- 360 pipe segments, with the conditional reliability functions co-ordinates

$[R_{ij}^{(3)}(t,1)]^{(2)} = \exp[-0.0059t]$,

$[R_{ij}^{(3)}(t,2)]^{(2)} = \exp[-.0074t]$,

$i = 1,2,\ j = 1,2,...,360$,

- 2 valves with the conditional reliability functions co-ordinates

$[R_{ij}^{(3)}(t,1)]^{(2)} = \exp[-0.0166t]$,

$[R_{ij}^{(3)}(t,2)]^{(2)} = \exp[-0.0181t]$,

$i = 1,2,\ j = 361,362$.

In the pipeline of the second type there are:

- 360 pipe segments with the conditional reliability functions co-ordinates

$[R_{ij}^{(3)}(t,1)]^{(2)} = \exp[-0.0071t]$,

$[R_{ij}^{(3)}(t,2)]^{(2)} = \exp[-0.0079t]$,

$i = 3,\ j = 1,2,...,360$,

- 2 valves with the conditional reliability functions co-ordinates

$[R_{ij}^{(3)}(t,1)]^{(2)} = \exp[-0.0166t]$,

$[R_{ij}^{(3)}(t,2)]^{(2)} = \exp[-0.0181t]$,

$i = 3,\ j = 361,362$.

At the system operation state $z_3$, the system is composed of two subsystems $S_1$, $S_2$, each containing 2 pipelines with the structure showed in *Figure 14*.
The subsystem $S_1$ consists of 2 identical pipelines, each composed of 178 components. In each pipeline there are:

- 176 pipe segments with the conditional reliability functions co-ordinates

$[R_{ij}^{(1)}(t,1)]^{(3)} = \exp[-0.0062t]$,

$[R_{ij}^{(1)}(t,2)]^{(3)} = \exp[-0.0088t]$,

$i = 1,2,\ j = 1,2,...,176$,

- 2 valves with the conditional reliability functions co-ordinates

$[R_{ij}^{(1)}(t,1)]^{(3)} = \exp[-0.0166t]$,

$[R_{ij}^{(1)}(t,2)]^{(3)} = \exp[-0.0181t],\ i = 1,2,\ j = 177,178$.

The subsystem $S_2$ consists of 2 identical pipelines, each composed of 719 components. In each pipeline there are:

- 717 pipe segments with the conditional reliability functions co-ordinates

$[R_{ij}^{(2)}(t,1)]^{(3)} = \exp[-0.0062t]$,

$[R_{ij}^{(2)}(t,2)]^{(3)} = \exp[-0.0088t]$,

$i = 1,2,\ j = 1,2,...,717$,

- 2 valves with the conditional multi-state reliability functions co-ordinates

$[R_{ij}^{(2)}(t,1)]^{(3)} = \exp[-0.0166t]$,

$[R_{ij}^{(2)}(t,2)]^{(3)} = \exp[-0.0181t]$,

$i = 1,2,\ j = 718,719$.

At the system operational state $z_4$, the system is composed two subsystems $S_1$, $S_2$, each containing 2 pipelines and one subsystem $S_3$ containing 3 pipelines with the structure showed in *Figure 15*.
The subsystem $S_1$ consists of 2 identical pipelines, each composed of 178 components. In each pipeline there are:

- 176 pipe segments with the conditional reliability functions co-ordinates

$[R_{ij}^{(1)}(t,1)]^{(4)} = \exp[-0.0062t]$,

$[R_{ij}^{(1)}(t,2)]^{(4)} = \exp[-0.0088t]$,

$i = 1,2,\ j = 1,2,...,176$,

- 2 valves with the conditional reliability functions co-ordinates

$[R_{ij}^{(1)}(t,1)]^{(4)} = \exp[-0.0166t]$,

$[R_{ij}^{(1)}(t,2)]^{(4)} = \exp[-0.0181t]$,

$i = 1,2, \ j = 177,178.$

The subsystem $S_2$ consists of 2 identical pipelines, each composed of 719 components. In each pipeline there are:

- 717 pipe segments with the conditional reliability functions co-ordinates

$[R_{ij}^{(2)}(t,1)]^{(4)} = \exp[-0.0062t]$,

$[R_{ij}^{(2)}(t,2)]^{(4)} = \exp[-0.0088t]$,

$i = 1,2, \ j = 1,2,...,717,$

- 2 valves with the conditional reliability functions co-ordinates

$[R_{ij}^{(2)}(t,1)]^{(4)} = \exp[-0.0166t]$,

$[R_{ij}^{(2)}(t,2)]^{(4)} = \exp[-0.0181t]$,

$i = 1,2, \ j = 718,719.$

The subsystem $S_3$ consists of 2 pipelines of the first type and 1 pipeline of the second type, each composed of 362 components. In each pipeline of the first type there are:

- 360 pipe segments with the conditional reliability functions co-ordinates

$[R_{ij}^{(3)}(t,1)]^{(4)} = \exp[-0.0059t]$,

$[R_{ij}^{(3)}(t,2)]^{(4)} = \exp[-0.0074t]$,

$i = 1,2, \ j = 1,2,...,360,$

- 2 valves with the conditional reliability functions co-ordinates

$[R_{ij}^{(3)}(t,1)]^{(4)} = \exp[-0.0166t]$,

$[R_{ij}^{(3)}(t,2)]^{(4)} = \exp[-0.0181t]$,

$i = 1,2, \ j = 361,362.$

In the pipeline of the second type there are:

- 360 pipe segments with the conditional reliability functions co-ordinates

$[R_{ij}^{(3)}(t,1)]^{(4)} = \exp[-0.0071t]$,

$[R_{ij}^{(3)}(t,2)]^{(4)} = \exp[-0.0079t]$,

$i = 3 \ j = 1,2,...,360,$

- 2 valves with the conditional reliability functions co-ordinates

$[R_{ij}^{(3)}(t,1)]^{(4)} = \exp[-0.0166t]$,

$[R_{ij}^{(3)}(t,2)]^{(4)} = \exp[-0.0181t]$,

$i = 3, \ j = 361,362.$

At the system operational state $z_5$, the system is series and composed of two subsystems $S_1$, $S_2$, each containing 2 pipelines with the structure showed in *Figure 16*.
The subsystem $S_1$ consists of 2 identical pipelines, each composed of 178 components. In each pipeline there are:

- 176 pipe segments with the conditional reliability functions co-ordinates

$[R_{ij}^{(1)}(t,1)]^{(5)} = \exp[-0.0062t]$,

$[R_{ij}^{(1)}(t,2)]^{(5)} = \exp[-0.0088t]$,

$i = 1,2, \ j = 1,2,...,176,$

- 2 valves with the conditional reliability functions co-ordinates

$[R_{ij}^{(1)}(t,1)]^{(5)} = \exp[-0.0166t]$,

$[R_{ij}^{(1)}(t,2)]^{(5)} = \exp[-0.0181t]$,

$i = 1,2, \ j = 177,178.$

The subsystem $S_2$ consists of 2 identical pipelines, each composed of 719 components. In each pipeline there are:

- 717 pipe segments with he conditional reliability functions co-ordinates

$[R_{ij}^{(2)}(t,1)]^{(5)} = \exp[-0.0062t]$,

$[R_{ij}^{(2)}(t,2)]^{(5)} = \exp[-0.0088t]$,

$i = 1,2, \ j = 1,2,...,717$,

- 2 valves with the conditional reliability functions co-ordinates

$[R_{ij}^{(2)}(t,1)]^{(5)} = \exp[-0.0166t]$,

$[R_{ij}^{(2)}(t,2)]^{(5)} = \exp[-0.0181t]$,

$i = 1,2, \ j = 718,719$.

At the system operational state $z_6$, the system is composed of two subsystems $S_1$, $S_2$, each containing 2 pipelines and one subsystem $S_3$ containing 3 pipelines with the structure showed in *Figure 17*.
The subsystem $S_1$ consists of 2 identical pipelines, each composed of 178 components. In each pipeline there are:

- 176 pipe segments with the conditional reliability functions co-ordinates

$[R_{ij}^{(1)}(t,1)]^{(6)} = \exp[-0.0062t]$,

$[R_{ij}^{(1)}(t,2)]^{(6)} = \exp[-0.0088t]$,

$i = 1,2, \ j = 1,2,...,176$,

- 2 valves with the conditional reliability functions co-ordinates

$[R_{ij}^{(1)}(t,1)]^{(6)} = \exp[-0.0166t]$,

$[R_{ij}^{(1)}(t,2)]^{(6)} = \exp[-0.0181t]$,

$i = 1,2, \ j = 177,178$.

The subsystem $S_2$ consists of 2 identical pipelines, each composed of 717 components. In each pipeline there are:

- 717 pipe segments with the conditional reliability functions co-ordinates

$[R_{ij}^{(2)}(t,1)]^{(6)} = \exp[-0.0062t]$,

$[R_{ij}^{(2)}(t,2)]^{(6)} = \exp[-0.0088t]$,

$i = 1,2, \ j = 1,2,...,717$,

- 2 valves with the conditional reliability functions co-ordinates

$[R_{ij}^{(2)}(t,1)]^{(6)} = \exp[-0.0166t]$,

$[R_{ij}^{(2)}(t,2)]^{(6)} = \exp[-0.0181t]$,

$i = 1,2, \ j = 718.719$.

The subsystem $S_3$ consists of 2 pipelines of the first type and 1 pipeline of the second type, each composed of 362 components. In each pipeline of the first type there are:

- 360 pipe segments with the conditional reliability functions co-ordinates

$[R_{ij}^{(3)}(t,1)]^{(6)} = \exp[-0.0059t]$,

$[R_{ij}^{(3)}(t,2)]^{(6)} = \exp[-0.0074t]$,

$i = 1,2, \ j = 1,2,...,360$,

- 2 valves with the conditional reliability functions co-ordinates

$[R_{ij}^{(3)}(t,1)]^{(6)} = \exp[-0.0166t]$,

$[R_{ij}^{(3)}(t,2)]^{(6)} = \exp[-0.0181t]$,

$i = 1,2, \ j = 361,362$.

In the pipeline of the second type there are:

- 360 pipe segments with the conditional reliability functions co-ordinates

$[R_{ij}^{(3)}(t,1)]^{(6)} = \exp[-0.0071t]$,

$[R_{ij}^{(3)}(t,2)]^{(6)} = \exp[-0.0079t]$,

$i = 3, \ j = 1,2,...,360$,

- 2 valves with the conditional reliability functions co-ordinates

$[R_{ij}^{(3)}(t,1)]^{(6)} = \exp[-0.0166t]$,

$[R_{ij}^{(3)}(t,2)]^{(6)} = \exp[-0.0181t]$,

$i = 3,\ j = 361.362.$

At the system operational state $z_7$, the system is composed of the subsystem $S_3$, which contains 3 pipelines with the structure showed in *Figure 18*.
The subsystem $S_3$ consists of 2 pipelines of the first type and 1 pipeline of the second type , each composed of 362 elements. In each pipeline of the first type there are:

- 360 pipe segments with the conditional reliability functions co-ordinates

$$[R_{ij}^{(3)}(t,1)]^{(7)} = \exp[-0.0059t],$$

$$[R_{ij}^{(3)}(t,2)]^{(7)} = \exp[-0.0074t],$$

$$i = 1,2,\ j = 1,2,...,360,$$

- 2 valves with the conditional reliability functions co-ordinates

$$[R_{ij}^{(3)}(t,1)]^{(7)} = \exp[-0.0166t],$$

$$[R_{ij}^{(3)}(t,2)]^{(7)} = \exp[-0.0181t],$$

$$i = 1,2,\ j = 361,362.$$

In the pipeline of the second type there are:

- 360 pipe segments with the conditional reliability functions co-ordinates

$$[R_{ij}^{(3)}(t,1)]^{(7)} = \exp[-0.0071t],$$

$$[R_{ij}^{(3)}(t,2)]^{(7)} = \exp[-0.0079t],$$

$$i = 3,\ j = 1,2,...,360,$$

- 2 valves with the conditional reliability functions co-ordinates

$$[R_{ij}^{(3)}(t,1)]^{(7)} = \exp[-0.0166t],$$

$$[R_{ij}^{(3)}(t,2)]^{(7)} = \exp[-0.0181t],$$

$$i = 3,\ j = 361,362.$$

## 5.2. Statistical identification of the shipyard ship-rope elevator components reliability models

### 5.2.1. The subsystems and components of the shipyard ship-rope elevator in various operation states

The considered ship-rope elevator, with the scheme presented in *Figure 19*, is composed of a steel platform-carriage moved vertically with 10 rope-hoisting winches. In our further analysis we will discuss the reliability of the rope system only, so we assume the considered system is composed of 10 subsystems i.e. ropes in rope-hoisting winches. Each of the ropes is composed of 22 identical strands and we consider strands as a basic components of the system.

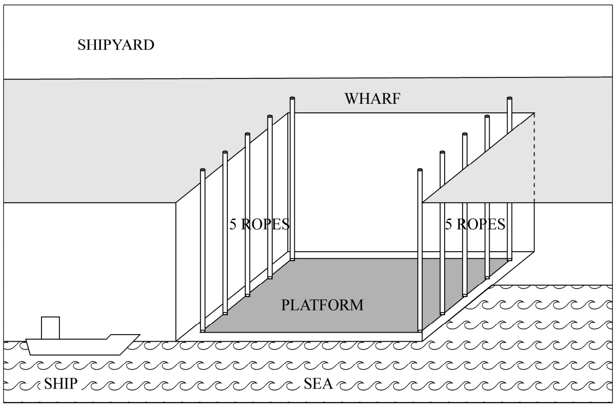


*Figure 19.* The scheme of the ship-rope elevator

The ship-rope elevator consists of ten subsystems $S_k$, $k = 1,2,3,...,10$:

- the subsystem $S_1$ composed of twenty two identical strands, denoted respectively by $E_i^{(1)}$, $i = 1,2,...,22$,
- the subsystem $S_2$ composed of twenty two identical strands, denoted respectively by $E_i^{(2)}$, $i = 1,2,...,22$,
- the subsystem $S_3$ composed of twenty two identical strands, denoted respectively by $E_i^{(3)}$, $i = 1,2,...,22$,
- the subsystem $S_4$ composed of twenty two identical strands, denoted respectively by $E_i^{(4)}$, $i = 1,2,...,22$,
- the subsystem $S_5$ composed of twenty two identical strands, denoted respectively by $E_i^{(5)}$, $i = 1,2,...,22$,
- the subsystem $S_6$ composed of twenty two identical strands, denoted respectively by $E_i^{(6)}$, $i = 1,2,...,22$,
- the subsystem $S_7$ composed of twenty two identical strands, denoted respectively by $E_i^{(7)}$, $i = 1,2,...,22$,

- the subsystem $S_8$ composed of twenty two identical strands, denoted respectively by $E_i^{(8)}$, $i = 1,2,...,22$,
- the subsystem $S_9$ composed of twenty two identical strands, denoted respectively by $E_i^{(9)}$, $i = 1,2,...,22$,
- the subsystem $S_{10}$ composed of twenty two identical strands, denoted respectively by $E_i^{(10)}$, $i = 1,2,...,22$.

