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## **Integrated software tools supporting decision making on identification, prediction and optimization of complex technical systems operation, reliability and safety**

### **Part 4**

## **Integrated software tools application – Exemplary system operation and reliability optimization**

### **Keywords**

operation process optimization, optimal characteristics, reliability, availability, renewal, software tools

### **Abstract**

There is presented the application of the integrated software tools to the operation and reliability of an exemplary complex technical system optimization. First using the computer program CP 8.9 there are determined the optimal limit transient probabilities of the exemplary system operation process at the particular operation states maximizing the system lifetime in the reliability states not worse than the critical reliability state and its optimal sojourn times at the particular operation states. Program CP 8.9 allows also for automatic evaluation of the exemplary system optimal unconditional multistate reliability function, the optimal expected values and standard deviations of its unconditional lifetimes in the reliability state subsets and the optimal mean values of its lifetimes in the particular reliability states. Moreover, in the case when the system is repairable, its optimal renewal and availability characteristics are obtained using the computer program CP 8.11.

## **8. The exemplary system operation process optimization**

### **8.1. Optimal transient probabilities of the system operation process at operation states**

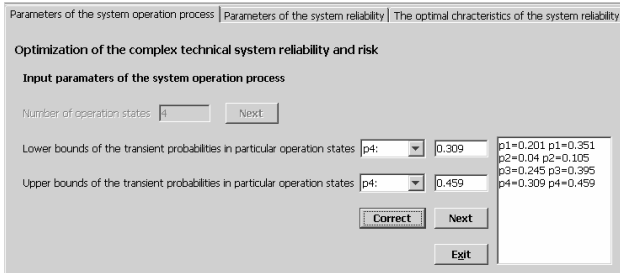
Considering the results given in [5], it is natural to assume that the system operation process has a significant influence on the system reliability. This influence is also clearly expressed for the mean values of the system unconditional lifetimes in the reliability state subsets that can be used for the system operation process optimization performed in the accordance with the procedure proposed in Section 9.2.1 of IS&RDSS 9 [7].

To determine the optimal characteristics of the exemplary system reliability and risk: the optimal unconditional reliability function, the optimal mean values of unconditional lifetimes in the reliability state subsets, the optimal risk function of the system and the optimal moment when the system risk exceeds a permitted level we use the computer program CP 8.9 “Optimization of system operation and reliability” [2].

The computer program is composed of three panels. The first panel “Parameters of the system operation process” is used for reading input parameters of the system operation process [6]:

– the number of operation states of the system operation process  $v$ ,

- the lower bounds of the transient probabilities  $p_b$ ,  $b = 1, 2, \dots, \nu$ , in particular operation states  $\check{p}_1, \check{p}_2, \dots, \check{p}_\nu$ ,
- the upper bounds of the transient probabilities  $p_b$ ,  $b = 1, 2, \dots, \nu$ , in particular operation states  $\hat{p}_1, \hat{p}_2, \dots, \hat{p}_\nu$ , fixed in [9].



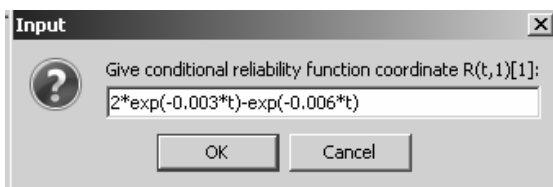
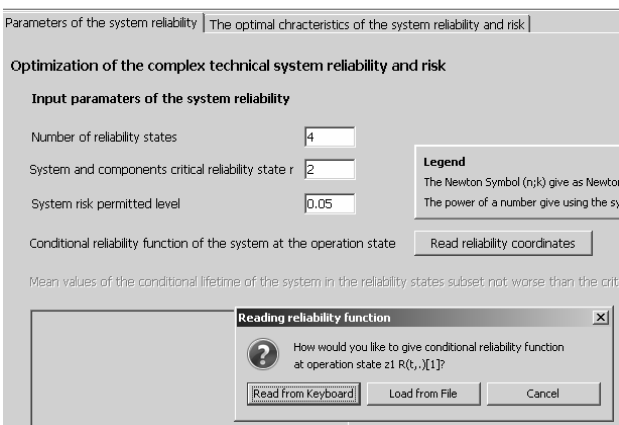
The second panel “Parameters of the system reliability” is served for reading input parameters of the system reliability model [2]:

