RELIABILITY AND AVAILABILITY OF A GROUND SHIP-ROPE TRANSPORTER IN VARIABLE OPERATION CONDITIONS

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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](image)

**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,
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 $z_2$ – the ship with a tonnage over 1300 tonnes is transferred from the platform to the traverser, 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 $z_3$ – the ship with a tonnage up to 1300 tonnes is transferred from the platform to the traverser, from the traverser to the repair posts R6-R9, from the repair posts R1-R5 to the traverser and from the traverser to the broaching machine number 3 is difficult (the broaching machine no. 2 is used), 

- an operation state $z_4$ – the ship with a tonnage over 1300 up to 1800 tonnes is transferred from the platform 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 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 (Blokus-Roszkowska et al. 2009) 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.

$$
[p_{bl}] = \begin{bmatrix}
0 & 0.3529 & 0.3529 & 0.0441 & 0 & 0.1618 & 0.0883 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

On the basis of statistical data coming from experiment (Blokus-Roszkowska et al. 2009) 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 (Blokus-Roszkowska et al. 2008b, Kołowercki & Soszyńska 2008, Soszyńska 2006) the unconditional mean sojourn times in the particular operation states are determined from the formula

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

and takes values:

$M_1 \approx 3494.92$, $M_2 \approx 65.25$, $M_3 \approx 65.61$, $M_4 = 0$, $M_5 \approx 73.00$, $M_6 = 0$, $M_7 \approx 92.72$, $M_8 \approx 120.00$. 


The limit values of the transient probabilities \( p_b(t) \) at the operational states \( z_b \), according to results given in (Blokus-Roszkowska et al. 2008b, Grabski 2002, Kołowrocki & Soszyńska 2008) are equal to:

\[
p_1 = 0.9790, \quad p_2 = 0.0064, \quad p_3 = 0.0065, \quad p_4 = 0, \quad p_5 = 0.0009, \quad p_6 = 0, \quad p_7 = 0.0042, \quad p_8 = 0.0030. \tag{1}
\]

### 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

\[
R_i(t,.) = [R_i(t,0), R_i(t,1), R_i(t,2), R_i(t,3)], \ t \in (0,\infty),
\]

with the co-ordinates

\[
R_i(t,u) = P(S_i(t) \geq u \mid S_i(0) = 3) = P(T_i(u) > t), \ t \in (0,\infty), \ u = 0,1,2,3, \ i = 1,2,3, \ R_i(t,0) = 1.
\]

\( T_i(u), \ i = 1,2,3 \) are independent random variables representing the lifetimes of subsystems \( S_i \) in the reliability state subset \{0, 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 \( t, \ t \in (0,\infty) \).

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 (Blokus-Roszkowska et al. 2008a), the reliability of the ground ship-rope transporter is defined by the vector

\[
\overline{R}(t,.) = [1, \overline{R}(t,1), \overline{R}(t,2), \overline{R}(t,3)], \ t \in (0,\infty),
\]

where

\[
\overline{R}(t,u) = \prod_{i=1}^{3} R_i(t,u), \ t \in (0,\infty), \ u = 1,2,3. \tag{2}
\]

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

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 $\overline{R}^{(b)}_{36}(t,\cdot)$.  

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: 

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

where 

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

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: 

$$R^{(1)}(t,1) = \exp[-0.0097t], \quad R^{(1)}(t,2) = \exp[-0.0147t], \quad R^{(1)}(t,3) = \exp[-0.0278t], \quad t \geq 0.$$  

Thus, considering (3) and from (Blokus-Roszkowska et al. 2008b), the conditional multi-state reliability function of the ground ship-rope transporter at the operational state $z_1$ is given by:  

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

where 

$$[\overline{R}(t,1)]^{(1)} = \left[\overline{R}^{(b)}_{6,36}(t,1)\right]^{(1)} = \left[\sum_{i=0}^{36} \left\{1 - \exp[-(36-i)0.0097t]\right\}\right]^{18}, \quad (4)$$  

$$[\overline{R}(t,2)]^{(1)} = \left[\overline{R}^{(b)}_{6,36}(t,2)\right]^{(1)} = \left[\sum_{i=0}^{36} \left\{1 - \exp[-(36-i)0.0147t]\right\}\right]^{18}, \quad (5)$$  

$$[\overline{R}(t,3)]^{(1)} = \left[\overline{R}^{(b)}_{6,36}(t,3)\right]^{(1)} = \left[\sum_{i=0}^{36} \left\{1 - \exp[-(36-i)0.0278t]\right\}\right]^{18}. \quad (6)$$  