The subsystems $S_k$, $k = 1,2,...,10$ are forming a general ship-rope elevator structure presented in *Figure20.*

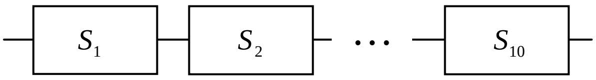


*Figure 20.* General scheme of ship-rope elevator

However, the ship-rope elevator structure and the subsystem components reliability depend on its changing in time operation states.

Taking into account the expert opinion on the operation process of the considered ship-rope elevator we fix the number of ship-rope elevator operation process states $\nu = 5$ and we distinguish the following as its five operation states:

- an operation state $z_1$ – loading over 0 up to 500 tones,
- an operation state $z_2$ – loading over 500 up to 1000 tones,
- an operation state $z_3$ – loading over 1000 up to 1500 tones,
- an operation state $z_4$ – loading over 1500 up to 2000 tones,
- an operation state $z_5$ – loading over 2000 up to 2500 tones.

In all five operational states the elevator has the same structure.

### 5.2.2. The parameters of the shipyard ship-rope elevator components multi-state reliability models

According to rope reliability data given in their technical certificates, experts' opinions based on the nature of strand failures and taking into account the safety of the operation of the ship-rope elevator in all operation states $z_b$, $b = 1,2,...,5$, we distinguish the following four reliability states $(z = 3)$ of the system and its components:

- 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).

Moreover, we fix that there are possible the transitions between the components reliability states only from better to worse ones.

From the above, the shipyard ship-rope elevator subsystems $S_k$, $k = 1,2,3,...,10$, (ropes) are composed of four-state (strands), i.e. $z = 3$, components $E_i^{(k)}$, $k = 1,2,3,...,10$, with the conditional multi-state reliability functions

$$[R_i^{(k)}(t,\cdot)]^{(b)}$$

$$=[1,[R_i^{(k)}(t,1)]^{(b)},[R_i^{(k)}(t,2)]^{(b)},[R_i^{(k)}(t,3)]^{(b)}],$$

$$b = 1,2,...,5,$$

with exponential co-ordinates $[R_i^{(k)}(t,1)]^{(b)}$, $[R_i^{(k)}(t,2)]^{(b)}$ and $[R_i^{(k)}(t,3)]^{(b)}$ different in various operation states $z_b$, $b = 1,2,...,5$.

More precisely, from the performed in Section 3.4.2 analysis, the unknown reliability parameters of the system components reliability models in various system operation states are:

i) at the system operation states $z_b$, $b = 1,2,...,5$:

- the reliability functions of the subsystem $S_1$ components

$$[R_i^{(1)}(t,\cdot)]^{(b)}$$

$$= [1,[R_i^{(1)}(t,1)]^{(b)},[R_i^{(1)}(t,2)]^{(b)},[R_i^{(1)}(t,3)]^{(b)}],$$

$$i = 1,2,...,22, \; b = 1,2,...,5,$$

coordinates

$$[R_i^{(1)}(t,1)]^{(b)} = \exp[-[\lambda_i^{(1)}(1)]^{(b)} t],$$

$$[R_i^{(1)}(t,2)]^{(b)} = \exp[-[\lambda_i^{(1)}(2)]^{(b)} t],$$

$$[R_i^{(1)}(t,3)]^{(b)} = \exp[-[\lambda_i^{(1)}(3)]^{(b)} t],$$

$i = 1,2,3,...,22, \ \ b = 1,2,...,5,$

with the intensities of departure from the reliability states subsets $\{1,2,3\}, \{2,3\}, \{3\}$, respectively

$[\lambda_i^{(1)}(1)]^{(b)}, [\lambda_i^{(1)}(2)]^{(b)}, [\lambda_i^{(1)}(3)]^{(b)},$

$i = 1,2,...,22, \ \ b = 1,2,...,5,$

- the reliability functions of the subsystem $S_2$ components

$$[R_i^{(2)}(t,\cdot)]^{(b)} =$$

$$= [1, [R_i^{(2)}(t,1)]^{(b)}, [R_i^{(2)}(t,2)]^{(b)}, [R_i^{(2)}(t,3)]^{(b)}],$$

$i = 1,2,...,22, \ \ b = 1,2,...,5,$

coordinates

$$[R_i^{(2)}(t,1)]^{(b)} = \exp[-[\lambda_i^{(2)}(1)]^{(b)} t],$$

$$[R_i^{(2)}(t,2)]^{(b)} = \exp[-[\lambda_i^{(2)}(2)]^{(b)} t],$$

$$[R_i^{(2)}(t,3)]^{(b)} = \exp[-[\lambda_i^{(2)}(3)]^{(b)} t],$$

$i = 1,2,...,22, \ \ b = 1,2,...,5,$

with the intensities of departure from the reliability states subsets $\{1,2,3\}, \{2,3\}, \{3\}$, respectively

$[\lambda_i^{(2)}(1)]^{(b)}, [\lambda_i^{(2)}(2)]^{(b)}, [\lambda_i^{(2)}(3)]^{(b)}, \ i = 1,2,...,22,$

$b = 1,2,...,5,$

- the reliability functions of the subsystem $S_3$ components

$$[R_i^{(3)}(t,\cdot)]^{(b)} =$$

$$[1, [R_i^{(3)}(t,1)]^{(b)}, [R_i^{(3)}(t,2)]^{(b)}, [R_i^{(3)}(t,3)]^{(b)}],$$

$i = 1,2,...,22, \ \ b = 1,2,...,5,$

coordinates

$$[R_i^{(3)}(t,1)]^{(b)} = \exp[-[\lambda_i^{(3)}(1)]^{(b)} t],$$

$$[R_i^{(3)}(t,2)]^{(b)} = \exp[-[\lambda_i^{(3)}(2)]^{(b)} t],$$

$$[R_i^{(3)}(t,3)]^{(b)} = \exp[-[\lambda_i^{(3)}(3)]^{(b)} t],$$

$i = 1,2,...,22, \ \ b = 1,2,...,5,$

with the intensities of departure from the reliability states subsets $\{1,2,3\}, \{2,3\}, \{3\}$, respectively

$[\lambda_i^{(3)}(1)]^{(b)}, [\lambda_i^{(3)}(2)]^{(b)}, [\lambda_i^{(3)}(3)]^{(b)},$

$i = 1,2,...,22, \ \ b = 1,2,...,5,$

- the reliability functions of the subsystem $S_4$ components

$$[R_i^{(4)}(t,\cdot)]^{(b)}$$

$$= [1, [R_i^{(4)}(t,1)]^{(b)}, [R_i^{(4)}(t,2)]^{(b)}, [R_i^{(4)}(t,3)]^{(b)}],$$

$i = 1,2,...,22, \ \ b = 1,2,...,5,$

coordinates

$$[R_i^{(4)}(t,1)]^{(b)} = \exp[-[\lambda_i^{(4)}(1)]^{(b)} t],$$

$$[R_i^{(4)}(t,2)]^{(b)} = \exp[-[\lambda_i^{(4)}(2)]^{(b)} t],$$

$$[R_i^{(4)}(t,3)]^{(b)} = \exp[-[\lambda_i^{(4)}(3)]^{(b)} t],$$

$i = 1,2,...,22, \ \ b = 1,2,...,5,$

with the intensities of departure from the reliability states subsets $\{1,2,3\}, \{2,3\}, \{3\}$, respectively

$[\lambda_i^{(4)}(1)]^{(b)}, [\lambda_i^{(4)}(2)]^{(b)}, [\lambda_i^{(4)}(3)]^{(b)},$

$i = 1,2,...,22, \ \ b = 1,2,...,5,$

- the reliability functions of the subsystem $S_5$ components

$$[R_i^{(5)}(t,\cdot)]^{(b)} =$$

$$= [1, [R_i^{(5)}(t,1)]^{(b)}, [R_i^{(5)}(t,2)]^{(b)}, [R_i^{(5)}(t,3)]^{(b)}],$$

$i = 1,2,...,22, \ \ b = 1,2,...,5,$

coordinates

$$[R_i^{(5)}(t,1)]^{(b)} = \exp[-[\lambda_i^{(5)}(1)]^{(b)} t],$$

$[R_i^{(5)}(t,2)]^{(b)} = \exp[-[\lambda_i^{(5)}(2)]^{(b)} t]$,

$[R_i^{(5)}(t,3)]^{(b)} = \exp[-[\lambda_i^{(5)}(3)]^{(b)} t]$,

$i = 1,2,...,22, \ b = 1,2,...,5,$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_i^{(5)}(1)]^{(b)}$, $[\lambda_i^{(5)}(2)]^{(b)}$, $[\lambda_i^{(5)}(3)]^{(b)}$,

$i = 1,2,...,22, \ b = 1,2,...,5,$

- the reliability functions of the subsystem $S_6$ components

$$[R_i^{(6)}(t,\cdot)]^{(b)} = [1, [R_i^{(6)}(t,1)]^{(b)}, [R_i^{(6)}(t,2)]^{(b)}, [R_i^{(6)}(t,3)]^{(b)}],$$

$i = 1,2,...,22, \ b = 1,2,...,5,$

coordinates

$[R_i^{(6)}(t,1)]^{(b)} = \exp[-[\lambda_i^{(6)}(1)]^{(b)} t]$,

$[R_i^{(6)}(t,2)]^{(b)} = \exp[-[\lambda_i^{(6)}(2)]^{(b)} t]$,

$[R_i^{(6)}(t,3)]^{(b)} = \exp[-[\lambda_i^{(6)}(3)]^{(b)} t]$,

$i = 1,2,...,22, \ b = 1,2,...,5,$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_i^{(6)}(1)]^{(b)}$, $[\lambda_i^{(6)}(2)]^{(b)}$, $[\lambda_i^{(6)}(3)]^{(b)}$,

$i = 1,2,...,22, \ b = 1,2,...,5,$

- the reliability functions of the subsystem $S_7$ components

$$[R_i^{(7)}(t,\cdot)]^{(b)} = [1, [R_i^{(7)}(t,1)]^{(b)}, [R_i^{(7)}(t,2)]^{(b)}, [R_i^{(7)}(t,3)]^{(b)}],$$

$i = 1,2,...,22, \ b = 1,2,...,5,$

coordinates

$[R_i^{(7)}(t,1)]^{(b)} = \exp[-[\lambda_i^{(7)}(1)]^{(b)} t]$,

$[R_i^{(7)}(t,2)]^{(b)} = \exp[-[\lambda_i^{(7)}(2)]^{(b)} t]$,

$[R_i^{(7)}(t,3)]^{(b)} = \exp[-[\lambda_i^{(7)}(3)]^{(b)} t]$

$i = 1,2,...,22, \ b = 1,2,...,5,$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_i^{(7)}(1)]^{(b)}$, $[\lambda_i^{(7)}(2)]^{(b)}$, $[\lambda_i^{(7)}(3)]^{(b)}$,

$i = 1,2,3,...,22, \ b = 1,2,...,5,$

- the reliability functions of the subsystem $S_8$ components

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

$i = 1,2,...,22, \ b = 1,2,...,5,$

coordinates

$[R_i^{(8)}(t,1)]^{(b)} = \exp[-[\lambda_i^{(8)}(1)]^{(b)} t]$,

$[R_i^{(8)}(t,2)]^{(b)} = \exp[-[\lambda_i^{(8)}(2)]^{(b)} t]$,

$[R_i^{(8)}(t,3)]^{(b)} = \exp[-[\lambda_i^{(8)}(3)]^{(b)} t]$,

$i = 1,2,...,22, \ b = 1,2,...,5,$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_i^{(b)}(1)]^{(1)}$, $[\lambda_i^{(b)}(2)]^{(1)}$, $[\lambda_i^{(b)}(3)]^{(1)}$,

$i = 1,2,...,22, \ b = 1,2,...,5,$

- the reliability functions of the subsystem $S_9$ components

$$[R_i^{(9)}(t,\cdot)]^{(b)} = [1, [R_i^{(9)}(t,1)]^{(b)}, [R_i^{(9)}(t,2)]^{(b)}, [R_i^{(9)}(t,3)]^{(b)}],$$

$i = 1,2,...,22, \ b = 1,2,...,5,$

coordinates

$$[R_i^{(9)}(t,1)]^{(b)} = \exp[-[\lambda_i^{(9)}(1)]^{(b)} t],$$

$$[R_i^{(9)}(t,2)]^{(b)} = \exp[-[\lambda_i^{(9)}(2)]^{(b)} t],$$

$$[R_i^{(9)}(t,3)]^{(b)} = \exp[-[\lambda_i^{(9)}(3)]^{(b)} t],$$

$$i = 1,2,...,22, \; b = 1,2,...,5,$$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$$[\lambda_i^{(9)}(1)]^{(b)}, \; [\lambda_i^{(9)}(2)]^{(b)}, \; [\lambda_i^{(9)}(3)]^{(b)},$$

$$i = 1,2,...,22, \; b = 1,2,...,5,$$

- the reliability functions of the subsystem $S_{10}$ components

$$[R_i^{(10)}(t,\cdot)]^{(b)}$$

$$= [1, [R_i^{(10)}(t,1)]^{(b)}, [R_i^{(10)}(t,2)]^{(b)}, [R_i^{(10)}(t,3)]^{(b)}],$$

$$i = 1,2,...,22, \; b = 1,2,...,5,$$

coordinates

$$[R_i^{(10)}(t,1)]^{(b)} = \exp[-[\lambda_i^{(10)}(1)]^{(b)} t],$$

$$[R_i^{(10)}(t,2)]^{(b)} = \exp[-[\lambda_i^{(10)}(2)]^{(b)} t],$$

$$[R_i^{(10)}(t,3)]^{(b)} = \exp[-[\lambda_i^{(10)}(3)]^{(b)} t],$$

$$i = 1,2,...,22, \; b = 1,2,...,5,$$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$$[\lambda_i^{(10)}(1)]^{(b)}, \; [\lambda_i^{(10)}(2)]^{(b)}, \; [\lambda_i^{(10)}(3)]^{(b)},$$

$$i = 1,2,...,22, \; b = 1,2,...,5,$$

### 5.2.3. The shipyard ship-rope elevator components reliability data collection

#### 5.2.3.1. Data coming from experts

In the *Table 5* there are given the approximate realizations

$$[\hat{\mu}_i^{(k)}(u)]^{(b)}, \; k = 1,2,...,10, \; u = 1,2,3, \; b = 1,2,...,5,$$

of the mean values

$$[\mu_i^{(k)}(u)]^{(b)} = E[[T_i^{(k)}(u)]^{(b)}],$$

$$k = 1,2,...,10, \; u = 1,2,3, \; b = 1,2,...,5,$$

of the conditional lifetimes $[T_i^{(k)}(u)]^{(b)}$, $k = 1,2,...,10$, $u = 1,2,3$, $b = 1,2,...,5$, in reliability states of the component $E_i^{(k)}$ of the shipyard ship-rope elevator subsystems $S_k$, $k = 1,2,...,10$, in particular operation states $z_b$, $b = 1,2,...,5$, estimated on the basis of the expert opinions.
$k = 1,2,...,10$,

*Table 5.* The approximate mean values $[\hat{\mu}_i^{(k)}(u)]^{(b)}$ of the subsystem $S_k$, $k = 1,2,...,10$, components conditional lifetimes $[T_i^{(k)}(u)]^{(b)}$, $k = 1,2,...,10$, in particular operation states $z_b$

| Subsystem $S_k$ components (strand) | $E_i^{(k)}$ $i = 1,2,...,22$, $u = 1$ | $E_i^{(k)}$ $i = 1,2,...,22$, $u = 2$ | $E_i^{(k)}$ $i = 1,2,...,22$, $u = 3$ |
|---|---|---|---|
| Operation state $z_b$ | The approximate mean values $[\hat{\mu}_i^{(k)}(u)]^{(b)}$, $k = 1,2,...,10$, of the conditional lifetimes $[T_i^{(k)}(u)]^{(b)}$ of the component $E_i^{(k)}$ (*in years*) | | |
| $z_1$ | 4.9 | 3.9 | 3.4 |
| $z_2$ | 4.5 | 3.5 | 3.1 |
| $z_3$ | 3.7 | 2.85 | 2.4 |
| $z_4$ | 3 | 2.1 | 1.7 |

| | | | |
|---|---|---|---|
| $z_5$ | 2.3 | 1.4 | 1.1 |

### 5.2.3.2. Data coming from components reliability states changing processes

There are no data collected from the shipyard ship-rope elevator components reliability states changing processes.