- the number of the system and components reliability states  $z + 1$ ,
- the system and components critical reliability state  $r$ ,
- the conditional reliability function of the system at the operation state  $z_b$ ,  $b = 1, 2, \dots, \nu$ ,

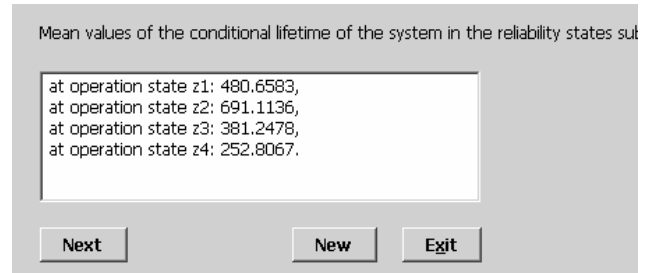
$$[R(t, \cdot)]^{(b)} = [1, [R(t, 1)]^{(b)}, \dots, [R(t, z)]^{(b)}],$$

for  $b = 1, 2, \dots, \nu$ , determined in Section 6 [5],

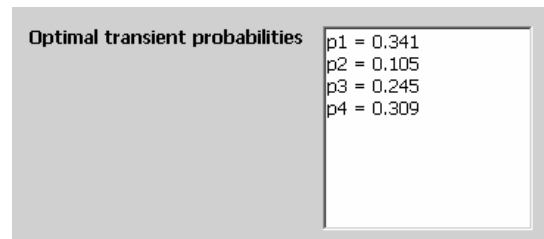
- the system risk permitted level  $\delta$ .



After giving the last coordinate of the conditional reliability function, the computer program determines and shows in the Text Area the mean values of the system conditional lifetimes  $\mu_b(r)$ ,  $b = 1, 2, \dots, \nu$ , in the reliability states subset not worse than the system critical reliability state  $r$ .



Then the computer program determines [6] the optimal transient probabilities  $\dot{p}_1, \dot{p}_2, \dots, \dot{p}_\nu$ , of the complex technical system operation process.



## 8.2. Optimal sojourn times of the system operation process at operation states

Having the values of the optimal transient probabilities determined in Section 8.1, it is possible to find the optimal unconditional and conditional mean values of the sojourn times of the exemplary system operation process at the operation states and the optimal mean values of the total unconditional sojourn times of the exemplary system operation process at the operation states during the fixed operation time as well.

Considering, obtained from Section 8.1, the optimal transient probabilities at operation states

$$\dot{p}_1 = 0.341, \dot{p}_2 = 0.105, \dot{p}_3 = 0.245, \dot{p}_4 = 0.309,$$

in [9] there are determined the optimal mean values  $\dot{M}_b$  of the exemplary system unconditional sojourn times in the operation states

$$\dot{M}_1 \cong 675, \dot{M}_2 \cong 290, \dot{M}_3 \cong 490, \dot{M}_4 = 400.$$

Then using the probabilities [4]

Prediction of characteristics

Number of operation states: 4

Matrix of transition probabilities between the operation states

	0	0,22	0,32	0,46
	0,2	0	0,3	0,5
	0,12	0,16	0	0,72
	0,48	0,22	0,3	0

and the optimal values  $\dot{M}_{bl}$  of the mean values  $M_{bl}$  of the conditional sojourn times at operation states

Mean values of conditional sojourn times of system operation process at op...

	0	200	500	1 024
	100	0	100	480
	900	500	0	419
	300	500	487	0

determined in [9], applying the computer program CP 8.5 we can obtain the optimal mean values of the total unconditional sojourn times of the exemplary system operation process at the operation states during the fixed operation time  $\theta = 1$  year = 365 days. In the window below there are presented results of the computer program CP 8.5.

