Blokus-Roszkowska Agnieszka

Kołowrocki Krzysztof
Maritime University, Gdynia, Poland

Reliability and availability of a shipyard ship-rope elevator in variable operation conditions

Keywords

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

Abstract

In the paper the environment and infrastructure influence of the ship-rope elevator 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 elevator operation process is described and its statistical identification is given. Next, the elevator is considered in varying in time operation conditions with different its components' reliability functions in different operation states. Finally, the reliability, risk and availability evaluation of the elevator in variable operation conditions is presented.

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

Ship-rope elevators are used to dock and undock ships coming to shipyards for repairs. The elevator utilized in the Naval Shipyard in Gdynia, with the scheme presented in *Figure 4,* is composed of a steel platform-carriage placed in its syncline (hutch). The platform is moved vertically with 10 rope-hoisting winches fed by separate electric motors. Motors are equipped in ropes "Bridon" with the diameter 47 mm each rope having a maximum load of 300 tonnes. During ship docking the platform, with the ship settled in special supporting carriages on the platform, is raised to the wharf level (upper position). During undocking, the operation is reversed. While the ship is moving into or out of the syncline and while stopped in the upper position the platform is held on hooks and the loads in the ropes are relieved. Since the platform-carriage and electric motors are highly reliable in comparison to the ropes, which work in extremely aggressive conditions, in our further analysis we will discuss the reliability of the rope system only.

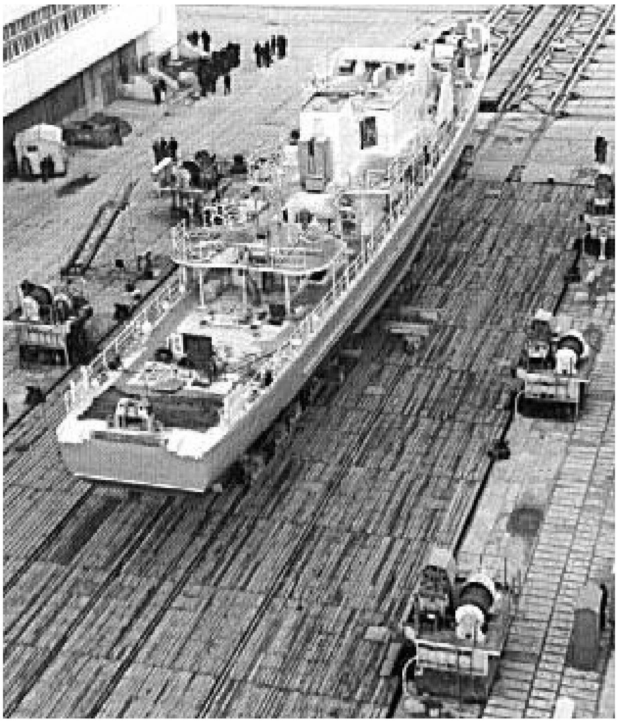

Figure 1. The ship-rope transportation system (upper position)

The system under consideration is composed of 10 ropes linked in series. Each of the ropes is composed of 22 strands: 10 outer and 12 inner.

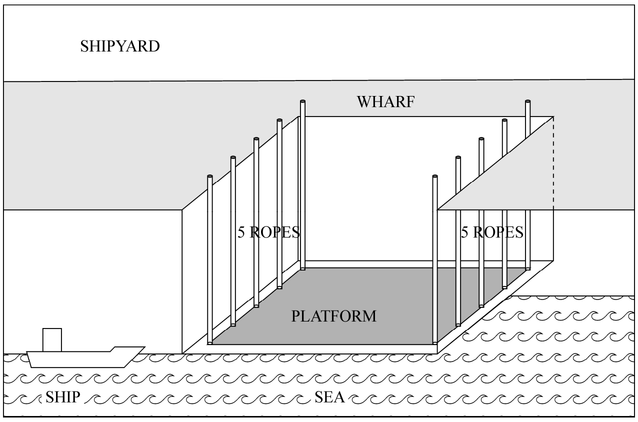

Figure 2. The scheme of the ship-rope elevator

The assumption that ropes satisfy the technical conditions when at least one of its strands satisfies these conditions is not always true. In reality it is said that a rope is failed after some number of strands use. Therefore better, closer in reality approach to the system reliability evaluation is assumption that the ship-rope transportation system is "m out of l_n"-series system. Further we assume that m = 5.