### 5.2.4. Statistical identification of the shipyard ship-rope elevator components reliability

### 5.2.4.1. Statistical identification of the shipyard ship-rope elevator components reliability on the basis of data coming from experts

To identify the parameters of multistate reliability functions of the ship-rope elevator components the statistical data coming from their failure processes are needed. The statistical data that has been collected are given in *Table 5*.

From data given in the *Table 5*, on the basis of the results from (8) formula

$$[\hat{\lambda}_i^{(k)}(u)]^{(b)} = \frac{1}{[\hat{\mu}_i^{(k)}(u)]^{(b)}},\ k = 1,2,...,10,\ u = 1,2,3,$$

$$b = 1,2,...,5,$$

we get the approximate values $[\hat{\lambda}_i^{(k)}(u)]^{(b)}$ of the subsystems $S_k$, $k = 1,2,...,10$, components unknown intensities $[\lambda_i^{(k)}(u)]^{(b)}$ of departure from the reliability states subset $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, while the system is operating in the operation state $z_b$, $b = 1,2,...,5$. The results are presented below.

At the system operation state $z_1$, the system is composed of ten subsystems (ropes) $S_k$, $k = 1,2,...,10$. Each of the ropes is composed of 22 identical strands with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$$[\lambda_i^{(k)}(1)]^{(1)} = 0.2041,\ [\lambda_i^{(k)}(2)]^{(1)} = 0.2564,$$

$$[\lambda_i^{(k)}(3)]^{(1)} = 0.2941,\ k = 1,2,...10,\ i = 1,2,...,22.$$

At the system operation state $z_2$, the system is composed of ten subsystems (ropes) $S_k$, $k = 1,2,...,10$. Each of the ropes is composed of 22 identical strands with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$$[\lambda_i^{(k)}(1)]^{(2)} = 0.2222,\ [\lambda_i^{(k)}(2)]^{(2)} = 0.2857,$$

$$[\lambda_i^{(k)}(3)]^{(2)} = 0.3226,\ k = 1,2,...10,\ i = 1,2,...,22.$$

At the system operation state $z_3$, the system is composed of ten subsystems (ropes) $S_k$, $k = 1,2,...,10$. Each of the ropes is composed of 22 identical strands with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$$[\lambda_i^{(k)}(1)]^{(3)} = 0.2703,\ [\lambda_i^{(k)}(2)]^{(3)} = 0.3509,$$

$$[\lambda_i^{(k)}(3)]^{(3)} = 0.4167,\ k = 1,2,...10,\ i = 1,2,...,22.$$

At the system operation state $z_4$, the system is composed of ten subsystems (ropes) $S_k$, $k = 1,2,...,10$. Each of the ropes is composed of 22 identical strands with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$$[\lambda_i^{(k)}(1)]^{(4)} = 0.3333,\ [\lambda_i^{(k)}(2)]^{(4)} = 0.4762,$$

$$[\lambda_i^{(k)}(3)]^{(4)} = 0.5882,\ k = 1,2,...10,\ i = 1,2,...,22.$$

At the system operation state $z_5$, the system is composed of ten subsystems (ropes) $S_k$, $k = 1,2,...,10$. Each of the ropes is composed of 22 identical strands with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$$[\lambda_i^{(k)}(1)]^{(5)} = 0.4348,\ [\lambda_i^{(k)}(2)]^{(5)} = 0.71143,$$

$$[\lambda_i^{(k)}(3)]^{(5)} = 0.9091,\ k = 1,2,...10,\ i = 1,2,...,22.$$

### 5.2.4.2. Statistical identification of the shipyard ship-rope elevator components reliability models on the basis of data coming from their failure processes

As there are no data collected from the system components failure processes their reliability models identification using the methods of Section 3.4.2 and Section 3.5 is not possible.

### 5.2.5. Identifying the shipyard ship-rope elevator components conditional multistate exponential reliability functions

As there are no data collected from the shipyard ship-rope elevator components reliability states changing processes, then it is not possible to verify the hypotheses on the exponential forms of the shipyard ship-rope elevator components conditional reliability functions. We arbitrarily assume that these reliability functions are exponential and using the results of the previous section and the relationships given in Section 5.2.2 we fix heir forms.

At the system operation state $z_1$, the system is composed of ten subsystems (ropes) $S_k$, $k = 1,2,...,10.$ Each of the ropes is composed of 22 identical strands with the conditional reliability functions co-ordinates

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

$$[R_i^{(k)}(t,2)]^{(1)} = \exp[-0.2564t],$$

$$[R_i^{(k)}(t,3)]^{(1)} = \exp[-0.2941t],$$

$$k = 1,2,...10, \ \ i = 1,2,...,22.$$

At the system operation state $z_2$, the system is composed of ten subsystems (ropes) $S_k$, $k = 1,2,...,10.$ Each of the ropes is composed of 22 identical strands with the conditional reliability functions co-ordinates

$$[R_i^{(k)}(t,1)]^{(2)} = \exp[-0.2222t],$$

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

$$[R_i^{(k)}(t,3)]^{(3)} = \exp[-0.3226t],$$

$$k = 1,2,...10, \ \ i = 1,2,...,22.$$

At the system operation state $z_3$, the system is composed of ten subsystems (ropes) $S_k$, $k = 1,2,...,10.$ Each of the ropes is composed of 22 identical strands with the conditional reliability functions co-ordinates

$$[R_i^{(k)}(t,1)]^{(3)} = \exp[-0.2703t],$$

$$[R_i^{(k)}(t,2)]^{(3)} = \exp[-0.3509t],$$

$$[R_i^{(k)}(t,3)]^{(3)} = \exp[-0.4167t],$$

$$k = 1,2,...10, \ \ i = 1,2,...,22.$$

At the system operation state $z_4$, the system is composed of ten subsystems (ropes) $S_k$, $k = 1,2,...,10.$ Each of the ropes is composed of 22 identical strands with the conditional reliability functions co-ordinates

$$[R_i^{(k)}(t,1)]^{(4)} = \exp[-0.3333t],$$

$$[R_i^{(k)}(t,2)]^{(4)} = \exp[-0.4762t],$$

$$[R_i^{(k)}(t,3)]^{(4)} = \exp[-0.5882t],$$

$$k = 1,2,...10, \ \ i = 1,2,...,22.$$

At the system operation state $z_5$, the system is composed of ten subsystems (ropes) $S_k$, $k = 1,2,...,10.$ Each of the ropes is composed of 22 identical strands with the conditional reliability functions co-ordinates

$$[R_i^{(k)}(t,1)]^{(5)} = \exp[-0.4348t],$$

$$[R_i^{(k)}(t,2)]^{(5)} = \exp[-0.7143t],$$

$$[R_i^{(k)}(t,3)]^{(5)} = \exp[-0.9091t],$$

$$k = 1,2,...10, \ \ i = 1,2,...,22.$$

## 5.3. Statistical identification of the shipyard ground ship-rope transporter system components reliability models

### 5.3.1. The subsystem and components of the shipyard ground ship-rope transporter in various operation states

The considered ground ship-rope transporter consists of three broaching machines – subsystems $S_1$, $S_2$, $S_3$:

- the subsystem $S_1$ is composed of 6 identical strands and each strand consists of 36 wires with a webbing core, denoted respectively by $E_{ij}^{(1)}$, $i = 1,2,...,6$ $j = 1,2,...,36,$
- the subsystem $S_2$ is composed of 6 identical strands and each strand consists of 36 wires with a

webbing core, denoted respectively by $E_{ij}^{(2)}$, $i = 1,2,...,6$ $j = 1,2,...,36$,

- the subsystem $S_3$ is composed of 6 identical strands and each strand consists of 36 wires with a webbing core, denoted respectively by $E_{ij}^{(3)}$, $i = 1,2,...,6$ $j = 1,2,...,36$.

The subsystems $S_1$, $S_2$, $S_3$ are forming a general ground ship-rope transporter structure presented in *Figure 21*.

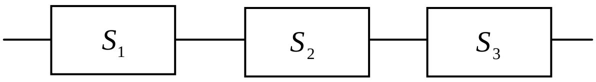


*Figure 21.* General scheme of ground ship-rope transporter

However, the ground ship-rope transporter structure and the subsystem components reliability depend on its changing in time operation states.

Taking into account the expert opinion on the operation process of the considered ground ship-rope transporter we fix the number of the ground ship-rope transporter operation process states $\nu = 7$ and we distinguish the following as its seven operation states:

- an operation state $z_1$ – the ship with a tonnage up to 1300 tones is transferred from the platform to the traverse, from the traverse to the repair posts R1-R5 and from the repair posts R6-R9 to the traverse (the broaching machine number 1 is used ($S_1$)),
- an operation state $z_2$ – the ship with a tonnage up to 1300 tones is transferred from the traverse to the repair posts R6-R9, from the repair posts R1-R5 to the traverse and from the traverse to the platform (the broaching machine number 3 is used ($S_3$)),
- an operation state $z_3$ – the ship with a tonnage up to 1300 tones is transferred from the repair posts R1-R5 to the traverse and the access to the broaching machine number 3 is difficult (the broaching machine number 2 is used ($S_2$)),
- an operation state $z_4$ – the ship with a tonnage over 1300 up to 1800 tones (or the ship with a tonnage up to 1300 tones after long period of renovation or after taking some special kind of measures) is transferred from the platform to the traverse, from the traverse to the repair posts R1-R5 or from the repair posts R6-R9 to the traverse (the broaching machines 1 and 3 are used ($S_1$, $S_3$)),
- an operation state $z_5$ – the ship with a tonnage over 1300 up to 1800 tones (or the ship with a tonnage up to 1300 tones after long period of renovation or after taking some special kind of measures) is transferred from the platform to the traverse, from the traverse to the repair posts R1-R5 or from the repair posts R6-R9 to the traverse and the access to the broaching machine number 3 is difficult (the broaching machines 1 and 2 are used ($S_1$, $S_2$)),
- an operation state $z_6$ – the ship with a tonnage over 1300 up to 1800 tones (or the ship with a tonnage up to 1300 tones after long period of renovation or after taking some special kind of measures) is transferred from the traverse to the repair posts R6-R9, from the repair posts R1-R5 to the traverse or from the traverse to the platform (the broaching machines 2 and 3 are used ($S_2$, $S_3$)),
- an operation state $z_7$ – the ship with a tonnage over 1800 tones is transferred (all broaching machines 1, 2 and 3 are used ($S_1$, $S_2$, $S_3$)).

At the system operational state $z_1$ the system is composed of subsystem $S_1$. The ship is transferred using the broaching machine number 1 and the scheme of the ground ship-rope transporter at the operational state $z_1$ is showed in *Figure 22*.

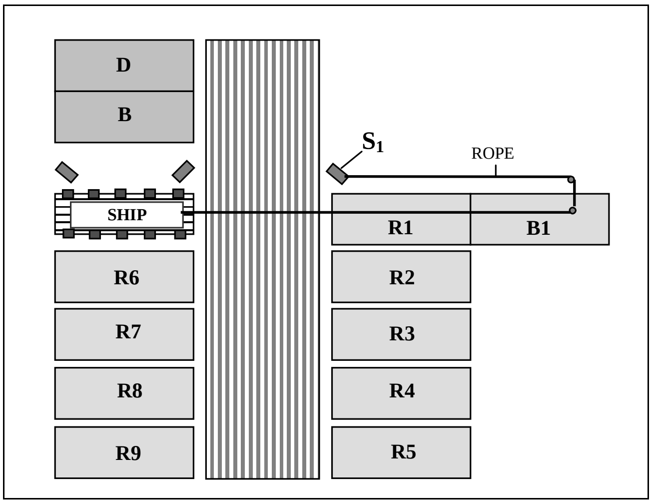


*Figure 22.* The scheme of the ground ship-rope transporter at the operational state $z_1$

At the system operational state $z_2$ the system is composed of subsystem $S_3$. The ship is transferred using the broaching machine number 3 and the scheme of the ground ship-rope transporter at the operational state $z_2$ is showed in *Figure 23*.

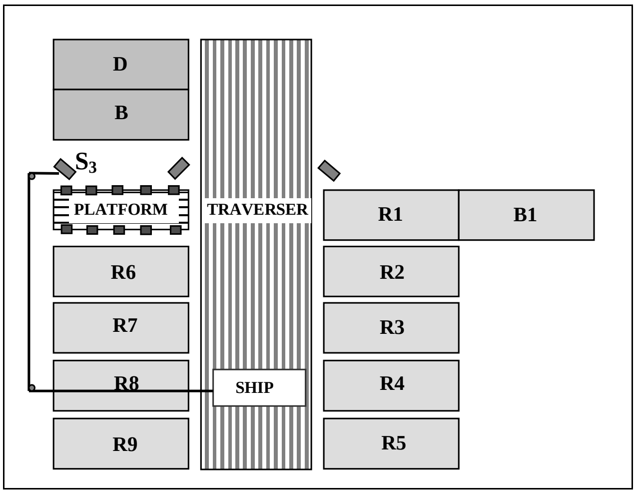


*Figure 23.* The scheme of the ground ship-rope transporter at the operational state $z_2$

At the system operational state $z_3$ the system is composed of subsystem $S_2$. The ship is transferred using the broaching machine number 2 and the scheme of the ground ship-rope transporter at the operational state $z_3$ is showed in *Figure 24*.