Prediction of characteristics

Number of operation states: 4

Operation duration time: 365

INPUT

4 x 4 matrix

0.000000	0.220000	0.320000	0.460000
0.200000	0.000000	0.300000	0.500000
0.120000	0.160000	0.000000	0.720000
0.480000	0.220000	0.300000	0.000000

Mean values of conditional sojourn times of system operation process 4 x 4 matrix

0.000000	200.000000	500.000000	1024.000000
100.000000	0.000000	100.000000	480.000000
900.000000	500.000000	0.000000	419.000000
300.000000	500.000000	487.000000	0.000000

OUTPUT

Vector of unconditional mean lifetimes at operation states:  
675.04 290.0 489.68 400.1

Limit values of transient probabilities at operation states:  
0.3401 0.1048 0.2457 0.3095

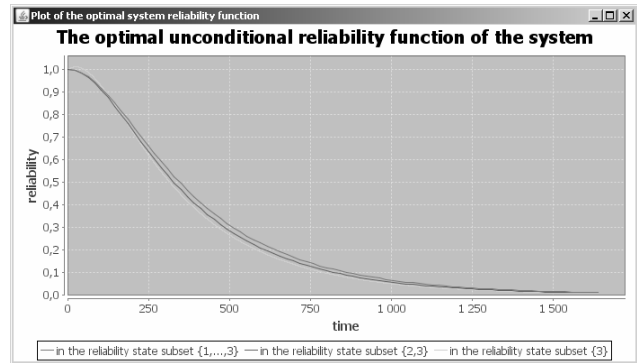
Expected values of total sojourn times at operation states:  
124.1241 38.2417 89.664 112.9701

### 9. The exemplary system reliability optimization

In the third panel “The optimal characteristics of the system reliability and risk” there are presented the results of the program. Namely, the computer program CP 8.9 determines the following characteristics [6]:

- the coordinates of the optimal unconditional multistate reliability function of the system (with plotting)

$$\dot{R}(t, \cdot) = [1, \dot{R}(t, 1), \dots, \dot{R}(t, z)], \quad t \geq 0,$$



Optimal characteristics of the complex technical system reliability and risk

Coordinates of the optimal unconditional multistate reliability function of the system:  
 $R(t, 1) = 0.341 * [2 * \exp(-0.003 * t) - \exp(-0.006 * t)] + 0.105 * [4 * \exp(-0.0028 * t) - 6 * \exp(-0.0056 * t) + 4 * \exp(-0.0084 * t)] + 0.105 * [4 * \exp(-0.0031 * t) - 6 * \exp(-0.0062 * t) + 4 * \exp(-0.0093 * t)] - \exp(-0.0031 * t)$   
 $R(t, 2) = 0.341 * [2 * \exp(-0.0031 * t) - \exp(-0.0062 * t)] + 0.105 * [4 * \exp(-0.003 * t) - 6 * \exp(-0.006 * t) + 4 * \exp(-0.009 * t)] - \exp(-0.003 * t)$   
 $R(t, 3) = 0.341 * [2 * \exp(-0.0032 * t) - \exp(-0.0064 * t)] + 0.105 * [4 * \exp(-0.0032 * t) - 6 * \exp(-0.0064 * t) + 4 * \exp(-0.0096 * t)] - \exp(-0.0032 * t)$

The optimal mean values of the system unconditional lifetimes in the subset of reliability states:  
 in the subset of reliability states not worse than 1: 429.4385,  
 in the subset of reliability states not worse than 2: 407.9944,  
 in the subset of reliability states not worse than 3: 395.4304.

The optimal values of the standard deviations of the system unconditional lifetimes in the subset of reliability states:  
 in the subset of reliability states not worse than 1: 317.2658,  
 in the subset of reliability states not worse than 2: 302.3139,  
 in the subset of reliability states not worse than 3: 285.3211.

