J. (2008). *General methods for safety, reliability and availability evaluation of technical systems*. WP 3 – Task 3.1 – English – 31.05.2008. Poland-Singapore Joint Project.

[5] Blokus-Roszkowska, A., Guze, S., Kołowrocki, K., Kwiatuszewska-Sarnecka, B. & Soszyńska, J. (2008). *Models of safety, reliability and availability evaluation of complex technical systems related to their operation processes.* WP 4 – Task 4.1 – English – 31.05.2008. Poland-Singapore Joint Project.

[6] Blokus-Roszkowska, A., Kołowrocki, K. & Namysłowski, M. (2009). *Data mining for identification and prediction of safety and reliability characteristics of complex industrial systems and processes.* WP 6 – Task 6.2 – English – 31.01.2009. Sub-Task 6.2.4 – Appendix 4A. Preliminary statistical data collection of a shipyard ground ship-rope transporter operation process and its preliminary statistical identification. Poland-Singapore Joint Project.

[7] Blokus-Roszkowska, A. & Kołowrocki, K. (2009). Reliability and risk analysis of a ground ship-rope transporter in variable operation conditions. *Proc. International Conference ESREL'09* (*in prep.*).

[8] Grabski, F. (2002). *Semi-Markov Models of Systems Reliability and Operations*. Systems Research Institute, Polish Academy of Sciences, Warsaw.

[9] Kołowrocki, K. (2004). *Reliability of Large Systems*. Elsevier, Amsterdam - Boston - Heidelberg - London - New York - Oxford - Paris - San Diego - San Francisco - Singapore - Sydney - Tokyo.

[10] Kołowrocki, K. & Soszyńska, J. (2006). Reliability and availability of complex systems. *Quality and Reliability Engineering International*. Vol. 22, Issue 1, J. Wiley & Sons Ltd., 79-99.

[11] Kołowrocki, K. & Soszyńska, J. (2008). *A general model of technical systems operation processes related to their environment and infrastructure.* WP 2 – Task 2.1 – English – 31.05.2008. Poland-Singapore Joint Project. MSHE Decision No. 63/N-Singapore/2007/0.

[12] Smith, R. L. (1982). The asymptotic distribution of the strength of a series-parallel system with equal load-sharing. *Annals of Probability*. 10, 137-171.

[13] Soszyńska, J. (2006). Reliability evaluation of a port oil transportation system in variable operation conditions. *International Journal of Pressure Vessels and Piping*. 83(4), 304-310.