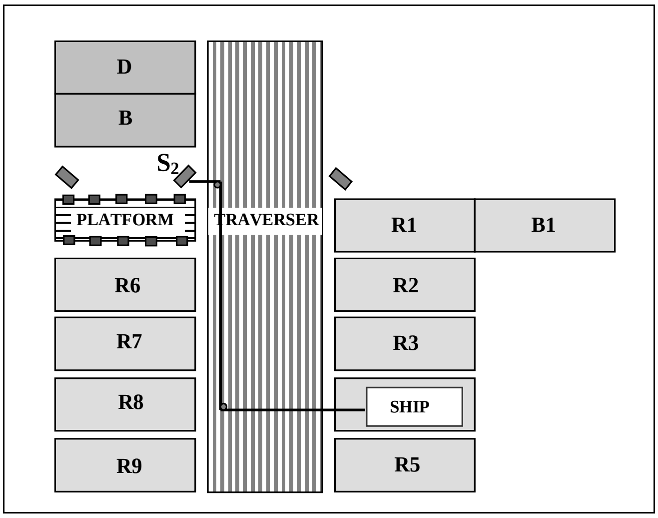


*Figure 24.* The scheme of the ground ship-rope transporter at the operational state $z_3$

At the system operational state $z_4$ the system is composed of subsystems $S_1$ and $S_3$ linked in series. 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 $z_4$ is showed in *Figure 25*.

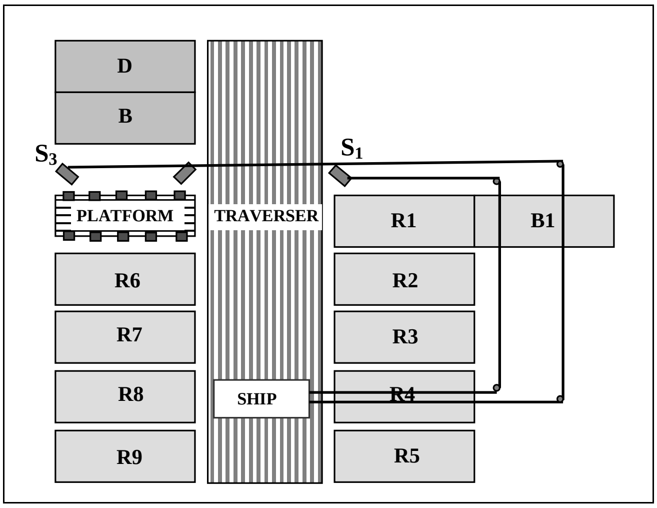


*Figure 25.* The scheme of the ground ship-rope transporter at the operational state $z_4$

At the system operational state $z_5$ 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 $z_5$ is showed in *Figure 26*.

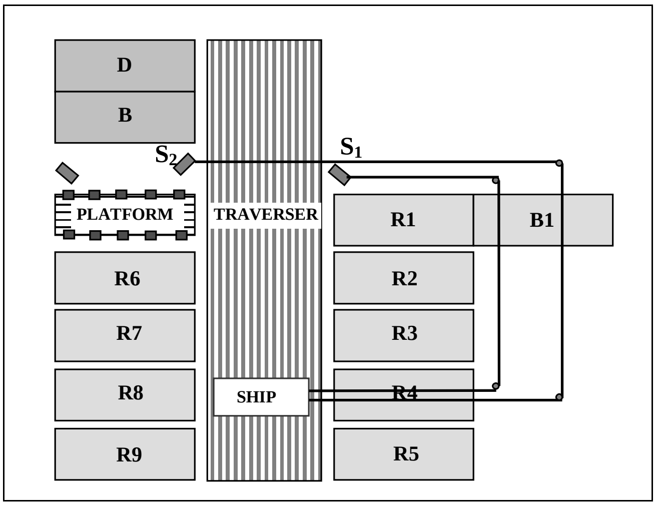


*Figure 26.* The scheme of the ground ship-rope transporter at the operational state $z_5$

At the system operational state $z_6$ the system is composed of subsystems $S_2$ and $S_3$ linked in series. The ship is transferred using the broaching machines number 2 and 3 and the scheme of the ground ship-rope transporter at the operational state $z_6$ is showed in *Figure 27*.

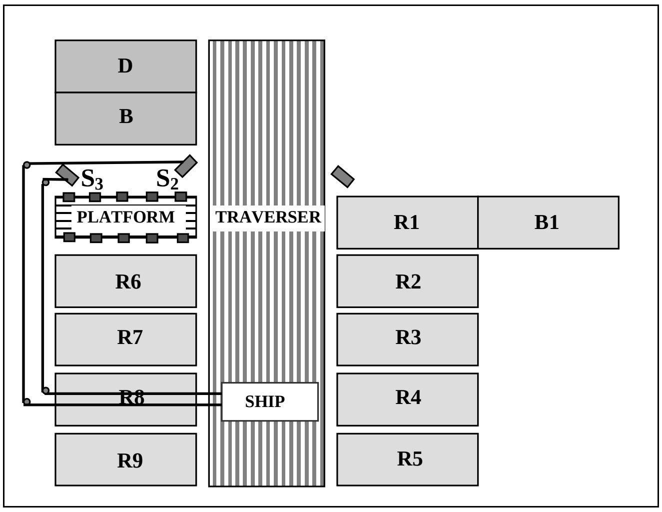


*Figure 27.* The scheme of the ground ship-rope transporter at the operational state $z_6$

At the system operational state $z_7$ the system is composed of subsystems $S_1$, $S_2$ and $S_3$ linked in series. The ship is transferred using all three broaching machines 1, 2 and 3 and the scheme of the ground ship-rope transporter at the operational state $z_7$ is showed in *Figure 28*.

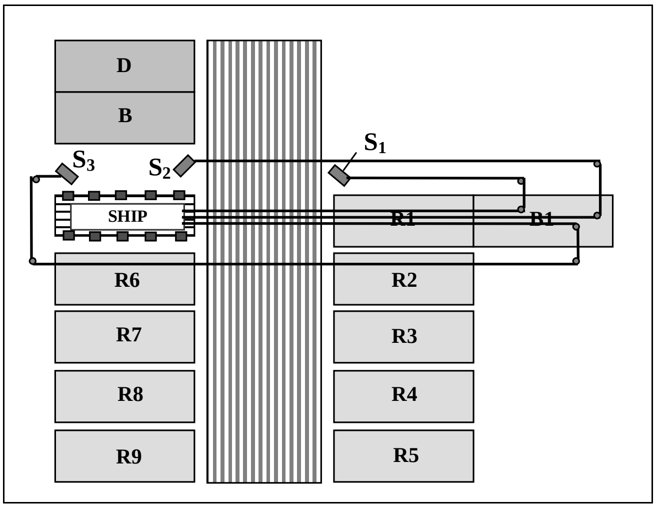


*Figure 28.* The scheme of the ground ship-rope transporter at the operational state $z_7$

## 5.3.2. The parameters of the shipyard ground ship-rope transporter components multi-state reliability models

According to rope reliability data given in their technical certificates, experts' opinions and taking into account the safety of the operation of the ground ship-rope transporter in all operation states $z_b$, $b = 1,2,...,7,$ we distinguish the following four reliability states $(z = 3)$ of the system and its components:

- 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).

Moreover, we fix that there are possible the transitions between the components reliability states only from better to worse ones.

From the above, the ground ship-rope transporter $S_k$, $k = 1,2,3,$ are composed of four-state, i.e. $z$ = 3, components $E_{ij}^{(k)}$, $k = 1,2,3,$ with the conditional multi-state reliability functions

$$[R_{ij}^{(k)}(t,\cdot)]^{(b)} = [1,[R_{ij}^{(k)}(t,1)]^{(b)},[R_{ij}^{(k)}(t,2)]^{(b)}],$$

$$b = 1,2,...,7,$$

with exponential co-ordinates $[R_{ij}^{(k)}(t,1)]^{(b)}$, $[R_{ij}^{(k)}(t,2)]^{(b)}$ and $[R_{ij}^{(k)}(t,3)]^{(b)}$ different in various operation states $z_b$, $b = 1,2,...,7.$

More precisely, from the performed in Section 3.4.2 analysis, the unknown reliability parameters of the system components reliability models in various system operation states are:

i) at the system operation states $z_1$ :

- the reliability functions of the subsystem $S_1$ components

$$[R_{ij}^{(1)}(t,\cdot)]^{(1)}$$

$$= [1,[R_{ij}^{(1)}(t,1)]^{(1)},[R_{ij}^{(1)}(t,2)]^{(1)},[R_{ij}^{(1)}(t,3)]^{(1)}],$$

$$i = 1,2,...,6 \quad j = 1,2,...,36,$$

coordinates

$$[R_{ij}^{(1)}(t,1)]^{(1)} = \exp[-[\lambda_{ij}^{(1)}(1)]^{(1)} t],$$

$$[R_{ij}^{(1)}(t,2)]^{(1)} = \exp[-[\lambda_{ij}^{(1)}(2)]^{(1)} t],$$

$$[R_{ij}^{(1)}(t,3)]^{(1)} = \exp[-[\lambda_{ij}^{(1)}(3)]^{(1)} t],$$

$$i = 1,2,...,6, \; j = 1,2,...,36,$$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$$[\lambda_{ij}^{(1)}(1)]^{(1)},\ [\lambda_{ij}^{(1)}(2)]^{(1)},\ [\lambda_{ij}^{(1)}(3)]^{(1)},$$

$$i = 1,2,...,6,\ \ j = 1,2,...,36;$$

ii) at the system operation states $z_2$:

- the reliability functions of the subsystem $S_3$ components

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

$$i = 1,2,...,6\ \ \ j = 1,2,...,36,$$

coordinates

$$[R_{ij}^{(3)}(t,1)]^{(2)} = \exp[-[\lambda_{ij}^{(3)}(1)]^{(2)}t],$$

$$[R_{ij}^{(3)}(t,2)]^{(2)} = \exp[-[\lambda_{ij}^{(3)}(2)]^{(2)}t],$$

$$[R_{ij}^{(3)}(t,3)]^{(2)} = \exp[-[\lambda_{ij}^{(3)}(3)]^{(2)}t],$$

$$i = 1,2,...,6,\ \ j = 1,2,...,36,$$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$$[\lambda_{ij}^{(3)}(1)]^{(2)},\ [\lambda_{ij}^{(3)}(2)]^{(2)},\ [\lambda_{ij}^{(3)}(3)]^{(2)},$$

$$i = 1,2,...,6,\ \ j = 1,2,...,36;$$

iii) at the system operation states $z_3$:

- the reliability functions of the subsystem $S_2$ components

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

$$i = 1,2,...,6\ \ \ j = 1,2,...,36,$$

coordinates

$$[R_{ij}^{(2)}(t,1)]^{(3)} = \exp[-[\lambda_{ij}^{(2)}(1)]^{(3)}t],$$

$$[R_{ij}^{(2)}(t,2)]^{(3)} = \exp[-[\lambda_{ij}^{(2)}(2)]^{(3)}t],$$

$$[R_{ij}^{(2)}(t,3)]^{(3)} = \exp[-[\lambda_{ij}^{(2)}(3)]^{(3)}t],$$

$$i = 1,2,...,6,\ \ j = 1,2,...,36,$$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$$[\lambda_{ij}^{(2)}(1)]^{(3)},\ [\lambda_{ij}^{(2)}(2)]^{(3)},\ [\lambda_{ij}^{(2)}(3)]^{(3)},$$

$$i = 1,2,...,6\ \ \ j = 1,2,...,36;$$

iv) at the system operation states $z_4$:

- the reliability functions of the subsystem $S_1$ components

$$[R_{ij}^{(1)}(t,\cdot)]^{(4)}$$
$$= [1, [R_{ij}^{(1)}(t,1)]^{(4)}, [R_{ij}^{(1)}(t,2)]^{(4)}, [R_{ij}^{(1)}(t,3)]^{(4)}],$$

$$i = 1,2,...,6,\ \ j = 1,2,...,36,$$

coordinates

$$[R_{ij}^{(1)}(t,1)]^{(4)} = \exp[-[\lambda_{ij}^{(1)}(1)]^{(4)}t],$$

$$[R_{ij}^{(1)}(t,2)]^{(4)} = \exp[-[\lambda_{ij}^{(1)}(2)]^{(4)}t],$$

$$[R_{ij}^{(1)}(t,3)]^{(4)} = \exp[-[\lambda_{ij}^{(1)}(3)]^{(4)}t],$$

$$i = 1,2,...,6,\ \ j = 1,2,...,36,$$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$$[\lambda_{ij}^{(1)}(1)]^{(4)},\ [\lambda_{ij}^{(1)}(2)]^{(4)},\ [\lambda_{ij}^{(1)}(3)]^{(4)},$$

$$i = 1,2,...,6,\ \ j = 1,2,...,36,$$

- the reliability functions of the subsystem $S_3$ components

$$[R_{ij}^{(3)}(t,\cdot)]^{(4)}$$
$$= [1, [R_{ij}^{(3)}(t,1)]^{(4)}, [R_{ij}^{(3)}(t,2)]^{(4)}, [R_{ij}^{(3)}(t,3)]^{(4)}],$$
$$i = 1,2,...,6,\ \ j = 1,2,...,36,$$

coordinates

$[R_{ij}^{(3)}(t,1)]^{(4)} = \exp[-[\lambda_{ij}^{(3)}(1)]^{(4)} t]$,

$[R_{ij}^{(3)}(t,2)]^{(4)} = \exp[-[\lambda_{ij}^{(3)}(2)]^{(4)} t]$,

$[R_{ij}^{(3)}(t,3)]^{(4)} = \exp[-[\lambda_{ij}^{(3)}(3)]^{(4)} t]$,

$i = 1,2,\ldots,6, \quad j = 1,2,\ldots,36,$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(3)}(1)]^{(4)}$, $[\lambda_{ij}^{(3)}(2)]^{(4)}$, $[\lambda_{ij}^{(3)}(3)]^{(4)}$,

$i = 1,2,\ldots,6, \quad j = 1,2,\ldots,36;$

v) at the system operation states $z_5$:

- the reliability functions of the subsystem $S_1$ components

$$[R_{ij}^{(1)}(t,\cdot)]^{(5)} = [1, [R_{ij}^{(1)}(t,1)]^{(5)}, [R_{ij}^{(1)}(t,2)]^{(5)}, [R_{ij}^{(1)}(t,3)]^{(5)}],$$