Buttons: Save, Print, New, Exit, Reliability Plot, Risk Plot, Save Plot, Save Plot

**Optimal characteristics of the complex technical system reliability and risk**

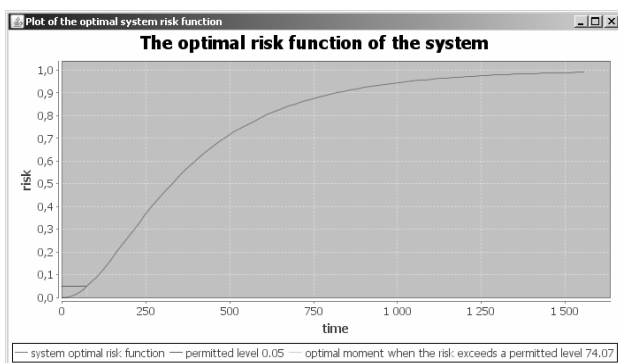
in the subset of reliability states not worse than 1: 317.2658,  
in the subset of reliability states not worse than 2: 302.3139,  
in the subset of reliability states not worse than 3: 285.3211.

The optimal mean values of the system unconditional lifetimes in the particular reliability states:  
in the reliability state 1: 21.4441,  
in the reliability state 2: 12.564,  
in the reliability state 3: 395.4304.

The optimal system risk function:  
 $r(t) = 1 - R(t,2) = 1 - [0.341 * [2 * \exp(-0.0031t) - \exp(-0.0062t)] + 0.105 * [4 * \exp(-0.003t) - 6 * \exp(-0.006t) + 4 * \exp(-0.009t)]]$

The optimal moment when the risk exceeds the permitted level: 74.0703.

- the optimal mean values  $\dot{\mu}(u)$  of the system unconditional lifetimes in the reliability state subsets  $\{u, u + 1, \dots, z\}$ ,  $u = 1, 2, \dots, z$ ,
- the optimal values  $\dot{\sigma}(u)$  of the standard deviations of the system unconditional lifetimes in the system reliability state subsets  $\{u, u + 1, \dots, z\}$ ,  $u = 1, 2, \dots, z$ ,
- the optimal mean values  $\ddot{\mu}(u)$  of the system unconditional lifetimes in the particular reliability states  $u = 1, 2, \dots, z$ ,
- the optimal system risk function (with plotting)  $\dot{r}(t)$ ,  $t \geq 0$ ,
- the optimal moment  $\dot{t}$  when the risk exceeds the permitted level  $\delta$



## 10. The exemplary system renewal and availability optimization

To determine the optimal renewal and availability characteristics of the exemplary system after its operation process optimization, we use the results of the system reliability characteristics optimization performed in Sections 8 and 9 and the results of the Section 11.2 of IS&RDSS 11 [7].

In the case when the exemplary system renovation time is ignored, considering the optimal values  $\dot{\mu}(2)$  and  $\dot{\sigma}(2)$  determined in Section 9, we predict the optimal renewal and availability characteristics of the exemplary system using the computer program CP 8.11 “Optimization of system availability” [3].

The computer program is reading:

- the number of the system reliability states,
- the system critical reliability state  $r$ ,
- the optimal mean value  $\dot{\mu}(r)$  of the unconditional lifetime of the system in the reliability states subset not worse than the system critical reliability state  $r$ ,
- the optimal standard deviation  $\dot{\sigma}(r)$  of the unconditional lifetime of the system in the reliability states subset not worse than the system critical reliability state  $r$ ,

from results of Section 9 and from [9],

Choose the renovation type  Ignored time  Non-ignored time  Results - ignored time

Renovation with ignored time  
 Renovation with non-ignored time

**INPUT PARAMETERS OF THE COMPLEX TECHNICAL SYSTEM RELIABILITY**

the number of the system reliability states:

the system and components reliability critical state:

the optimal mean value of unconditional lifetime:

the optimal standard deviation of unconditional lifetime:

- the number  $N$  of the system exceeding the critical reliability state  $r$  and renovations,
- the system renewal process duration time  $t$ .

Choose the renovation type: Ignored time | Non-ignored time | Results - ignored time

**PARAMETERS OF THE COMPLEX TECHNICAL SYSTEM RELIABILITY**

the number of the system reliability states:

the system reliability critical state:

the optimal mean value of unconditional lifetime:

the optimal standard deviation of unconditional lifetime:

**INPUT PARAMETERS OF THE SYSTEM RENEWAL PROCESS**

number of system exceeding:

system renewal process duration time:

The results of the predicting the optimal renewal process characteristics of the exemplary system in case the renovation time is ignored are given in the "Results – ignored time" tab below.