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 (Blokus-Roszkowska et al. 2008b, Kołowrocki 2004) at the operation state $z_1$ are respectively given in years by:  

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

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

and further, using (7), from (Kołowrocki 2004) it follows that the conditional lifetimes in the particular reliability states at the operation state $z_1$ in years are:  

$$\overline{t}_1(1) \equiv 3.0673, \quad \overline{t}_1(2) \equiv 3.0094, \quad \overline{t}_1(3) \equiv 3.3772.$$  

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.
A.Blokus-Ronakowska, K. Kołowrocki – RELIABILITY AND AVAILABILITY OF A GROUND SHIP-ROPE TRANSPORTER IN VARIABLE OPERATION CONDITIONS

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

$$R^{(2)}(t,1) = \exp[-0.0158t], \ R^{(2)}(t,2) = \exp[-0.0235t], \ R^{(2)}(t,3) = \exp[-0.0388t], \ t \geq 0.$$  

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:

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

where

$$[\overline{R}(t,1)]^{(2)} = [\overline{R}_{6,36}(t,1)]^{(2)} = \prod_{i=0}^{6} \left[1 - \exp[-0.0158t] \right]^i \exp[-(36 - i)0.0158t].$$  (9)

$$[\overline{R}(t,2)]^{(2)} = [\overline{R}_{6,36}(t,2)]^{(2)} = \prod_{i=0}^{6} \left[1 - \exp[-0.0235t] \right]^i \exp[-(36 - i)0.0235t].$$  (10)

$$[\overline{R}(t,3)]^{(2)} = [\overline{R}_{6,36}(t,3)]^{(2)} = \prod_{i=0}^{6} \left[1 - \exp[-0.0388t] \right]^i \exp[-(36 - i)0.0388t].$$  (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 (Kołowrocki 2004) at the operation state $z_2$ given in years are:

$$\mu_2(1) \equiv 7.7309, \ \mu_2(2) \equiv 5.2210, \ \mu_2(3) \equiv 3.1622,$$

$$\sigma_2(1) \equiv 2.1062, \ \sigma_2(2) \equiv 1.4722, \ \sigma_2(3) \equiv 0.8912,$$

and further, using (12), from (Kołowrocki 2004) it follows that the conditional lifetimes in the particular reliability states at the operation state $z_2$ in years are:

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

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:

\[
\vec{R}(t,\cdot) = [1, \vec{R}(t,1), \vec{R}(t,2), \vec{R}(t,3)], \quad t \in (-\infty, 0),
\]

where

\[
\vec{R}(t,u) = \left[ \vec{R}_{6,36}^{(6)}(t,u) \right]^2, \quad t \in (-\infty, 0), \quad u = 1,2,3.
\]  

(14)
The subsystems $S_1$ and $S_2$ are 4-state “30 out of 36”-series systems, in which components (wires in the ropes) have identical following conditional reliability functions co-ordinates:

$$R^{(5)}(t,1) = \exp[-0.0175t]$$,  
$$R^{(5)}(t,2) = \exp[-0.0361t]$$,  
$$R^{(5)}(t,3) = \exp[-0.0551t]$$,  
$t \geq 0$.

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

Thus, considering (14) and from (Bloks-Roszkowska et al. 2008b), the conditional multi-state reliability function of the ground ship-rope transporter at the operational state $z_5$ is given by:

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

where

$$[\overline{R}(t,1)]^{(S)} = \left[\left[\frac{\overline{R}}{R_{6,36}}(t,1)\right]^{(S)}\right]^2 = \left[\sum_{i=0}^{36} \left(1 - \exp[-0.0175t]\right)^i \exp[-(36-i)0.0175t]\right]^{12}$$,  
$$[\overline{R}(t,2)]^{(S)} = \left[\left[\frac{\overline{R}}{R_{6,36}}(t,2)\right]^{(S)}\right]^2 = \left[\sum_{i=0}^{36} \left(1 - \exp[-0.0361t]\right)^i \exp[-(36-i)0.361t]\right]^{12}$$,  
$$[\overline{R}(t,3)]^{(S)} = \left[\left[\frac{\overline{R}}{R_{6,36}}(t,3)\right]^{(S)}\right]^2 = \left[\sum_{i=0}^{36} \left(1 - \exp[-0.0551t]\right)^i \exp[-(36-i)0.551t]\right]^{12}$$,  
for $t \geq 0$.