2. Operation process and its statistical identification

Considering the tonnage of the docked and undocked ships by the rope elevator in Naval Shipyard in Gdynia we can divide the system's load, similarly as in the previous ships' transportation system, into six groups and due to fact that the rope elevator system depends mainly on the tonnage of docking ships we can distinguish the following (v = 6) operation states of the rope elevator system operation process:

- an operation state z_1 – without loading (the system is not working),
- an operation state z_2 – loading over 0 up to 500 tonnes,
- an operation state z_3 – loading over 500 up to 1000 tonnes,
- an operation state z_4 – loading over 1000 up to 1500 tonnes,
- an operation state z_5 – loading over 1500 up to 2000 tonnes,
- an operation state z_6 – loading over 2000 up to 2500 tonnes.

In all six operational states system has the same structure. There are 10 rope-hoisting winches equipped in identical ropes and each of the ropes is composed of 22 strands. We assume that the rope is "5 out of 22" system, so we consider the ship-rope elevator as a regular "5 out of 22"-series system.

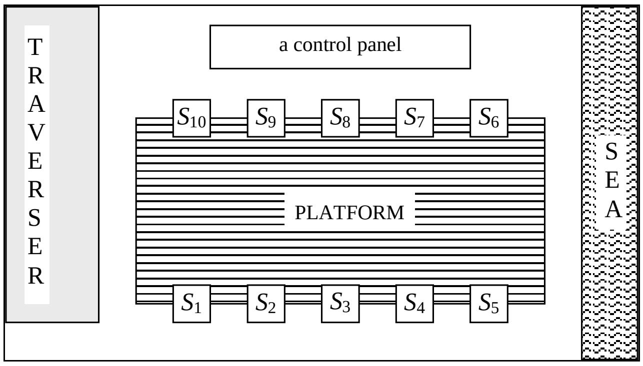

Figure 3. The scheme of the rope-hoisting winches placing

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

$$[p_{bl}] =$$

$$\begin{bmatrix} 0 & 0.2931 & 0.2931 & 0.2414 & 0.1207 & 0.0517 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}.$$

On the basis of the realizations of the operation process $Z(t)$ conditional sojourn times θ_{bl}, $b, l = 1,2,...,6,\ b \neq l,$ in the state z_b while the next transition is to the state z_l, given in [6], there were formulated hypotheses about the distributions of the conditional sojourn times θ_{bl}. These hypotheses allows us to estimate the conditional mean values $M_{bl} = E[\theta_{bl}],\ b, l = 1,2,...,6,\ b \neq l,$ of the lifetimes in the particular operation states:

$$M_{12} = 3057.06,\ M_{13} = 3319.12,\ M_{14} = 10406.07,$$

$$M_{15} = 4687.86,\ M_{16} = 5540.00,$$

$$M_{21} = 58.00,\ M_{31} = 37.18,\ M_{41} = 183.21,$$

$M_{51} = 124.50,\ M_{61} = 270.00.$

Hence, by [10], the unconditional mean sojourn times in the particular operation states are determined from the formula

$$M_b = E[\theta_b] = \sum_{l=1}^{6} p_{bl} M_{bl},\ b = 1,...,6,$$

and takes values:

$$M_1 \cong 5233.13,\ M_2 \cong 58.00,\ M_3 \cong 37.18,$$

$$M_4 \cong 183.21,\ M_5 \cong 124.50,\ M_6 \cong 270.00.$$

Since from the system of equations below [10], [11]

$$\begin{cases} [\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6] = [\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6][p_{bl}] \\ \pi_1 + \pi_2 + \pi_3 + \pi_4 + \pi_5 + \pi_6 = 1, \end{cases}$$

we get

$$\pi_1 = 0.5,\ \pi_2 = 0.14655,\ \pi_3 = 0.14655,$$

$$\pi_4 = 0.1207,\ \pi_5 = 0.06035,\ \pi_6 = 0.02585.$$

Then the limit values of the transient probabilities $p_b(t)$ at the operational states z_b, according to results given in [5],[7], are equal to:

$$p_1 = 0.9810,\ p_2 = 0.0032,\ p_3 = 0.0021,$$

$$p_4 = 0.0083,\ p_5 = 0.0028,\ p_6 = 0.0026. \qquad (1)$$

3. Reliability of the shipyard ship-rope elevator

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

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

We consider the strands as basic components of the system. The system of ropes is in the reliability state subset $\{1,2,3\}, \{2,3\}, \{3\}$, when all of its ropes are in this state subset and each of the ropes is in the reliability state subset $\{1,2,3\}, \{2,3\}, \{3\}$, if at least 5 of 22 strands are in this state subset. Thus, we conclude that the ship-rope elevator is a regular 4-states "5 out of 22"-series system composed of k_n = 10 series-linked subsystems (ropes) with l_n = 22 parallel-linked components (strands).

Then, taking into account above remarks, we obtain the reliability function of the considered ship-rope elevator given by the vector

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

$$= [1, \overline{\boldsymbol{R}}^{(5)}_{10,22}(t,1), \overline{\boldsymbol{R}}^{(5)}_{10,22}(t,2), \overline{\boldsymbol{R}}^{(5)}_{10,22}(t,3)],\ t \in <0,\infty). \qquad (2)$$

We assume strands as a basic components of a system with the reliability functions given by the vector

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

with the co-ordinates

$$R(t,u) = P(S(t) \geq u \mid S(0) = 3) = P(T(u) > t)$$

for $t \in <0,\infty)$, $u = 0,1,2,3,$ and $R(t,0) = 1$. $T(u)$ is independent random variable representing the lifetime of system components in the reliability state subset $\{u,u+1,...,3\}$, while they were at the reliability state 3 at the moment $t = 0$ and $S(t)$ are components' reliability states at the moment t, $t \in <0,\infty)$.

Moreover we assume that the components of the ship-rope elevator i.e. strands have 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, $b = 1,2,...,6.$

At the system operational state z_1 the strands in the ropes have following conditional reliability functions co-ordinates:

$$R^{(1)}(t,1) = \exp[-0.1613t],$$

$$R^{(1)}(t,2) = \exp[-0.2041t],$$

$R^{(1)}(t,3) = \exp[-0.2326t]$ for $t \geq 0$.

Thus the conditional multi-state reliability function of the ship-rope elevator 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

$$[\overline{\boldsymbol{R}}(t,1)]^{(1)} = [\overline{\boldsymbol{R}}^{(5)}_{10,22}(t,1)]^{(1)}$$

$$= [1 - \sum_{i=1}^{4} \binom{22}{i} \exp[-0.1613it]$$

$$[1 - \exp[-0.1613t]]^{22-i}]^{10}, \quad (3)$$

$$[\overline{\boldsymbol{R}}(t,2)]^{(1)} = [\overline{\boldsymbol{R}}^{(5)}_{10,22}(t,2)]^{(1)}$$

$$= [1 - \sum_{i=1}^{4} \binom{22}{i} \exp[-0.2041it]$$

$$[1 - \exp[-0.2041t]]^{22-i}]^{10}, \quad (4)$$

$$[\overline{\boldsymbol{R}}(t,3)]^{(1)} = [\overline{\boldsymbol{R}}^{(5)}_{10,22}(t,3)]^{(1)}$$

$$= [1 - \sum_{i=1}^{4} \binom{22}{i} \exp[-0.2326it]$$

$$[1 - \exp[-0.2326t]]^{22-i}]^{10} \text{ for } t \geq 0. \quad (5)$$

The expected values and standard deviations of the ship-rope elevator conditional lifetimes in the reliability state subsets calculated from the above result given by (3)-(5), according to [4], [8], at the operation state z_1, in years, are respectively given by:

$$\mu_1(1) \cong 6.4415, \mu_1(2) \cong 5.0907, \mu_1(3) \cong 4.4669, \quad (6)$$

$$\sigma_1(1) \cong 1.0563, \sigma_1(2) \cong 0.8345, \sigma_1(3) \cong 0.7323, \quad (7)$$

and further, using (6), from [8] it follows that the conditional lifetimes in the particular reliability states at the operation state z_1, in years, are:

$$\bar{\mu}_1(1) \cong 1.3508, \ \bar{\mu}_1(2) \cong 0.6239, \ \bar{\mu}_1(3) \cong 4.4669.$$

At the system operational state z_2 the strands in the ropes have following conditional reliability functions co-ordinates:

$R^{(2)}(t,1) = \exp[-0.2041t]$,

$R^{(2)}(t,2) = \exp[-0.2564t]$,

$R^{(2)}(t,3) = \exp[-0.2941t]$ for $t \geq 0$.