$i = 1,2,\ldots,6, \quad j = 1,2,\ldots,36,$

coordinates

$[R_{ij}^{(1)}(t,1)]^{(5)} = \exp[-[\lambda_{ij}^{(1)}(1)]^{(5)} t]$,

$[R_{ij}^{(1)}(t,2)]^{(5)} = \exp[-[\lambda_{ij}^{(1)}(2)]^{(5)} t]$,

$[R_{ij}^{(1)}(t,3)]^{(5)} = \exp[-[\lambda_{ij}^{(1)}(3)]^{(5)} t]$,

$i = 1,2,\ldots,6, \quad j = 1,2,\ldots,36,$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(1)}(1)]^{(5)}$, $[\lambda_{ij}^{(1)}(2)]^{(5)}$, $[\lambda_{ij}^{(1)}(3)]^{(5)}$,

$i = 1,2,\ldots,6, \quad j = 1,2,\ldots,36,$

- the reliability functions of the subsystem $S_2$ components

$$[R_{ij}^{(2)}(t,\cdot)]^{(5)} = [1, [R_{ij}^{(2)}(t,1)]^{(5)}, [R_{ij}^{(2)}(t,2)]^{(5)}, [R_{ij}^{(2)}(t,3)]^{(5)}],$$

$i = 1,2,\ldots,6, \quad j = 1,2,\ldots,36,$

coordinates

$[R_{ij}^{(2)}(t,1)]^{(5)} = \exp[-[\lambda_{ij}^{(2)}(1)]^{(5)} t]$,

$[R_{ij}^{(2)}(t,2)]^{(5)} = \exp[-[\lambda_{ij}^{(2)}(2)]^{(5)} t]$,

$[R_{ij}^{(2)}(t,3)]^{(5)} = \exp[-[\lambda_{ij}^{(2)}(3)]^{(5)} t]$,

$i = 1,2,\ldots,6, \quad j = 1,2,\ldots,36,$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(2)}(1)]^{(5)}$, $[\lambda_{ij}^{(2)}(2)]^{(5)}$, $[\lambda_{ij}^{(2)}(3)]^{(5)}$,

$i = 1,2,\ldots,6, \quad j = 1,2,\ldots,36;$

vi) at the system operation states $z_6$:

- the reliability functions of the subsystem $S_2$ components

$$[R_{ij}^{(2)}(t,\cdot)]^{(6)} = [1, [R_{ij}^{(2)}(t,1)]^{(6)}, [R_{ij}^{(2)}(t,2)]^{(6)}, [R_{ij}^{(2)}(t,3)]^{(6)}],$$

$i = 1,2,\ldots,6, \quad j = 1,2,\ldots,36,$

coordinates

$[R_{ij}^{(2)}(t,1)]^{(6)} = \exp[-[\lambda_{ij}^{(2)}(1)]^{(6)} t]$,

$[R_{ij}^{(2)}(t,2)]^{(6)} = \exp[-[\lambda_{ij}^{(2)}(2)]^{(6)} t]$,

$[R_{ij}^{(2)}(t,3)]^{(6)} = \exp[-[\lambda_{ij}^{(2)}(3)]^{(6)} t]$,

$i = 1,2,\ldots,6, \quad j = 1,2,\ldots,36,$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(2)}(1)]^{(6)}$, $[\lambda_{ij}^{(2)}(2)]^{(6)}$, $[\lambda_{ij}^{(2)}(3)]^{(6)}$,

$i = 1,2,...,6, \quad j = 1,2,...,36,$

- the reliability functions of the subsystem $S_3$ components

$$[R_{ij}^{(3)}(t,\cdot)]^{(6)}$$
$$= [1, [R_{ij}^{(3)}(t,1)]^{(6)}, [R_{ij}^{(3)}(t,2)]^{(6)}, [R_{ij}^{(3)}(t,3)]^{(6)}],$$

$i = 1,2,...,6, \quad j = 1,2,...,36,$

coordinates

$$[R_{ij}^{(3)}(t,1)]^{(6)} = \exp[-[\lambda_{ij}^{(3)}(1)]^{(6)} t],$$

$$[R_{ij}^{(3)}(t,2)]^{(6)} = \exp[-[\lambda_{ij}^{(3)}(2)]^{(6)} t],$$

$$[R_{ij}^{(3)}(t,3)]^{(6)} = \exp[-[\lambda_{ij}^{(3)}(3)]^{(6)} t],$$

$i = 1,2,...,6, \quad j = 1,2,...,36,$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$$[\lambda_{ij}^{(3)}(1)]^{(6)}, [\lambda_{ij}^{(3)}(2)]^{(6)}, [\lambda_{ij}^{(3)}(3)]^{(6)},$$

$i = 1,2,...,6, \quad j = 1,2,...,36;$

vii) at the system operation states $z_7$:
- the reliability functions of the subsystem $S_1$ components

$$[R_{ij}^{(1)}(t,\cdot)]^{(7)}$$
$$= [1, [R_{ij}^{(1)}(t,1)]^{(7)}, [R_{ij}^{(1)}(t,2)]^{(7)}, [R_{ij}^{(1)}(t,3)]^{(7)}],$$

$i = 1,2,...,6, \quad j = 1,2,...,36,$

coordinates

$$[R_{ij}^{(1)}(t,1)]^{(7)} = \exp[-[\lambda_{ij}^{(1)}(1)]^{(7)} t],$$

$$[R_{ij}^{(1)}(t,2)]^{(7)} = \exp[-[\lambda_{ij}^{(1)}(2)]^{(7)} t],$$

$$[R_{ij}^{(1)}(t,3)]^{(7)} = \exp[-[\lambda_{ij}^{(1)}(3)]^{(7)} t],$$

$i = 1,2,...,6, \quad j = 1,2,...,36,$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$$[\lambda_{ij}^{(1)}(1)]^{(7)}, [\lambda_{ij}^{(1)}(2)]^{(7)}, [\lambda_{ij}^{(1)}(3)]^{(7)},$$

$i = 1,2,...,6, \quad j = 1,2,...,36,$

- the reliability functions of the subsystem $S_2$ components

$$[R_{ij}^{(2)}(t,\cdot)]^{(7)}$$
$$= [1, [R_{ij}^{(2)}(t,1)]^{(7)}, [R_{ij}^{(2)}(t,2)]^{(7)}, [R_{ij}^{(2)}(t,3)]^{(7)}],$$

$i = 1,2,...,6, \quad j = 1,2,...,36,$

coordinates

$$[R_{ij}^{(2)}(t,1)]^{(7)} = \exp[-[\lambda_{ij}^{(2)}(1)]^{(7)} t],$$

$$[R_{ij}^{(2)}(t,2)]^{(7)} = \exp[-[\lambda_{ij}^{(2)}(2)]^{(7)} t],$$

$$[R_{ij}^{(2)}(t,3)]^{(7)} = \exp[-[\lambda_{ij}^{(2)}(3)]^{(7)} t],$$

$i = 1,2,...,6, \quad j = 1,2,...,36,$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$$[\lambda_{ij}^{(2)}(1)]^{(7)}, [\lambda_{ij}^{(2)}(2)]^{(7)}, [\lambda_{ij}^{(2)}(3)]^{(7)},$$

$i = 1,2,...,6, \quad j = 1,2,...,36,$

- the reliability functions of the subsystem $S_3$ components

$$[R_{ij}^{(3)}(t,\cdot)]^{(7)}$$
$$= [1, [R_{ij}^{(3)}(t,1)]^{(7)}, [R_{ij}^{(3)}(t,2)]^{(7)}, [R_{ij}^{(3)}(t,3)]^{(7)}],$$

$i = 1,2,...,6, \quad j = 1,2,...,36,$

coordinates

$$[R_{ij}^{(3)}(t,1)]^{(7)} = \exp[-[\lambda_{ij}^{(3)}(1)]^{(7)} t],$$

$$[R_{ij}^{(3)}(t,2)]^{(7)} = \exp[-[\lambda_{ij}^{(3)}(2)]^{(7)} t],$$

$$[R_{ij}^{(3)}(t,3)]^{(7)} = \exp[-[\lambda_{ij}^{(3)}(3)]^{(7)} t],$$
$i = 1,2,...,6, \quad j = 1,2,...,36,$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(3)}(1)]^{(7)}$, $[\lambda_{ij}^{(3)}(2)]^{(7)}$, $[\lambda_{ij}^{(3)}(3)]^{(7)}$,

$i = 1,2,...,6, \quad j = 1,2,...,36.$

### 5.3.3. The shipyard ground ship-rope transporter components reliability data collection

#### 5.3.3.1. Data coming from experts

In the *Tables 6-8* there are given the approximate realizations

$[\hat{\mu}_{ij}^{(k)}(u)]^{(b)}$, $k = 1,2,3$, $u = 1,2,3$, $b = 1,2,...,7$,

of the mean values

$[\mu_{ij}^{(k)}(u)]^{(b)} = E[[T_{ij}^{(k)}(u)]^{(b)}]$, $k = 1,2,3$,

$u = 1,2,3$, $b = 1,2,...,7$,

of the conditional lifetimes $[T_{ij}^{(k)}(u)]^{(b)}$, $k = 1,2,3$, $u = 1,2,3$, $b = 1,2,...,7$, in reliability states of the component $E_{ij}^{(k)}$ of the shipyard ground ship-rope transporter subsystems $S_k$, $k = 1,2,3$, in particular operation states $z_b$, $b = 1,2,...,7$, estimated on the basis of the expert opinions.

*Table 6.* The approximate mean values $[\hat{\mu}_{ij}^{(1)}(u)]^{(b)}$ of the subsystem $S_1$ components (wires) conditional lifetimes $[T_{ij}^{(1)}(u)]^{(b)}$ in particular operation states $z_b$

| Subsystem $S_1$ components (wires) | $E_{ij}^{(1)}$ $i = 1,2,...,6,$ $j = 1,2,...,36,$ $u = 1$ | $E_{ij}^{(1)}$ $i = 1,2,...,6,$ $j = 1,2,...,36,$ $u = 2$ | $E_{ij}^{(1)}$ $i = 1,2,...,6,$ $j = 1,2,...,36,$ $u = 3$ |
|---|---|---|---|
| Operation state $z_b$ | The mean values $[\hat{\mu}_{ij}^{(1)}(u)]^{(b)}$ of the conditional lifetimes $[T_{ij}^{(1)}(u)]^{(b)}$ of the component $E_{ij}^{(1)}$ (*in years*) | | |
| $z_1$ | 63 | 43 | 26 |
| $z_2$ | | | |
| $z_3$ | | | |
| $z_4$ | 57 | 28 | 18 |
| $z_5$ | 57 | 28 | 18 |
| $z_6$ | | | |
| $z_7$ | 46 | 25 | 16 |

*Table 7.* The approximate mean values $[\hat{\mu}_{ij}^{(2)}(u)]^{(b)}$ of the subsystem $S_2$ components (wires) conditional lifetimes $[T_{ij}^{(2)}(u)]^{(b)}$ in particular operation states $z_b$

| Subsystem $S_2$ components (wires) | $E_{ij}^{(2)}$ $i = 1,2,...,6,$ $j = 1,2,...,36,$ $u = 1$ | $E_{ij}^{(2)}$ $i = 1,2,...,6,$ $j = 1,2,...,36,$ $u = 2$ | $E_{ij}^{(2)}$ $i = 1,2,...,6,$ $j = 1,2,...,36,$ $u = 3$ |
|---|---|---|---|
| Operation state $z_b$ | The mean values $[\hat{\mu}_{ij}^{(2)}(u)]^{(b)}$ of the conditional lifetimes $[T_{ij}^{(2)}(u)]^{(b)}$ of the component $E_{ij}^{(2)}$ (*in years*) | | |
| $z_1$ | | | |
| $z_2$ | | | |
| $z_3$ | 63 | 43 | 26 |

| | | | |
|---|---|---|---|
| $z_4$ | | | |
| $z_5$ | 57 | 28 | 18 |
| $z_6$ | 57 | 28 | 18 |
| $z_7$ | 46 | 25 | 16 |

*Table 8.* The approximate mean values $[\hat{\mu}_{ij}^{(3)}(u)]^{(b)}$ of the subsystem $S_3$ components (wires) conditional lifetimes $[T_{ij}^{(3)}(u)]^{(b)}$ in particular operation states $z_b$

| Subsystem $S_3$ components (wires) | $E_{ij}^{(3)}$ $i=1,2,...,6,$ $j=1,2,...,36,$ $u=1$ | $E_{ij}^{(3)}$ $i=1,2,...,6,$ $j=1,2,...,36,$ $u=2$ | $E_{ij}^{(3)}$ $i=1,2,...,6,$ $j=1,2,...,36,$ $u=3$ |
|---|---|---|---|
| Operation state $z_b$ | The mean values $[\hat{\mu}_{ij}^{(3)}(u)]^{(b)}$ of the conditional lifetimes $[T_{ij}^{(3)}(u)]^{(b)}$ of the component $E_{ij}^{(3)}$ (*in years*) | | |
| $z_1$ | | | |
| $z_2$ | 63 | 43 | 26 |
| $z_3$ | | | |
| $z_4$ | 57 | 28 | 18 |
| $z_5$ | | | |
| $z_6$ | 57 | 28 | 18 |
| $z_7$ | 46 | 25 | 16 |

#### 5.3.3.2 Data coming from components reliability states changing processes

There are no data collected from the shipyard ground ship-rope transporter components reliability states changing processes.

### 5.3.4. Statistical identification of the shipyard ground ship-rope transporter components reliability

#### 5.3.4.1. Statistical identification of the shipyard ground ship-rope transporter components reliability on the basis of data coming from experts

To identify the parameters of multistate reliability functions of the shipyard ground ship-rope transporter components the statistical data coming from their failure processes are needed. The statistical data that has been collected are given in *Tables 6-8*.

From data given in the *Tables 6-8,* on the basis of the resulting from (8) formula

$$[\hat{\lambda}_{ij}^{(k)}(u)]^{(b)} = \frac{1}{[\hat{\mu}_{ij}^{(k)}(u)]^{(b)}},\ k=1,2,3,\ \ u=1,2,3,$$

$$b=1,2,...,7,$$

we get the approximate values $[\hat{\lambda}_{ij}^{(k)}(u)]^{(b)}$ of the subsystems $S_k$, $k=1,2,3,$ components unknown intensities $[\lambda_{ij}^{(k)}(u)]^{(b)}$ of departure from the reliability states subset $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, while the system is operating in the operation state $z_b$, $b=1,2,...,7.$ The results are presented below.

At the system operational state $z_1$ the system is composed of subsystem $S_1$. The ship is transferred using the broaching machine number 1 and the scheme of the ground ship-rope transporter at the operational state $z_1$ is showed in *Figure 22*.