Choose the renovation type: Ignored time | Non-ignored time | Results - ignored time | Results - non-ignored time

RESULTS:

the distribution of the optimal time until the Nth exceeding of reliability critical state  $r$  of this system:

the expected value:  and the variance of the optimal time:

the distribution of the optimal number of exceeding the reliability critical state  $r$  of this system:

the expected value:  and the variance:  of optimal number of the exceeding the reliability critical state

Each characteristic can be presented in the table of values for fixed parameter  $t$ . For example, the table of distribution values of the optimal time until the  $N$ th exceeding the reliability critical state and the table of distribution values of the optimal number exceeding the reliability critical state are shown below.

N	Values
0	0.095778460010645
1	0.241075791391216
2	0.319250684940067
3	0.222591129838546
4	0.081637804892566
5	0.015713480636288
6	0.001581987497007
7	0.000082988446833
8	0.000002259588423
9	0.000000031817583
10	0.00000000230967
11	0.00000000000862
12	0.00000000000002
13	0

The computer program is predicted the following characteristics of the complex technical system renewal and availability [6]:

- the distribution  $\dot{F}^{(N)}(t, r), t \in (-\infty, \infty)$ , of the optimal time  $\dot{S}_N(r), r \in \{1, 2, \dots, z\}$  until the  $N$ th exceeding of reliability critical state  $r$  of this system, for sufficiently large  $N$ ,
- the expected value  $E[\dot{S}_N(r)]$  and the variance  $D[\dot{S}_N(r)]$  of the optimal time  $\dot{S}_N(r)$ ,

- the distribution  $P(\dot{N}(t, r) = N), N = 0, 1, 2, \dots, r \in \{1, 2, \dots, z\}$  of the optimal number  $\dot{N}(t, r)$  of exceeding the reliability critical state  $r$  of this system up to the moment  $t, t \geq 0$ , for sufficiently large  $t$ ,
- the expected value  $\dot{H}(t, r)$  and the variance  $\dot{D}(t, r)$  of the optimal number  $\dot{N}(t, r), r \in \{1, 2, \dots, z\}$  of exceeding the reliability critical state  $r$  of this system at the moment  $t, t \geq 0$ , for sufficiently large  $t$ .

t	Values
0	0.00002368224814
1	0.000023783230095
2	0.000023884620216
3	0.000023986420052
4	0.00002408863116
5	0.000024191255099
6	0.000024294293435
7	0.00002439774774
8	0.000024501619592
9	0.000024605910573
10	0.00002471062227
11	0.000024815756279
12	0.000024921314197
13	0.000025027297631
14	0.000025133708191
15	0.000025240547493
16	0.000025347817159
17	0.000025455518817
18	0.0000255636541

Further, to make the estimation of the renewal and availability of the exemplary system in the case when the time of renovation is non-ignored, considering the optimal values  $\dot{\mu}(2)$  and  $\dot{\sigma}(2)$  determined in Section 9, assuming the mean value of the system renovation time  $\mu_0(2) = 10$  years and the standard deviation of the system renovation time  $\sigma_0(2) = 5$  years, we use the computer program CP 8.11 in the following way [3].

The computer program is reading:

- the number of the system reliability states,
- the system critical reliability state  $r$ ,
- the optimal mean value  $\dot{\mu}(r)$  of the unconditional lifetime of the system in the reliability states subset not worse than the system critical reliability state  $r$ ,
- the optimal standard deviation  $\dot{\sigma}(r)$  of the unconditional lifetime of the system in the reliability states subset not worse than the system critical reliability state  $r$ ,

Choose the renovation type | Ignored time | Non-ignored time | Results - ignored time