Thus the conditional multi-state reliability function of the ship-rope elevator 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

$$[\overline{\boldsymbol{R}}(t,1)]^{(2)} = [\overline{\boldsymbol{R}}^{(5)}_{10,22}(t,1)]^{(2)}$$

$$= [1 - \sum_{i=1}^{4} \binom{22}{i} \exp[-0.2041it]$$

$$[1 - \exp[-0.2041t]]^{22-i}]^{10}, \quad (8)$$

$$[\overline{\boldsymbol{R}}(t,2)]^{(2)} = [\overline{\boldsymbol{R}}^{(5)}_{10,22}(t,2)]^{(2)}$$

$$= [1 - \sum_{i=1}^{4} \binom{22}{i} \exp[-0.2564it]$$

$$[1 - \exp[-0.2564t]]^{22-i}]^{10}, \quad (9)$$

$$[\overline{\boldsymbol{R}}(t,3)]^{(2)} = [\overline{\boldsymbol{R}}^{(5)}_{10,22}(t,3)]^{(2)}$$

$$= [1 - \sum_{i=1}^{4} \binom{22}{i} \exp[-0.2941it]$$

$$[1 - \exp[-0.2941t]]^{22-i}]^{10} \text{ for } t \geq 0. \quad (10)$$

The expected values and standard deviations of the ship-rope elevator conditional lifetimes in the reliability state subsets calculated from the above result given by (8)-(10), according to [8] at the operation state z_2 are respectively given by:

$$\mu_2(1) \cong 5.0907, \mu_2(2) \cong 4.0523,$$
$$\mu_2(3) \cong 3.5335, \quad (11)$$

$$\sigma_2(1) \cong 0.8345, \sigma_2(2) \cong 0.6639,$$

$$\sigma_2(3) \cong 0.5744, \quad (12)$$

and further, using (11), from [8] it follows that the conditional lifetimes in the particular reliability states at the operation state z_2 are:

$$\bar{\mu}_2(1) \cong 1.0384, \bar{\mu}_2(2) \cong 0.5188, \bar{\mu}_2(3) \cong 3.5335.$$

At the system operational state z_3 the strands in the ropes have following conditional reliability functions co-ordinates:

$$R^{(3)}(t,1) = \exp[-0.2222t],$$

$$R^{(3)}(t,2) = \exp[-0.2857t],$$

$$R^{(3)}(t,3) = \exp[-0.3226t] \text{ for } t \geq 0.$$

Thus the conditional multi-state reliability function of the ship-rope elevator at the operational state z_3 is given by:

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

where

$$[\bar{\boldsymbol{R}}(t,1)]^{(3)} = [\bar{\boldsymbol{R}}^{(5)}_{10,22}(t,1)]^{(3)}$$

$$= [1 - \sum_{i=1}^{4} \binom{22}{i} \exp[-0.2222it]$$

$$[1 - \exp[-0.2222t]]^{22-i}]^{10}, \quad (13)$$

$$[\bar{\boldsymbol{R}}(t,2)]^{(3)} = [\bar{\boldsymbol{R}}^{(5)}_{10,22}(t,2)]^{(3)}$$

$$= [1 - \sum_{i=1}^{4} \binom{22}{i} \exp[-0.2857it]$$

$$[1 - \exp[0.2857t]]^{22-i}]^{10}, \quad (14)$$

$$[\bar{\boldsymbol{R}}(t,3)]^{(3)} = [\bar{\boldsymbol{R}}^{(5)}_{10,22}(t,3)]^{(3)}$$

$$= [1 - \sum_{i=1}^{4} \binom{22}{i} \exp[-0.3226it]$$

$$[1 - \exp[-0.3226t]]^{22-i}]^{10} \text{ for } t \geq 0. \quad (15)$$

The expected values and standard deviations of the ship-rope elevator conditional lifetimes in the reliability state subsets calculated from the above result given by (13)-(15), according to results given in [8], at the operation state z_3, in years are equal to:

$$\mu_3(1) \cong 4.6760, \mu_3(2) \cong 3.6367,$$
$$\mu_3(3) \cong 3.2207, \quad (16)$$

$$\sigma_3(1) \cong 0.7665, \sigma_3(2) \cong 0.5956,$$
$$\sigma_3(3) \cong 0.5273, \quad (17)$$

and further, from (16) and [8] it follows that the conditional lifetimes in the particular reliability states at the operation state z_3 are:

$$\bar{\mu}_3(1) \cong 1.0393, \bar{\mu}_3(2) \cong 0.4160, \bar{\mu}_3(3) \cong 3.2207.$$

At the system operational state z_4 the strands in the ropes have following conditional reliability functions co-ordinates:

$$R^{(4)}(t,1) = \exp[-0.2702t],$$

$$R^{(4)}(t,2) = \exp[-0.3508t],$$

$$R^{(4)}(t,3) = \exp[-0.4167t] \text{ for } t \geq 0.$$

Thus the conditional multi-state reliability function of the ship-rope elevator at the operational state z_4 is given by:

$$[\bar{\boldsymbol{R}}(t,\cdot)]^{(4)} = [1, [\bar{\boldsymbol{R}}(t,1)]^{(4)}, [\bar{\boldsymbol{R}}(t,2)]^{(4)}, [\bar{\boldsymbol{R}}(t,3)]^{(4)}],$$

where

$$[\bar{\boldsymbol{R}}(t,1)]^{(4)} = [\bar{\boldsymbol{R}}^{(5)}_{10,22}(t,1)]^{(4)}$$

$$= [1 - \sum_{i=1}^{4} \binom{22}{i} \exp[-0.2702it]$$

$$[1 - \exp[-0.2702t]]^{22-i}]^{10}, \quad (18)$$

$$[\bar{\boldsymbol{R}}(t,2)]^{(4)} = [\bar{\boldsymbol{R}}^{(5)}_{10,22}(t,2)]^{(4)}$$

$$= [1 - \sum_{i=1}^{4} \binom{22}{i} \exp[-0.3508it]$$

$$[1 - \exp[-0.3508t]]^{22-i}]^{10}, \quad (19)$$

$$[\bar{\boldsymbol{R}}(t,3)]^{(4)} = [\bar{\boldsymbol{R}}^{(5)}_{10,22}(t,3)]^{(4)}$$

$$= [1 - \sum_{i=1}^{4} \binom{22}{i} \exp[-0.4167it]$$

$$[1 - \exp[-0.4167t]]^{22-i}]^{10} \text{ for } t \geq 0. \quad (20)$$

The expected values and standard deviations of the ship-rope elevator conditional lifetimes in the reliability state subsets calculated from the above result given by (18)-(20), according to results in [8], at the operation state z_4 are respectively given by:

$$\mu_4(1) \cong 3.8453, \mu_4(2) \cong 2.9618,$$
$$\mu_4(3) \cong 2.4934, \quad (21)$$

$$\sigma_4(1) \cong 0.6301, \sigma_4(2) \cong 0.4846,$$
$$\sigma_4(3) \cong 0.4074, \quad (22)$$

and further, using (21), from [8] it follows that the conditional lifetimes in the particular reliability states at the operation state z_4 are:

$$\bar{\mu}_4(1) \cong 0.8835, \bar{\mu}_4(2) \cong 0.4684, \bar{\mu}_4(3) \cong 2.4934.$$

At the system operational state z_5 the strands in the ropes have following conditional reliability functions co-ordinates:

$$R^{(5)}(t,1) = \exp[-0.3333t],$$

$$R^{(5)}(t,2) = \exp[-0.4762t],$$

$$R^{(5)}(t,3) = \exp[-0.5882t] \text{ for } t \geq 0.$$

Thus the conditional multi-state reliability function of the ship-rope elevator at the operational state z_5 is given by:

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

where

$$[\boldsymbol{\bar{R}}(t,1)]^{(5)} = [\boldsymbol{\bar{R}}_{10,22}^{(5)}(t,1)]^{(5)}$$

$$= [1 - \sum_{i=1}^{4} \binom{22}{i} \exp[-0.3333it]$$

$$[1 - \exp[-0.3333t]]^{22-i}]^{10}, \quad (23)$$

$$[\boldsymbol{\bar{R}}(t,2)]^{(5)} = [\boldsymbol{\bar{R}}_{10,22}^{(5)}(t,2)]^{(5)}$$

$$= [1 - \sum_{i=1}^{4} \binom{22}{i} \exp[-0.4762it]$$

$$[1 - \exp[-0.4762t]]^{22-i}]^{10}, \quad (24)$$

$$[\boldsymbol{\bar{R}}(t,3)]^{(5)} = [\boldsymbol{\bar{R}}_{10,22}^{(5)}(t,3)]^{(5)}$$

$$= [1 - \sum_{i=1}^{4} \binom{22}{i} \exp[-0.5882it]$$

$$[1 - \exp[-0.5882t]]^{22-i}]^{10} \text{ for } t \geq 0. \quad (25)$$

The expected values and standard deviations of the ship-rope elevator conditional lifetimes in the reliability state subsets from the above result given by (31)-(33), and from [8] at the operation state z_5 are respectively given in years by:

$$\mu_5(1) \cong 3.1173, \mu_5(2) \cong 2.1819,$$
$$\mu_5(3) \cong 1.7664, \quad (26)$$

$$\sigma_5(1) \cong 0.5103, \sigma_5(2) \cong 0.3574,$$
$$\sigma_5(3) \cong 0.2894, \quad (27)$$

and further, using (26), from [8] it follows that the conditional lifetimes in the particular reliability states at the operation state z_5 are:

$$\bar{\mu}_5(1) \cong 0.9354, \bar{\mu}_5(2) \cong 0.4155, \bar{\mu}_5(3) \cong 1.7664.$$

At the system operational state z_6 the strands in the ropes have following conditional reliability functions co-ordinates:

$$R^{(6)}(t,1) = \exp[-0.4348t],$$

$$R^{(6)}(t,2) = \exp[-0.7143t],$$

$$R^{(6)}(t,3) = \exp[-0.9091t] \text{ for } t \geq 0.$$

Thus the conditional multi-state reliability function of the ship-rope elevator at the operational state z_6 is given by:

$$[\boldsymbol{\bar{R}}(t,\cdot)]^{(6)} = [1, [\boldsymbol{\bar{R}}(t,1)]^{(6)}, [\boldsymbol{\bar{R}}(t,2)]^{(6)}, [\boldsymbol{\bar{R}}(t,3)]^{(6)}],$$

where

$$[\boldsymbol{\bar{R}}(t,1)]^{(6)} = [\boldsymbol{\bar{R}}_{10,22}^{(5)}(t,1)]^{(6)}$$

$$= [1 - \sum_{i=1}^{4} \binom{22}{i} \exp[-0.4348it]$$

$$[1 - \exp[-0.4348t]]^{22-i}]^{10}, \quad (28)$$

$$[\overline{\boldsymbol{R}}(t,2)]^{(6)} = [\overline{\boldsymbol{R}}^{(5)}_{10,22}(t,2)]^{(6)}$$

$$= [1 - \sum_{i=1}^{4} \binom{22}{i} \exp[-0.7143it]$$

$$[1 - \exp[-0.7143t]]^{22-i}]^{10}, \quad (29)$$

$$[\overline{\boldsymbol{R}}(t,3)]^{(6)} = [\overline{\boldsymbol{R}}^{(5)}_{10,22}(t,3)]^{(6)}$$

$$= [1 - \sum_{i=1}^{4} \binom{22}{i} \exp[-0.9091it]$$

$$[1 - \exp[-0.9091t]]^{22-i}]^{10} \text{ for } t \geq 0 \quad (30)$$

The expected values and standard deviations of the ship-rope elevator conditional lifetimes in the reliability state subsets calculated from the above result given by (28)-(30), and from [8] at the operation state z_6 are respectively given in years by:

$$\mu_6(1) \cong 2.3896, \mu_6(2) \cong 1.4546,$$
$$\mu_6(3) \cong 1.1429, \quad (31)$$

$$\sigma_6(1) \cong 0.3918, \sigma_6(2) \cong 0.2378,$$
$$\sigma_6(3) \cong 0.1865, \quad (32)$$

and further, from (31) and [8] it follows that the conditional lifetimes in the particular reliability states at the operation state z_6 in years are equal to:

$$\bar{\mu}_6(1) \cong 0.9350, \bar{\mu}_6(2) \cong 0.3117, \bar{\mu}_6(3) \cong 1.1429.$$