The subsystem $S_1$ is composed of 6 identical strands and each strand consists of 36 wires with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(1)}(1)]^{(1)}$ = 0.0159, $[\lambda_{ij}^{(1)}(2)]^{(1)}$ = 0.0233,

$[\lambda_{ij}^{(1)}(3)]^{(1)} = 0.0385, \ i = 1,2,...,6, \ \ j = 1,2,...,36.$

At the system operational state $z_2$ the system is composed of subsystem $S_3$. The ship is transferred using the broaching machine number 3 and the scheme of the ground ship-rope transporter at the operational state $z_2$ is showed in *Figure 23*.

The subsystem $S_3$ is composed of 6 identical strands and each strand consists of 36 wires with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(3)}(1)]^{(2)} = 0.0159, \ [\lambda_{ij}^{(3)}(2)]^{(2)} = 0.0233,$

$[\lambda_{ij}^{(3)}(3)]^{(2)} = 0.0385, \ i = 1,2,...,6, \ \ j = 1,2,...,36.$

At the system operational state $z_3$ the system is composed of subsystem $S_2$. The ship is transferred using the broaching machine number 2 and the scheme of the ground ship-rope transporter at the operational state $z_3$ is showed in *Figure 24*.

The subsystem $S_2$ is composed of 6 identical strands and each strand consists of 36 wires with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(2)}(1)]^{(3)} = 0.0159, \ [\lambda_{ij}^{(2)}(2)]^{(3)} = 0.0233,$

$[\lambda_{ij}^{(2)}(3)]^{(3)} = 0.0385, \ i = 1,2,...,6, \ \ j = 1,2,...,36.$

At the system operational state $z_4$ the system is composed of subsystems $S_1$ and $S_3$ linked in series. 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 $z_4$ is showed in *Figure 25*.

The subsystem $S_1$ is composed of 6 identical strands and each strand consists of 36 wires with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(1)}(1)]^{(4)} = 0.0175, \ [\lambda_{ij}^{(1)}(2)]^{(4)} = 0.0357,$

$[\lambda_{ij}^{(1)}(3)]^{(4)} = 0.0556, \ i = 1,2,...,6, \ \ j = 1,2,...,36.$

The subsystem $S_3$ is composed of 6 identical strands and each strand consists of 36 wires with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(3)}(1)]^{(4)} = 0.0175, \ [\lambda_{ij}^{(3)}(2)]^{(4)} = 0.0357,$

$[\lambda_{ij}^{(3)}(3)]^{(4)} = 0.0556, \ i = 1,2,...,6, \ \ j = 1,2,...,36.$

At the system operational state $z_5$ 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 $z_5$ is showed in *Figure 26*.

The subsystem $S_1$ is composed of 6 identical strands and each strand consists of 36 wires with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(1)}(1)]^{(5)} = 0.0175, \ [\lambda_{ij}^{(1)}(2)]^{(5)} = 0.0357,$

$[\lambda_{ij}^{(1)}(3)]^{(5)} = 0.0556, \ i = 1,2,...,6, \ \ j = 1,2,...,36.$

The subsystem $S_2$ is composed of 6 identical strands and each strand consists of 36 wires with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(2)}(1)]^{(5)} = 0.0175, \ [\lambda_{ij}^{(2)}(2)]^{(5)} = 0.0357,$

$[\lambda_{ij}^{(2)}(3)]^{(5)} = 0.0556, \ i = 1,2,...,6, \ \ j = 1,2,...,36.$

At the system operational state $z_6$ the system is composed of subsystems $S_2$ and $S_3$ linked in series. The ship is transferred using the broaching machines number 2 and 3 and the scheme of the ground ship-rope transporter at the operational state $z_6$ is showed in *Figure 27*.

The subsystem $S_2$ is composed of 6 identical strands and each strand consists of 36 wires with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(2)}(1)]^{(6)} = 0.0175, \ [\lambda_{ij}^{(2)}(2)]^{(6)} = 0.0357,$

$[\lambda_{ij}^{(2)}(3)]^{(5)} = 0.0556, \ i = 1,2,...,6, \ \ j = 1,2,...,36.$

The subsystem $S_3$ is composed of 6 identical strands and each strand consists of 36 wires with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(3)}(1)]^{(6)} = 0.0175$, $[\lambda_{ij}^{(3)}(2)]^{(6)} = 0.0357$,

$[\lambda_{ij}^{(3)}(3)]^{(5)} = 0.0556$, $i = 1,2,...,6$, $j = 1,2,...,36$.

At the system operational state $z_7$ the system is composed of subsystems $S_1$, $S_2$ and $S_3$ linked in series. The ship is transferred using all three broaching machines 1, 2 and 3 and the scheme of the ground ship-rope transporter at the operational state $z_7$ is showed in *Figure 28*.

The subsystem $S_1$ is composed of 6 identical strands and each strand consists of 36 wires with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(1)}(1)]^{(7)} = 0.0217$, $[\lambda_{ij}^{(1)}(2)]^{(7)} = 0.0400$,

$[\lambda_{ij}^{(1)}(3)]^{(7)} = 0.0625$, $i = 1,2,...,6$, $j = 1,2,...,36$.

The subsystem $S_2$ is composed of 6 identical strands and each strand consists of 36 wires with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(2)}(1)]^{(7)} = 0.0217$, $[\lambda_{ij}^{(2)}(2)]^{(7)} = 0.0400$,

$[\lambda_{ij}^{(2)}(3)]^{(7)} = 0.0625$, $i = 1,2,...,6$, $j = 1,2,...,36$.

The subsystem $S_3$ is composed of 6 identical strands and each strand consists of 36 wires with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(3)}(1)]^{(7)} = 0.0217$, $[\lambda_{ij}^{(3)}(2)]^{(7)} = 0.0400$,

$[\lambda_{ij}^{(3)}(3)]^{(7)} = 0.0625$, $i = 1,2,...,6$, $j = 1,2,...,36$.

### 5.3.4.2. Statistical identification of the shipyard ground ship-rope transporter components reliability on the basis of data coming from their reliability states changing processes

As there are no data collected from the system components failure processes their reliability models identification using the methods of Section 3.4,2 and Section 3.5 is not possible.

### 5.3.5. Identifying the shipyard ground ship-rope transporter components conditional multistate exponential reliability functions

As there are no data collected from the shipyard ground ship-rope transporter components reliability states changing processes, then it is not possible to verify the hypotheses on the exponential forms of the shipyard ground ship-rope transporter components conditional reliability functions. We arbitrarily assume that these reliability functions are exponential and using the results of the previous section and the relationships given in Section 5.3.2 we fix heir forms.

At the system operational state $z_1$ the system is composed of subsystem $S_1$. The ship is transferred using the broaching machine number 1 and the scheme of the ground ship-rope transporter at the operational state $z_1$ is showed in *Figure 22*.

The subsystem $S_1$ is composed of 6 identical strands and each strand consists of 36 wires with the conditional reliability functions co-ordinates

$[R_{ij}^{(1)}(t,1)]^{(1)} = \exp[-0.0159t]$,

$[R_{ij}^{(1)}(t,2)]^{(1)} = \exp[-0.0233t]$,

$[R_{ij}^{(1)}(t,3)]^{(1)} = \exp[-0.0385t]$,

$i = 1,2,...,6$, $j = 1,2,...,36$.

At the system operational state $z_2$ the system is composed of subsystem $S_3$. The ship is transferred using the broaching machine number 3 and the scheme of the ground ship-rope transporter at the operational state $z_2$ is showed in *Figure 23*.

The subsystem $S_3$ is composed of 6 identical strands and each strand consists of 36 wires with the conditional reliability functions co-ordinates

$[R_{ij}^{(3)}(t,1)]^{(2)} = \exp[-0.0159t]$,

$[R_{ij}^{(3)}(t,2)]^{(2)} = \exp[-0.0233t]$,

$[R_{ij}^{(3)}(t,3)]^{(2)} = \exp[-0.0385t]$,

$i = 1,2,...,6$, $j = 1,2,...,36$.

At the system operational state $z_3$ the system is composed of subsystem $S_2$. The ship is transferred using the broaching machine number 2 and the scheme of the ground ship-rope transporter at the operational state $z_3$ is showed in *Figure 24*.

The subsystem $S_2$ is composed of 6 identical strands and each strand consists of 36 wires with the conditional reliability functions co-ordinates

$$[R_{ij}^{(2)}(t,1)]^{(3)} = \exp[-0.0159t],$$

$$[R_{ij}^{(2)}(t,2)]^{(3)} = \exp[-0.0233t],$$

$$[R_{ij}^{(2)}(t,3)]^{(3)} = \exp[-0.0385t],$$

$$i = 1,2,...,6, \quad j = 1,2,...,36.$$

At the system operational state $z_4$ the system is composed of subsystems $S_1$ and $S_3$ linked in series. 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 $z_4$ is showed in *Figure 25*.

The subsystem $S_1$ is composed of 6 identical strands and each strand consists of 36 wires with the conditional reliability functions co-ordinates

$$[R_{ij}^{(1)}(t,1)]^{(4)} = \exp[-0.0175t],$$

$$[R_{ij}^{(1)}(t,2)]^{(4)} = \exp[-0.0357t],$$

$$[R_{ij}^{(1)}(t,3)]^{(4)} = \exp[-0.0556t],$$

$$i = 1,2,...,6, \quad j = 1,2,...,36.$$

The subsystem $S_3$ is composed of 6 identical strands and each strand consists of 36 wires with the conditional reliability functions co-ordinates

$$[R_{ij}^{(3)}(t,1)]^{(4)} = \exp[-0.0175t],$$

$$[R_{ij}^{(3)}(t,2)]^{(4)} = \exp[-0.0357t],$$

$$[R_{ij}^{(3)}(t,3)]^{(4)} = \exp[-0.0556t],$$

$$i = 1,2,...,6, \quad j = 1,2,...,36.$$

At the system operational state $z_5$ 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 $z_5$ is showed in *Figure 26*.

The subsystem $S_1$ is composed of 6 identical strands and each strand consists of 36 wires with the conditional reliability functions co-ordinates

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

$$[R_{ij}^{(1)}(t,2)]^{(5)} = \exp[-0.0357t],$$

$$[R_{ij}^{(1)}(t,3)]^{(5)} = \exp[-0.0556t],$$

$$i = 1,2,...,6, \quad j = 1,2,...,36.$$

The subsystem $S_2$ is composed of 6 identical strands and each strand consists of 36 wires with the conditional reliability functions co-ordinates

$$[R_{ij}^{(2)}(t,1)]^{(5)} = \exp[-0.0175t],$$

$$[R_{ij}^{(2)}(t,2)]^{(5)} = \exp[-0.0357t],$$

$$[R_{ij}^{(2)}(t,3)]^{(5)} = \exp[-0.0556t],$$

$$i = 1,2,...,6, \quad j = 1,2,...,36.$$

At the system operational state $z_6$ the system is composed of subsystems $S_2$ and $S_3$ linked in series. The ship is transferred using the broaching machines number 2 and 3 and the scheme of the ground ship-rope transporter at the operational state $z_6$ is showed in *Figure 27*.

The subsystem $S_2$ is composed of 6 identical strands and each strand consists of 36 wires with the conditional reliability functions co-ordinates

$$[R_{ij}^{(2)}(t,1)]^{(6)} = \exp[-0.0175t],$$

$$[R_{ij}^{(2)}(t,2)]^{(6)} = \exp[-0.0357t],$$

$$[R_{ij}^{(2)}(t,3)]^{(6)} = \exp[-0.0556t],$$

$$i = 1,2,...,6, \quad j = 1,2,...,36.$$

The subsystem $S_3$ is composed of 6 identical strands and each strand consists of 36 wires with the conditional reliability functions co-ordinates

$[R_{ij}^{(3)}(t,1)]^{(6)} = \exp[-0.0175t]$,

$[R_{ij}^{(3)}(t,2)]^{(6)} = \exp[-0.0357t]$,

$[R_{ij}^{(3)}(t,3)]^{(6)} = \exp[-0.0556t]$,

$i = 1,2,...,6, \quad j = 1,2,...,36.$

At the system operational state $z_7$ the system is composed of subsystems $S_1$, $S_2$ and $S_3$ linked in series. The ship is transferred using all three broaching machines 1, 2 and 3 and the scheme of the ground ship-rope transporter at the operational state $z_7$ is showed in *Figure 28*.

The subsystem $S_1$ is composed of 6 identical strands and each strand consists of 36 wires with the conditional reliability functions co-ordinates

$[R_{ij}^{(1)}(t,1)]^{(7)} = \exp[-0.0217t]$,

$[R_{ij}^{(1)}(t,2)]^{(7)} = \exp[-0.0400t]$,

$[R_{ij}^{(1)}(t,3)]^{(7)} = \exp[-0.0625t]$,

$i = 1,2,...,6, \quad j = 1,2,...,36.$

The subsystem $S_2$ is composed of 6 identical strands and each strand consists of 36 wires with the conditional reliability functions co-ordinates

$[R_{ij}^{(2)}(t,1)]^{(7)} = \exp[-0.0217t]$,

$[R_{ij}^{(2)}(t,2)]^{(7)} = \exp[-0.0400t]$,

$[R_{ij}^{(2)}(t,3)]^{(7)} = \exp[-0.0625t]$,

$i = 1,2,...,6, \quad j = 1,2,...,36.$

The subsystem $S_3$ is composed of 6 identical strands and each strand consists of 36 wires with the conditional reliability functions co-ordinates

$[R_{ij}^{(3)}(t,1)]^{(7)} = \exp[-0.0217t]$,

$[R_{ij}^{(3)}(t,2)]^{(7)} = \exp[-0.0400t]$,

$[R_{ij}^{(3)}(t,3)]^{(7)} = \exp[-0.0625t]$,

$i = 1,2,...,6, \quad j = 1,2,...,36.$

## 5.4. Statistical identification of an exemplary system components reliability models

### 5.4.1. The subsystems and components of the system in various operation states

The considered system $S$ consists of two subsystems $S_1$, $S_2$.

The subsystem $S_1$ is composed of two series subsystems, each of them composed of 3 components, denoted respectively by

$E_{ij}^{(1)}, \quad i = 1,2, \quad j = 1,2,3,$

with the structure presented in *Figure 29*.

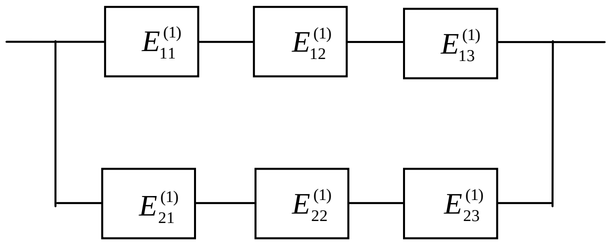


*Figure 29.* The scheme of the system $S_1$ structure

The subsystem $S_2$ is composed of four series subsystems, each of them composed of 2 components, denoted respectively by

$E_{ij}^{(2)}, \quad i = 1,2,3,4 \quad j = 1,2,$

with the structure presented in *Figure 30*

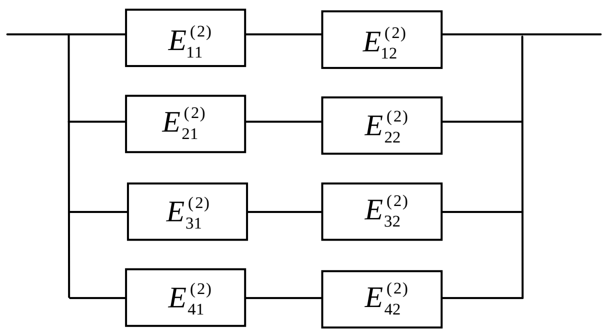


*Figure 30.* The scheme of the system $S_2$ structure

The subsystems $S_1$, $S_2$, illustrated in *Figures 29-30* are forming a series structure presented in *Figure 31*.