The expected values and standard deviations, from results in (Kołowrocki 2004), of the ground ship-rope transporter conditional lifetimes in the reliability state subsets at the operation state $z_5$ counted in years are:

$$\mu_5(1) \equiv 5.8962, \mu_5(2) \equiv 2.8583, \mu_5(3) \equiv 1.8727$$,  
(18)  
$$\sigma_5(1) \equiv 1.5326, \sigma_5(2) \equiv 0.7421, \sigma_5(3) \equiv 0.4852$$,  
(19)

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

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

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:

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

where

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

(20)
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:

$$ R^{(8)}(t,1) = \exp[-0.0215t], \quad R^{(8)}(t,2) = \exp[-0.0394t], \quad R^{(8)}(t,3) = \exp[-0.0607t], \quad t \geq 0. $$

Thus, considering (20) and from (Blokus-Roszkowska et al. 2008b), the conditional multi-state reliability function of the ground ship-rope transporter at the operational state $z_8$ is given by:

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

where

$$ [\overline{R}(t,1)]^{(8)} = \left[ [\overline{R}_{6,36}(t,1)]^{(8)} \right]^3 = \left[ \sum_{i=0}^{6} \left[ \sum_{j=0}^{36} \right] \right] [1 - \exp[-0.0215t]]^3 \exp[-(36 - i)0.0215t], \quad (21) $$

$$ [\overline{R}(t,2)]^{(8)} = \left[ [\overline{R}_{6,36}(t,2)]^{(8)} \right]^3 = \left[ \sum_{i=0}^{6} \left[ \sum_{j=0}^{36} \right] \right] [1 - \exp[-0.0394t]]^3 \exp[-(36 - i)0.0394t], \quad (22) $$

$$ [\overline{R}(t,3)]^{(8)} = \left[ [\overline{R}_{6,36}(t,3)]^{(8)} \right]^3 = \left[ \sum_{i=0}^{6} \left[ \sum_{j=0}^{36} \right] \right] [1 - \exp[-0.0607t]]^3 \exp[-(36 - i)0.0607t], \quad (23) $$

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, according to results given in (Kołowrocki 2004) at the operation state $z_8$, in years, are respectively given by:

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

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

and further, using (24) and from (Kołowrocki 2004), the conditional lifetimes in the particular reliability states at the operation state $z_8$ in years are:

$$ \overline{\mu}_8(1) \equiv 1.9839, \quad \overline{\mu}_8(2) \equiv 0.8362, \quad \overline{\mu}_8(3) \equiv 1.5467. $$

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

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

where according to (Blokus-Roszkowska et al. 2008b, Soszyńska 2006), the vector co-ordinates are given respectively by:

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

where $[\overline{R}(t,u)]^{(i)}, \quad i = 1, \ldots, 8$, 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 (Blokus-Roszkowska et al. 2008b) and after considering (7)-(8), (12)-(13), (18)-(19), (24)-(25) and (1), respectively are:

$$
\mu(1) = \sum_{i=1}^{8} p_i \mu_i(1) \equiv 9.3996, \quad \sigma(1) \equiv 2.0901,
$$

(27)

$$
\mu(2) = \sum_{i=1}^{8} p_i \mu_i(2) \equiv 6.3424, \quad \sigma(2) \equiv 1.6234,
$$

(28)

$$
\mu(3) = \sum_{i=1}^{8} p_i \mu_i(3) \equiv 3.3613, \quad \sigma(3) \equiv 0.8532.
$$

(29)

Next, the unconditional mean values of the ground ship-rope transporter lifetimes in the particular reliability states, by (Kołowrocki 2004) and considering (27)-(29), in years are:

$$
\mathbb{E}(1) = \mu(1) - \mu(2) = 3.0572, \quad \mathbb{E}(2) = \mu(2) - \mu(3) = 2.9811, \quad \mathbb{E}(3) = \mu(3) = 3.3613.
$$