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

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

where according to [5], [11], the vector co-ordinates are given respectively by:

$$\overline{\boldsymbol{R}}(t,u) = \sum_{i=1}^{6} p_i [\overline{\boldsymbol{R}}(t,u)]^{(i)} \text{ for } t \geq 0, \ u = 1,2,3, \quad (33)$$

where $[\overline{\boldsymbol{R}}(t,u)]^{(i)}$, $i = 1,\dots,6$, are given by (3)-(5), (8)-(10), (13)-(15), (18)-(20), (23)-(25), (28)-(30).
The mean values and the standard deviations of the ground ship-rope transporter unconditional lifetimes in the reliability state subsets, according to [10], [11] and after considering (6)-(7), (11)-(12), (16)-(17), (21)-(22), (26)-(27), (31)-(32) and (1), respectively are:

$$\mu(1) = \sum_{i=1}^{6} p_i \mu_i(1) \cong 6.3887, \quad (34)$$

$$\sigma(1) \cong 1.1336,$$

$$\mu(2) = \sum_{i=1}^{6} p_i \mu_i(2) \cong 5.0463, \quad (35)$$

$$\sigma(2) \cong 0.9041,$$

$$\mu(3) = \sum_{i=1}^{6} p_i \mu_i(3) \cong 4.4266, \quad (36)$$

$$\sigma(3) \cong 0.7964.$$

Next, the unconditional mean values of the ground ship-rope transporter lifetimes in the particular reliability states, by [8] and considering (34)-(36), in years are:

$$\bar{\mu}(1) = \mu(1) - \mu(2) = 1.3424,$$

$$\bar{\mu}(2) = \mu(2) - \mu(3) = 0.6197,$$

$$\bar{\mu}(3) = \mu(3) = 4.4266.$$

If the critical reliability state is r = 2, then according to [4], the system risk function takes the form

$$\boldsymbol{r}(t) = 1 - \overline{\boldsymbol{R}}(t,2) = 1 - \sum_{i=1}^{6} p_i [\overline{\boldsymbol{R}}(t,2)]^{(i)}, \ t \geq 0,$$

where $\overline{\boldsymbol{R}}(t,2)$ is the unconditional reliability function of the ground ship-rope transporter at the critical state and $[\overline{\boldsymbol{R}}(t,2)]^{(i)}$, $i = 1,\dots,6$, are given by (4), (9), (14), (19), (24), (29).
Hence, the moment when the system risk function exceeds a permitted level, for instance δ = 0.05, from [4], is

$$\tau = \boldsymbol{r}^{-1}(\delta) \cong 3.577 \text{ years } \cong 3 \text{ years 205 days.}$$

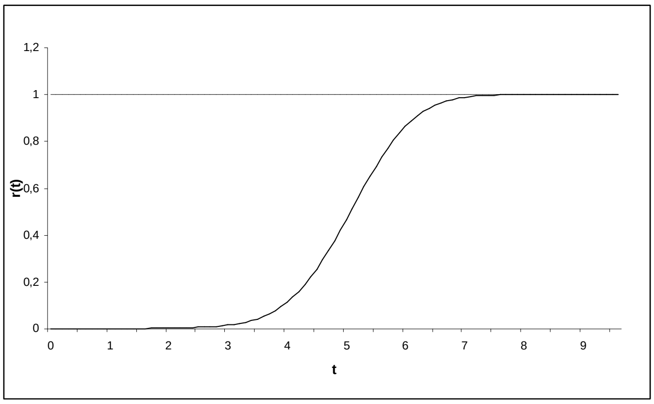

Figure 4. The graph of the ship-rope elevator risk function $r(t)$

4. Availability of the shipyard ship-rope elevator

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 shipyard ship-rope elevator. The theoretical results of multi-state systems availability analysis can be found in [1], [4]. Assuming that the ship-rope elevator 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 from [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 $N(5.0477N, 0.9041\sqrt{N})$, i.e.,

$$\overline{\overline{F}}^{(N)}(t,2) = P(\overline{\overline{S}}_N(2) < t) \cong F_{N(0,1)}(\frac{t - 5.0477N}{0.9041\sqrt{N}}),$$
$$t \in (-\infty, \infty),\ N = 1,2,...,$$