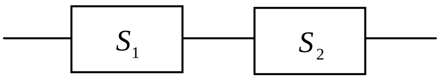


*Figure 31.* General scheme of the system $S$

However, the system structure and the subsystem components reliability depend on its changing in time operation states.

We arbitrarily fix the number of the pipeline system operation process states $\nu = 4$ and we mark its four operation states by $z_1$, $z_2$, $z_3$ and $z_4$.

At the system operational state $z_1$, the system is composed of the subsystem $S_1$, with the scheme showed in *Figure 29*, that is a series-parallel system.

At the system operational state $z_2$, the system is composed of the subsystem $S_2$, with the scheme showed in *Figure 30* that is a series-parallel system.

At the system operational state $z_3$, the system is composed of the subsystems $S_1$ and $S_2$, with the scheme showed in *Figure 31* that are series-parallel system with the schemes given in *Figures 29-30*.

At the system operational state $z_4$, the system is composed of the subsystem $S_1$ and $S_2$, with the scheme showed in *Figure 11*, while the subsystem $S_1$ is a series-parallel system with the scheme given in Figure 9 and the subsystem $S_2$ is series-“2 out of 4” system.

### 5.4.2. The parameters of the system components multi-state reliability models

In all operation states $z_b$, $b = 1,2,3,4,$ we distinguish the following four reliability states $(z = 3)$ of the system and its components:

- a reliability state 3 – the system operation is fully safe,
- a reliability state 2 – the system operation is less effective because of ageing,
- a reliability state 1 – the system operation is less effective because of ageing and more dangerous,
- a reliability state 0 – the system is destroyed.

Moreover, we fix that there are possible the transitions between the components reliability states only from better to worse ones.

From the above, the subsystems $S_k$, $k = 1,2,$ are composed of four-state, i.e. $z = 2$, components $E_{ij}^{(k)}$, $k = 1,2,$ with the conditional multi-state reliability functions

$$[R_{ij}^{(k)}(t,\cdot)]^{(b)}$$

$$= [1,\ [R_{ij}^{(k)}(t,1)]^{(b)}, [R_{ij}^{(k)}(t,2)]^{(b)}, [R_{ij}^{(k)}(t,3)]^{(b)}],$$

$$b = 1,2,3,4,$$

with exponential co-ordinates $[R_{ij}^{(k)}(t,1)]^{(b)}$, $[R_{ij}^{(k)}(t,2)]^{(b)}$ and $[R_{ij}^{(k)}(t,3)]^{(b)}$ different in various operation states $z_b$, $b = 1,2,3,4.$

More precisely, from the performed in Section 3.4.2 analysis, the unknown reliability parameters of the system components reliability models in various system operation states are:

i) at the system operation states $z_1$:

- the reliability functions of the subsystem $S_1$ components

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

$$i = 1,2, \quad j = 1,2,3,$$

coordinates

$$[R_{ij}^{(1)}(t,1)]^{(1)} = \exp[-[\lambda_{ij}^{(1)}(1)]^{(1)} t],$$

$$[R_{ij}^{(1)}(t,2)]^{(1)} = \exp[-[\lambda_{ij}^{(1)}(2)]^{(1)} t],$$

$$[R_{ij}^{(1)}(t,3)]^{(1)} = \exp[-[\lambda_{ij}^{(1)}(3)]^{(1)} t],$$

$$i = 1,2, \quad j = 1,2,3,$$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$$[\lambda_{ij}^{(1)}(1)]^{(1)},\ [\lambda_{ij}^{(1)}(2)]^{(1)},\ [\lambda_{ij}^{(1)}(3)]^{(1)},$$

$$i = 1,2, \quad j = 1,2,3,$$

ii) at the system operation states $z_2$:

- the reliability functions of the subsystem $S_2$ components

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

$$i = 1,2,3,4 \quad j = 1,2,$$

coordinates

$[R_{ij}^{(2)}(t,1)]^{(2)} = \exp[-[\lambda_{ij}^{(2)}(1)]^{(2)} t]$,

$[R_{ij}^{(2)}(t,2)]^{(2)} = \exp[-[\lambda_{ij}^{(2)}(2)]^{(2)} t]$,

$[R_{ij}^{(2)}(t,3)]^{(2)} = \exp[-[\lambda_{ij}^{(2)}(3)]^{(2)} t]$,

$i = 1,2,3,4 \quad j = 1,2,$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(2)}(1)]^{(2)}$, $[\lambda_{ij}^{(2)}(2)]^{(2)}$, $[\lambda_{ij}^{(2)}(3)]^{(2)}$,

$i = 1,2,3,4 \quad j = 1,2,$

iii) at the system operation states $z_3$:

- the reliability functions of the subsystem $S_1$ components

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

$i = 1,2, \quad j = 1,2,3,$

coordinates

$[R_{ij}^{(1)}(t,1)]^{(3)} = \exp[-[\lambda_{ij}^{(1)}(1)]^{(3)} t]$,

$[R_{ij}^{(1)}(t,2)]^{(3)} = \exp[-[\lambda_{ij}^{(1)}(2)]^{(3)} t]$,

$[R_{ij}^{(1)}(t,3)]^{(3)} = \exp[-[\lambda_{ij}^{(1)}(3)]^{(3)} t]$,

$i = 1,2, \quad j = 1,2,3,$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(1)}(1)]^{(3)}$, $[\lambda_{ij}^{(1)}(2)]^{(3)}$, $[\lambda_{ij}^{(1)}(3)]^{(3)}$,

$i = 1,2, \quad j = 1,2,3,$

- the reliability functions of the subsystem $S_2$ components

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

$i = 1,2,3,4 \quad j = 1,2,$

coordinates

$[R_{ij}^{(2)}(t,1)]^{(3)} = \exp[-[\lambda_{ij}^{(2)}(1)]^{(3)} t]$,

$[R_{ij}^{(2)}(t,2)]^{(3)} = \exp[-[\lambda_{ij}^{(2)}(2)]^{(3)} t]$,

$[R_{ij}^{(2)}(t,3)]^{(3)} = \exp[-[\lambda_{ij}^{(2)}(3)]^{(3)} t]$,

$i = 1,2,3,4 \quad j = 1,2,$

and the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(2)}(1)]^{(3)}$, $[\lambda_{ij}^{(2)}(2)]^{(3)}$, $[\lambda_{ij}^{(2)}(3)]^{(3)}$,

$i = 1,2,3,4 \quad j = 1,2,$

iv) at the system operation states $z_4$:

- the reliability functions of the subsystem $S_1$ components

$[R_{ij}^{(1)}(t,\cdot)]^{(4)} = [1, [R_{ij}^{(1)}(t,1)]^{(4)}, [R_{ij}^{(1)}(t,2)]^{(4)}, R_{ij}^{(1)}(t,3)]^{(4)}$,

$i = 1,2, \quad j = 1,2,3,$

coordinates

$[R_{ij}^{(1)}(t,1)]^{(4)} = \exp[-[\lambda_{ij}^{(1)}(1)]^{(4)} t]$,

$[R_{ij}^{(1)}(t,2)]^{(4)} = \exp[-[\lambda_{ij}^{(1)}(2)]^{(4)} t]$,

$[R_{ij}^{(1)}(t,3)]^{(4)} = \exp[-[\lambda_{ij}^{(1)}(3)]^{(4)} t]$,

$i = 1,2, \quad j = 1,2,3,$

and the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(1)}(1)]^{(4)}$, $[\lambda_{ij}^{(1)}(2)]^{(4)}$, $[\lambda_{ij}^{(1)}(3)]^{(4)}$,

$i = 1,2, \quad j = 1,2,3,$

- the reliability functions of the subsystem $S_2$ components

$[R_{ij}^{(2)}(t,\cdot)]^{(4)} = [1, [R_{ij}^{(2)}(t,1)]^{(4)}, [R_{ij}^{(4)}(t,2)]^{(4)}, R_{ij}^{(2)}(t,3)]^{(4)}$,

$i = 1,2,3,4 \quad j = 1,2,$

coordinates

$[R_{ij}^{(2)}(t,1)]^{(4)} = \exp[-[\lambda_{ij}^{(2)}(1)]^{(4)} t]$,

$[R_{ij}^{(2)}(t,2)]^{(4)} = \exp[-[\lambda_{ij}^{(2)}(2)]^{(4)} t]$,

$[R_{ij}^{(2)}(t,3)]^{(4)} = \exp[-[\lambda_{ij}^{(2)}(3)]^{(4)} t]$,

$i = 1,2,3,4 \quad j = 1,2,$

with the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively

$[\lambda_{ij}^{(2)}(1)]^{(4)}$, $[\lambda_{ij}^{(2)}(2)]^{(4)}$, $[\lambda_{ij}^{(2)}(3)]^{(4)}$,

$i = 1,2,3,4 \quad j = 1,2.$

## 5.4.3. The system components reliability data collection

### 5.4.3.1. Data coming from experts

There are no considered data collected on the basis of expert opinions.

### 5.4.3.2. Data coming from components reliability states changing processes

We suppose that we have in disposal data collected from the system components reliability states changing processes due to *Case 2* described in Section 3.3.2.

The following data for particular components $E_{ij}^{(k)}$, $k = 1,2$, of the system:

- the numbers of identical experiment posts $n^{(b)} = n_{ij}^{(b)}$,
- the observation times $\tau^{(b)} = \tau_{ij}^{(b)}$,
- the numbers $m^{(b)}(u) = m_{ij}^{(b)}(u)$ of components that have left the reliability states subset $\{u, u+1, ..., 3\}$, $u = 1,2,3,$
- the sets

$$A^{(b)}(u) = A_{ij}^{(b)}(u) = \{t_i^{(b)}(u) : i = 1,2,...,m^{(b)}(u)\}$$

of realizations $t_i^{(b)}(u) = t_{ij}^{(b)}(u)$ of the component lifetimes $T_{ij}^{(b)}(u)$ in the reliability states subset $\{u, u+1, ..., 3\}$, $u = 1,2,3,$ at the operation state $z_b$, $b = 1,2,3,4$, are given in the Appendix 6B [9].

These data for the component $E_{11}^{(1)}$ of the subsystem $S_1$ are as follows:

i) at the operation state $z_1$

$n^{(1)} = 40,\ \tau^{(1)} = 2600,\ m^{(1)}(1) = 32,$

$A^{(1)}(1) = \{$30, 37, 37, 60, 63, 65, 89, 89, 80, 85, 88, 452, 462, 470, 490, 441, 350, 302, 307, 381, 400, 430, 737, 852, 856, 769, 976, 991, 1153, 1697, 1700, 2454$\}$,

$n^{(1)} = 40,\ \tau^{(1)} = 2400,\ m^{(1)}(2) = 32,$

$A^{(1)}(2) = \{$30, 37, 37, 60, 63, 65, 69, 69, 80, 85, 88, 352, 362, 370, 390, 341, 350, 302, 307, 381, 400, 430, 637, 752, 756, 769, 876, 891, 1053, 1597, 1600, 2254$\}$

$n^{(1)} = 40,\ \tau^{(1)} = 2200,\ m^{(1)}(3) = 32,$

$A^{(1)}(3) = \{$20, 27, 27, 50, 53, 65, 69, 69, 70, 75, 78, 252, 262, 270, 290, 241, 250, 302, 307, 381, 400, 430, 437, 752, 756, 769, 776, 861, 953, 1497, 1400, 2054$\}$

ii) at the operation state $z_2$

$n^{(2)} = 70,\ \tau^{(2)} = 2600,\ m^{(2)}(1) = 64,$

$A^{(2)}(1) = \{$30, 37, 37, 60, 63, 65, 89, 89, 80, 85, 88, 452, 462, 470, 490, 441, 350, 302, 307, 381, 400, 430, 737, 852, 856, 769, 976, 991, 1153, 1697, 1700, 2454, 30, 37, 37, 60, 63, 65, 89, 89, 80, 85, 88, 452, 462, 470, 490, 441, 350, 302, 307, 381, 400, 430, 737, 852, 856, 769, 976, 991, 1153, 1697, 1700, 2454$\}$

$n^{(2)} = 70,\ \tau^{(2)} = 2400,\ m^{(2)}(2) = 64,$

$A^{(2)}(2) = \{$30, 37, 37, 60, 63, 65, 69, 69, 80, 85, 88, 352, 362, 370, 390, 341, 350, 302, 307, 381, 400, 430, 637, 752, 756, 769, 876, 891, 1053, 1597, 1600, 2254, 30, 37, 37, 60, 63, 65, 69, 69, 80, 85, 88, 352, 362, 370, 390, 341, 350, 302, 307, 381, 400, 430, 637, 752, 756, 769, 876, 891, 1053, 1597, 1600, 2254$\}$,

$n^{(2)} = 70,\ \tau^{(2)} = 2200,\ m^{(2)}(3) = 64,$

$A^{(2)}(3) = \{$20, 27, 27, 50, 53, 65, 69, 69, 70, 75, 78, 252, 262, 270, 290, 241, 250, 302, 307, 381, 400, 430, 437, 752, 756, 769, 776, 861, 953, 1497, 1400, 2054, 20, 27, 27, 50, 53, 65, 69, 69, 70, 75, 78, 252, 262, 270, 290, 241, 250, 302, 307, 381, 400, 430, 437, 752, 756, 769, 776, 861, 953, 1497, 1400, 2054$\}$,

iii) at the operation state $z_3$

$n^{(3)} = 40,\ \tau^{(3)} = 2700,\ m^{(3)}(1) = 36,$

$A^{(3)}(1) = \{30,$ 37, 37, 60, 63, 65, 89, 89, 80, 85, 88, 452, 462, 470, 490, 441, 350, 302, 307, 381, 400, 430, 737, 852, 856, 769, 976, 991, 1153, 1697, 1700, 2454, 2500, 2550, 2600, 2650},

$n^{(3)} = 40,\ \tau^{(3)} = 2700,\ m^{(3)}(2) = 36,$

$A^{(3)}(2) = \{30,$ 37, 37, 60, 63, 65, 69, 69, 80, 85, 88, 352, 362, 370, 390, 341, 350, 302, 307, 381, 400, 430, 637, 752, 756, 769, 876, 891, 1053, 1597, 1600, 2254, 2500, 2550, 2600, 2650},