If the critical reliability state is $r = 2$, then according to (Blokus-Roszkowska et al. 2008b, Kołowrocki 2004), the system risk function takes the form

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

where $\overline{R}(t,2)$ 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 (Blokus-Roszkowska et al. 2008a, Kołowrocki 2004), is

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

![Figure 10](image.png)

**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 $\mu_0(2) = 0.0014 \equiv 12$ hours and the standard deviation $\sigma_0(2) = 0.0002 \equiv 2$ hours, applying theoretical results presented in (Blokus-Roszkowska et al. 2008a), we obtain the following results:
Indeed, the distribution function of the time \( \bar{S}_N(2) \) until the \( N \)th system’s renovation, for sufficiently large \( N \), has approximately normal distribution \( N(6.3438N, 1.6234\sqrt{N}) \), i.e.,
\[
\bar{F}^{(N)}(t,2) = P(S_N(2) < t) \equiv F_{N,(0,1)}\left(\frac{t - 6.3438N}{1.6234\sqrt{N}}\right), \quad t \in (-\infty, \infty), \quad N = 1, 2, \ldots ,
\]
the expected value and the variance of the time \( \bar{S}_N(2) \) until the \( N \)th system’s renovation take respectively forms
\[
E[\bar{S}_N(2)] \equiv 6.3438N, \quad D[\bar{S}_N(2)] \equiv 2.6354N,
\]
the distribution function of the time \( \bar{S}_N(2) \) until the \( N \)th exceeding the reliability critical state 2 of this system takes form
\[
\bar{F}^{(N)}(t,2) = P(S_N(2) < t) = F_{N,(0,1)}\left(\frac{t - 6.438\left(1 + \frac{0.0103}{0.6445}\right) + 0.0014}{0.6445\sqrt{t}}\right), \quad t \in (-\infty, \infty), \quad N = 1, 2, \ldots ,
\]
the expected value and the variance of the time \( \bar{S}_N(2) \) until the \( N \)th exceeding the reliability critical state 2 of this system take respectively forms
\[
E[\bar{S}_N(2)] \equiv 6.3424N + 0.0014(N - 1), \quad D[\bar{S}_N(2)] \equiv 2.6354N,
\]
the distribution of the number \( \bar{N}(t,2) \) of system’s renovations up to the moment \( t, t \geq 0 \), is of the form
\[
P(N(t,2) = N) \equiv F_{N,(0,1)}\left(\frac{6.438N - t - 0.0014}{0.6445\sqrt{t}}\right) - F_{N,(0,1)}\left(\frac{6.438(N + 1) - t}{0.6445\sqrt{t}}\right), \quad N = 1, 2, \ldots ,
\]
the expected value and the variance of the number \( \bar{N}(t,2) \) of system’s renovations up to the moment \( t, t \geq 0 \), take respectively forms
\[
\bar{H}(t,2) \equiv 0.1576t, \quad \bar{D}(t,2) \equiv 0.0103t,
\]
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
\[
P(N(t,2) = 0) \equiv F_{N,(0,1)}\left(\frac{6.438N + 0.0014}{0.6445\sqrt{t} + 0.0014}\right) - F_{N,(0,1)}\left(\frac{6.438(N + 1) - 0.0014}{0.6445\sqrt{t} + 0.0014}\right), \quad N = 1, 2, \ldots ,
\]
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
\[
\bar{H}(t,2) \equiv 0.1576(t + 0.0014), \quad \bar{D}(t,1) \equiv 0.0103(t + 0.0014),
\]
the availability coefficient of the system at the moment \( t \) is given by the formula
\[
K(t,2) \equiv 0.9998, \quad t \geq 0,
\]
the availability coefficient of the system in the time interval \( <t, t+\tau), \tau > 0 \), is given by the formula
\[
K(t,\tau,2) \equiv 0.1576\int_{t}^{t+\tau} \bar{R}(t,2) dt, \quad t \geq 0, \quad \tau > 0,
\]
where the reliability function of a system at the critical state \( \bar{R}(t,2) \) 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-robe transporter assuming component failures’ dependence (Blokus-Roszkowska & Kołowrocki 2009). 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 (Blokus-Roszkowska 2007a, b).