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

$$E[\overline{\overline{S}}_N(2)] \cong 5.0477N,\ D[\overline{\overline{S}}_N(2)] \cong 0.8174N,$$

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

$$\overline{F}^{(N)}(t,2) =$$
$$P(\overline{S}_N(2) < t) = F_{N(0,1)}(\frac{t - 5.0477N + 0.0014}{0.9041\sqrt{N}}),$$
$$t \in (-\infty, \infty),\ N = 1,2,...,$$

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

$$E[\overline{S}_N(2)] \cong 5.0463N + 0.0014(N-1),$$

$$D[\overline{S}_N(2)] \cong 0.8174N,$$

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

$$P(\overline{\overline{N}}(t,2) = N) \cong F_{N(0,1)}(\frac{5.0477N - t}{0.4024\sqrt{t}})$$

$$- F_{N(0,1)}(\frac{5.0477(N+1) - t}{0.4024\sqrt{t}}),\ N = 1,2,...,$$

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

$$\overline{\overline{H}}(t,2) \cong 0.1981t,\ \overline{\overline{D}}(t,2) \cong 0.0064t,$$

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

$$P(\overline{N}(t,2) = N) \cong F_{N(0,1)}(\frac{5.0477N - t - 0.0014}{0.4024\sqrt{t + 0.0014}})$$

$$- F_{N(0,1)}(\frac{5.0477(N+1) - t - 00014}{0.4024\sqrt{t + 0.0014}}),\ N = 1,2,...,$$

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 $t, t \ge 0,$ are respectively given by

$$\overline{H}(t,2) \cong 0.1981t + 0.0003,$$

$$\overline{D}(t,1) \cong 0.0064(t + 0.0014),$$

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

$$K(t,2) \cong 0.9997, \; t \geq 0,$$

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

$$K(t,\tau,2) \cong 0.1981 \int_{\tau}^{\infty} \overline{\boldsymbol{R}}(t,2)dt, \; t \geq 0, \; \tau > 0,$$

where the reliability function of a system at the critical state $\overline{\boldsymbol{R}}(t,2)$ is given by the formula (33).

5. Conclusion

In the paper an analytical model of port transportation systems environment and infrastructure influence on their operation process is presented. The theoretical results of reliability, risk and availability evaluation of industrial systems in variable operation conditions are applied to the shipyard ship-rope elevator in Naval Shipyard in Gdynia. These results may be considered as an illustration of the proposed methods possibilities of application in rope transportation systems reliability analysis. Other technical systems reliability evaluation related to their operation process are presented for example in [3], [11]. The obtained evaluations may be discussed as an example in transportation systems reliability characteristics evaluation, especially during the design and while planning and improving its operation process safety and effectiveness.

Acknowledgements

The paper describes the work in the Poland-Singapore Joint Research Project titled "Safety and Reliability of Complex Industrial Systems and Processes" supported by grants from the Poland's Ministry of Science and Higher Education (MSHE grant No. 63/N-Singapore/2007/0) and the Agency for Science, Technology and Research of Singapore (A*STAR SERC grant No. 072 1340050).

References

[1] Blokus, A. (2006). Reliability and availability evaluation of large renewal systems. *International Journal of Materials & Structural Reliability,* Vol. 4, No. 1, 39-52.

[2] Blokus, A., Kołowrocki, K. & Kwiatuszewska-Sarnecka, B. (2005). Reliability and availability of large "m out of n"-series systems. *Proc. Qualita 2005 Conference,* Bordeaux, 445-453.

[3] Blokus, A., Kołowrocki, 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.

[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 6.2.3 – Appendix 3A. Preliminary statistical data collection of a shipyard ship-rope elevator operation process and its preliminary statistical identification. *Poland-Singapore Joint Project*.

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

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

[9] 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.

[10] 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.

[11] 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.