$n^{(3)} = 40,\ \tau^{(3)} = 2700,\ m^{(3)}(3) = 36,$

$A^{(3)}(3) = \{20,$ 27, 27, 50, 53, 65, 69, 69, 70, 75, 78, 252, 262, 270, 290, 241, 250, 302, 307, 381, 400, 430, 437, 752, 756, 769, 776, 861, 953, 1497, 1400, 2054, 2500, 2550, 2600, 2650},

iv) at the operation state $z_4$

$n^{(4)} = 70,\ \tau^{(4)} = 2700,\ m^{(4)}(1) = 68,$

$A^{(4)}(1) = \{30,$ 37, 37, 60, 63, 65, 89, 89, 80, 85, 88, 452, 462, 470, 490, 441, 350, 302, 307, 381, 400, 430, 737, 852, 856, 769, 976, 991, 1153, 1697, 1700, 2454, 30, 37, 37, 60, 63, 65, 89, 89, 80, 85, 88, 452, 462, 470, 490, 441, 350, 302, 307, 381, 400, 430, 737, 852, 856, 769, 976, 991, 1153, 1697, 1700, 2454, 2500, 2550, 2600, 2650},

$n^{(4)} = 70,\ \tau^{(4)} = 2700,\ m^{(4)}(2) = 68,$

$A^{(4)}(2) = \{30,$ 37, 37, 60, 63, 65, 69, 69, 80, 85, 88, 352, 362, 370, 390, 341, 350, 302, 307, 381, 400, 430, 637, 752, 756, 769, 876, 891, 1053, 1597, 1600, 2254, 30, 37, 37, 60, 63, 65, 69, 69, 80, 85, 88, 352, 362, 370, 390, 341, 350, 302, 307, 381, 400, 430, 637, 752, 756, 769, 876, 891, 1053, 1597, 1600, 2254, 2500, 2550, 2600, 2650},

$n^{(4)} = 70,\ \tau^{(4)} = 2700,\ m^{(4)}(3) = 68,$

$A^{(4)}(3) = \{20,$ 27, 27, 50, 53, 65, 69, 69, 70, 75, 78, 252, 262, 270, 290, 241, 250, 302, 307, 381, 400, 430, 437, 752, 756, 769, 776, 861, 953, 1497, 1400, 2054, 20, 27, 27, 50, 53, 65, 69, 69, 70, 75, 78, 252, 262, 270, 290, 241, 250, 302, 307, 381, 400, 430, 437, 752, 756, 769, 776, 861, 953, 1497, 1400, 2054, 2500, 2550, 2600, 2650}.

Similar data for the remaining component of the subsystem $S_1$ and for the components of the subsystem $S_2$ are given in the Appendix 6B [9].

### 5.4.4. Statistical identification of the system components reliability

#### 5.4.4.1. Statistical identification of the system components reliability on the basis of data coming from experts

As there are no data collected on the basis of expert opinions, then we do not perform their reliability models identification using the method of Section 3.4.1.

#### 5.4.4.2. Statistical identification of the system components reliability on the basis of data coming from their reliability states changing processes

As there are data collected from the system components failure processes, then their reliability models identification using the methods of Section 3.4.2 is possible.

To identify the parameters of multistate reliability functions of the system components, the statistical data coming from their failure processes given in the Appendix 6B [9] can be used.

From these data, on the basis of the resulting from (10) formula

$$[\hat{\lambda}_{ij}^{(k)}(u)]^{(b)} = \frac{m^{(b)}(u)}{\sum_{i=1}^{m^{(b)}(u)} t_i^{(b)}(u) + \tau^{(b)}[n^{(b)} - m^{(b)}(u)]},$$

$$k = 1,2,\ u = 1,2,3,\ b = 1,2,.3,4,$$

we get the approximate values $[\hat{\lambda}_{ij}^{(k)}(u)]^{(b)}$ of the subsystems $S_k$, $k = 1,2,$ components unknown intensities $[\lambda_{ij}^{(k)}(u)]^{(b)}$ of departure from the reliability states subset $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, while the system is operating in the operation state $z_b$, $b = 1,2,3,4,$ and resulting from (11) formula

$$[\hat{\lambda}_{ij}^{(k)}(u)]^{(b)} = \frac{n^{(b)}}{\sum_{i=1}^{m^{(b)}(u)} t_i^{(b)}(u) + \tau^{(b)}[n^{(b)} - m^{(b)}(u)]},$$

$$k = 1,2,\ u = 1,2,3,\ b = 1,2,.3,4,$$

their pessimistic evaluations.

The results are presented below.

At the system operation state $z_1$, in the first series subsystem of the subsystem $S_1$, the component $E_{11}^{(1)}$ intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively are

$[\lambda_{11}^{(1)}(1)]^{(1)} = 0.0008,\ [\lambda_{11}^{(1)}(2)]^{(1)} = 0.0009,$

$[\lambda_{11}^{(1)}(3)]^{(1)} = 0.0009$

and their pessimistic evaluations are

$[\lambda_{11}^{(1)}(1)]^{(1)} = 0.0010$, $[\lambda_{11}^{(1)}(2)]^{(1)} = 0.0011$,

$[\lambda_{11}^{(1)}(3)]^{(1)} = 0.0011$.

At the system operation state $z_2$, in the first series subsystem of the subsystem $S_1$, the component $E_{11}^{(1)}$ intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively are

$[\lambda_{11}^{(1)}(1)]^{(2)} = 0.0013$, $[\lambda_{11}^{(1)}(2)]^{(2)} = 0.0014$,

$[\lambda_{11}^{(1)}(3)]^{(2)} = 0.0015$

and their pessimistic evaluations are

$[\lambda_{11}^{(1)}(1)]^{(2)} = 0.0014$, $[\lambda_{11}^{(1)}(2)]^{(2)} = 0.0015$,

$[\lambda_{11}^{(1)}(3)]^{(2)} = 0.0016$.

.

At the system operational state $z_3$, in the first series subsystem of the subsystem $S_1$, the component $E_{11}^{(1)}$ intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively are

$[\lambda_{11}^{(1)}(1)]^{(3)} = 0.0009$, $[\lambda_{11}^{(1)}(2)]^{(3)} = 0.0009$,

$[\lambda_{11}^{(1)}(3)]^{(3)} = 0.0010$

and their pessimistic evaluations are

$[\lambda_{11}^{(1)}(1)]^{(3)} = 0.0010$, $[\lambda_{11}^{(1)}(2)]^{(3)} = 0.0011$,

$[\lambda_{11}^{(1)}(3)]^{(3)} = 0.0011$.

At the system operational state $z_4$, in the first series subsystem of the subsystem $S_1$, the component $E_{11}^{(1)}$ intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$, respectively are

$[\lambda_{11}^{(1)}(1)]^{(4)} = 0.0013$, $[\lambda_{11}^{(1)}(2)]^{(4)} = 0.0014$,

$[\lambda_{11}^{(1)}(3)]^{(4)} = 0.0015$

and their pessimistic evaluations are

$[\lambda_{11}^{(1)}(1)]^{(4)} = 0.0014$, $[\lambda_{11}^{(1)}(2)]^{(4)} = 0.0015$,

$[\lambda_{11}^{(1)}(3)]^{(4)} = 0.0016$.

The evaluations of the intensities of departure from the reliability states subsets $\{1,2,3\}$, $\{2,3\}$, $\{3\}$ of the remaining components of the subsystem $S_1$ and the components of the subsystem $S_2$ are given in the Appendix 6B [9].

### 5.4.5. Identifying the system components conditional multistate exponential reliability functions

As there are data collected from the system components reliability states changing processes, then it is possible to verify the hypotheses on the exponential forms of the system components conditional reliability functions. To this end, we use the procedure given in Section 3.5.

The results of the hypotheses testing are given below.

At the system operation state $z_1$, the subsystem $S_1$ component $E_{11}^{(1)}$ conditional reliability function co-ordinates respectively are

$[R_{11}^{(1)}(t,1)]^{(1)} = \exp[-0.0008t]$,

$[R_{11}^{(1)}(t,2)]^{(1)} = \exp[-0.0009t]$,

$[R_{11}^{(1)}(t,3)]^{(1)} = \exp[-0.0009t]$

and their pessimistic evaluations are

$[R_{11}^{(1)}(t,1)]^{(1)} = \exp[-0.0010t]$,

$[R_{11}^{(1)}(t,2)]^{(1)} = \exp[-0.0011t]$,

$[R_{11}^{(1)}(t,3)]^{(1)} = \exp[-0.0011t]$.

At the system operation state $z_2$, the subsystem $S_1$ component $E_{11}^{(1)}$ conditional reliability function co-ordinates respectively are

$[R_{11}^{(1)}(t,1)]^{(2)} = \exp[-0.0013t]$,

$[R_{11}^{(1)}(t,2)]^{(2)} = \exp[-0.0014t]$,

$[R_{11}^{(1)}(t,3)]^{(2)} = \exp[-0.0015t]$

and their pessimistic evaluations are

$[R_{11}^{(1)}(t,1)]^{(2)} = \exp[-0.0014t]$,

$[R_{11}^{(1)}(t,2)]^{(2)}$ = exp[-0.0015$t$],

$[R_{11}^{(1)}(t,3)]^{(2)}$ = exp[-0.0016$t$]

At the system operational state $z_3$, the subsystem $S_1$ component $E_{11}^{(1)}$ conditional reliability function co-ordinates respectively are

$[R_{11}^{(1)}(1)]^{(3)}$ = exp[-0.0009$t$],

$[R_{11}^{(1)}(2)]^{(3)}$ = exp[-0.0009$t$],

$[R_{11}^{(1)}(3)]^{(3)}$ = exp[-0.0010$t$]

and their pessimistic evaluations are

$[R_{11}^{(1)}(1)]^{(3)}$ = exp[-0.0010$t$],

$[R_{11}^{(1)}(2)]^{(3)}$ = exp[-0.0011$t$],

$[R_{11}^{(1)}(3)]^{(3)}$ = exp[-0.0011$t$].

At the system operational state $z_4$, the subsystem $S_1$ component $E_{11}^{(1)}$ conditional reliability function co-ordinates respectively are

$[R_{11}^{(1)}(1)]^{(4)}$ = exp[-0.0013$t$],

$[R_{11}^{(1)}(2)]^{(4)}$ = exp[-0.0014$t$],

$[R_{11}^{(1)}(3)]^{(4)}$ = exp[-0.0015$t$]

and their pessimistic evaluations are

$[R_{11}^{(1)}(1)]^{(4)}$ = exp[-0.0014$t$],

$[R_{11}^{(1)}(2)]^{(4)}$ = exp[-0.0015$t$],

$[R_{11}^{(1)}(3)]^{(4)}$ = exp[-0.0016$t$]

The evaluations of the conditional reliability function co-ordinates of the remaining components of the subsystem $S_1$ and the components of the subsystem $S_2$ are given in the Appendix 6B [9].

## 6. Identification of the components reliability models of real complex technical systems – using computer program

The computer program consists of two parts. In the first part, the program allows to estimate unknown parameters of the exponential distributions of the component conditional lifetimes of the complex technical system in the subsets of reliability states. This part of the program is based on the methods and algorithms for evaluating unknown parameters, especially the unknown intensities of component departure from the reliability state subset presented in [1]. The maximum likelihood method is applied to estimating these intensities, considering different cases of the empirical experiments and including the cases of small number of realizations and non-completed investigations. In the second part, the program allows to verify the hypotheses, that system components have exponential multistate reliability functions with intensities of departure from the reliability state subsets estimated by application of the first part of the program.

The computer program may be used for real technical systems i.e. port, shipyard and maritime transportation systems. It may also be used to construct the integrated safety and reliability decision support systems for various maritime and coastal transport sectors. This program together with the description may also be included into this training course addressed to industry.

## Acknowledgements

The paper describes the part of 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-Roszkowska A., Guze S., Kołowrocki K., Jurdziński M., Kwiatuszewska-Sarnecka B., Milczek B., Soszyńska J., Salahuddin Habibullah M. & Fu X. (2009). Integrated package of solutions for complex industrial systems and processes safety and reliability optimization. WP 7 – Task 7.3. Methods of unknown parameters of complex technical systems operation, reliability, availability, safety models evaluation. Report. Poland-Singapore Joint Project.

[2] 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. Report. Poland-Singapore Joint

Project.

[3] Blokus-Roszkowska A., Guze S., Kołowrocki K., Kwiatuszewska-Sarnecka B., Milczek B. & Soszyńska J. (2009). Integrated package of solutions for complex industrial systems and processes safety and reliability optimization. WP 7 – Task 7.2. Methods of complex technical systems reliability, availability and safety evaluation and prediction. Report. Poland-Singapore Joint Project.

[4] Blokus-Roszkowska, A., Kołowrocki, K. & Namysłowski, M. (2010). Applications and Testing of Packages of Tools in Complex Maritime Transportation Systems and Processes Safety and Reliability Optimization. WP9 – Task 9.2. Shipyard ship-rope elevator operation, reliability, risk, availability and cost identification, prediction and optimization. Report. Poland-Singapore Joint Project.

[5] Blokus-Roszkowska, A., Kołowrocki, K. & Namysłowski, M. (2010). Applications and Testing of Packages of Tools in Complex Maritime Transportation Systems and Processes Safety and Reliability Optimization. WP9 – Task 9.3. Shipyard ground ship-rope transporter operation, reliability, risk, availability and cost identification, prediction and optimization. Report. Poland-Singapore Joint Project.

[6] Blokus-Roszkowska, A., Guze, S., Kołowrocki, K. & Soszyńska, J. (2010). Packages of Tools for Complex Industrial Systems and Processes Safety and Reliability Optimization. WP8 - Task 8.3. The computer program for reliability models identification of the components of complex technical systems. Report. Poland-Singapore Joint Project.

[7] Kołowrocki K. & Soszyńska J. (2009). Integrated package of solutions for complex industrial systems and processes safety and reliability optimization. WP 7 – Task 7.1. Methods of complex technical systems operation processes modeling. Report. Poland-Singapore Joint Project.

[8] Kołowrocki, K., Soszyńska, J. & Baranowski, Z. (2010). Applications and Testing of Packages of Tools in Complex Maritime Transportation Systems and Processes Safety and Reliability Optimization. WP9 – Task 9.1. Port oil piping transportation system operation, reliability, risk, availability and cost identification, prediction and optimization. Report. Poland-Singapore Joint Project.

[9] Kołowrocki, K. & Soszyńska, J. (2010). Applications and Testing of Packages of Tools in Complex Maritime Transportation Systems and Processes Safety and Reliability Optimization. WP9 – Task 9.1. An exemplary system operation, reliability, risk, availability and cost identification, prediction and optimization. Report. Poland-Singapore Joint Project.