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 \( T_i(u), i = 1,2,\ldots,k, \ j = 1,2,\ldots,l_i, u = 1,2,\ldots,z \), the random variables representing the lifetimes of components \( E_{ij} \) in the state subset \( \{u, u + 1, \ldots, z\} \), 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

\[
E[T_{ij}(u)] = E[T_{ij}(u)] - \frac{v}{l_i} E[T_{ij}(u)] = \frac{1}{l_i}, j = 1,2,\ldots,l_i, \ v = 0,1,2,\ldots,l_i - 1, \ i = 1,2,\ldots,k, \ u = 1,2,\ldots,z.
\]

The ground ship-rope transporter is a system with dependent failures of components is described in (Blokus-Roszkowska & Kołowrocki 2009). 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 (Blokus-Roszkowska et al. 2008b, Soszyńska 2006), counted in years respectively are:

\[
\mu(1) = \sum_{i=1}^{8} p_i \mu_i(1) \equiv 8.7940, \ \sigma(1) \equiv 2.2355, \quad (30)
\]

\[
\mu(2) = \sum_{i=1}^{8} p_i \mu_i(2) \equiv 5.7981, \ \sigma(2) \equiv 1.4867, \quad (31)
\]

\[
\mu(3) = \sum_{i=1}^{8} p_i \mu_i(3) \equiv 3.0731, \ \sigma(3) \equiv 0.7797. \quad (32)
\]

Next, the unconditional mean values of the ground ship-rope transporter lifetimes in the particular reliability states, by (Kołowrocki 2004) 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 \( \mu(0)(2) = 0.0014 \equiv 12 \) hours and the standard deviation \( \sigma(0)(2) = 0.0002 \equiv 2 \) hours, applying results given in (Blokus-Roszkowska et al. 2008a), we obtain the following results:

- the distribution function of the time \( \bar{S}_N(2) \) until the \( N \)-th system’s renovation, for sufficiently large \( N \), has approximately normal distribution \( N(5.79951N, 1.4867\sqrt{N}) \), i.e.,

\[
\bar{F}^{(N)}(t,2) = P(S_N(2) < t) \equiv F_N(0)(\frac{t - 5.79951N}{1.4867\sqrt{N}}) \equiv \Phi(\frac{t - 5.79951N}{1.4867\sqrt{N}}), \ t \in (-\infty, \infty), \ N = 1,2,\ldots,
\]

- the expected value and the variance of the time \( \bar{S}_N(2) \) until the \( N \)-th system’s renovation take respectively forms

\[
\bar{E}[S_N(2)] = 5.79951N, \ \bar{D}[S_N(2)] = 2.2103N.
\]
– the distribution function of the time $\overline{S}_N(2)$ until the $N$th exceeding the reliability critical state 2 of this system takes form

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

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

$$E[S_N(2)] \equiv 5.7981N + 0.0014(N - 1), \; D[S_N(2)] \equiv 2.2103N$$

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

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

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

$$\overline{H}(t, 2) \equiv 0.1724t, \; \overline{D}(t, 2) \equiv 0.0113r,$$

– 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

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

– 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

$$\overline{H}(t, 2) \equiv 0.1724(t + 0.0014), \; \overline{D}(t, 1) \equiv 0.0113(t + 0.0014),$$

– the availability coefficient of the system at the moment $t$ is given by the formula

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

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

$$K(t, \tau, 2) \equiv 0.1724 \int_{t}^{\infty} \overline{R}(t, 2)d\tau, \; t \geq 0, \; \tau > 0,$$

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

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

where

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

$$[\overline{R}(t, 2)]^{(2)} = \left[ \sum_{j=0}^{6} \frac{(0.846t)^j}{j!}\exp[-0.846t]\right]^{26}, \; i = 2, 3, 4,$$

$$[\overline{R}(t, 2)]^{(3)} = \left[ \sum_{j=0}^{6} \frac{(1.2996t)^j}{j!}\exp[-1.2996t]\right]^{12}, \; i = 5, 6, 7,$$

$$[\overline{R}(t, 2)]^{(8)} = \left[ \sum_{j=0}^{6} \frac{(1.4184t)^j}{j!}\exp[-1.4184t]\right]^{18}, \; t \geq 0.$$
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 \textit{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.

6 CONCLUSIONS

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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