Renovation with ignored time  
 Renovation with non-ignored time

**INPUT PARAMETERS OF THE COMPLEX TECHNICAL SYSTEM RELIABILITY**

the number of the system reliability states:   
the system and components reliability critical state:   
the optimal mean value of unconditional lifetime:   
the optimal standard deviation of unconditional lifetime:

- the  $r$ -th coordinate  $\dot{R}(t, r)$ ,  $t \geq 0$ , of the system optimal unconditional reliability function  $\dot{R}(t, \cdot)$  determined in Section 6 [5],

Choose the renovation type | Ignored time | Non-ignored time | Results - ignored time | Results - ignored time

**PARAMETERS OF THE COMPLEX TECHNICAL SYSTEM RELIABILITY**

the number of the system reliability states:   
the system and components reliability critical state:   
the optimal mean value of unconditional lifetime:   
the optimal standard deviation of unconditional lifetime:

Input reliability function

**INPUT PARAMETERS OF THE SYSTEM RENEWAL PROCESS**

the mean value of system renovation time:   
the standard deviation of system renovation time:   
number of system exceeding the critical reliability state:   
renewal process duration time:   
length of system availability interval:

**Input** Give R(t,2)[1]  
 $2 * \exp(-0.0031t) - \exp(-0.0062t)$

- the mean value  $\mu_0(r)$  of the system renovation time,
- the standard deviation  $\sigma_0(r)$  of the system renovation time,
- the number  $N$  of the system exceeding the critical reliability state  $r$  and renovations,
- the system renewal process duration time  $t$ ,
- the length of the system availability interval  $\tau$ .

Choose the renovation type | Ignored time | Non-ignored time | Results - ignored time

**PARAMETERS OF THE COMPLEX TECHNICAL SYSTEM RELIABILITY**

the number of the system reliability states:   
the system and components reliability critical state:   
the optimal mean value of unconditional lifetime:   
the optimal standard deviation of unconditional lifetime:

Input reliability function

**INPUT PARAMETERS OF THE SYSTEM RENEWAL PROCESS**

the mean value of system renovation time:   
the standard deviation of system renovation time:   
number of system exceeding the critical reliability state:   
renewal process duration time:   
length of system availability interval:

The computer program is predicted the following characteristics of the complex technical system renewal and availability [6]:

- the distribution function  $\dot{F}^{(N)}(t, r) = P(\dot{S}_N(r) < t)$ ,  $t \in (-\infty, \infty)$  of the optimal time  $\dot{S}_N(r)$ ,  $r \in \{1, 2, \dots, z\}$ , until the  $N$ th exceeding the reliability critical state  $r$  of this system  $N = 1, 2, \dots$ ,
- the expected value  $E[\dot{S}_N(r)]$  and the variance  $D[\dot{S}_N(r)]$  of the optimal time  $\dot{S}_N(r)$ ,  $r \in \{1, 2, \dots, z\}$ , until the  $N$ th exceeding the reliability critical state  $r$  of this system,
- the distribution  $P(\dot{N}(t, r) = N)$ ,  $N = 1, 2, \dots$  of the optimal number  $\dot{N}(t, r)$ ,  $r \in \{1, 2, \dots, z\}$  of exceeding the reliability critical state  $r$  of this system up to the moment  $t$ ,  $t \geq 0$ ,
- the expected value  $\dot{H}(t, r)$  and the variance  $\dot{D}(t, r)$  of the optimal number  $\dot{N}(t, r)$ ,  $r \in \{1, 2, \dots, z\}$  of exceeding the reliability critical state  $r$  of this system up to the moment  $t$ ,  $t \geq 0$ , for sufficiently large  $t$ ,
- the distribution function  $\ddot{F}^{(N)}(t, r) = P(\ddot{S}_N(r) < t)$ ,  $t \in (-\infty, \infty)$  of the optimal time  $\ddot{S}_N(r)$ ,  $r \in \{1, 2, \dots, z\}$ , until the  $N$ th system's renovation, for sufficiently large  $N$ ,  $N = 1, 2, \dots$ ,
- the expected value  $E[\ddot{S}_N(r)]$  and the variance  $D[\ddot{S}_N(r)]$  of the optimal time  $\ddot{S}_N(r)$ ,  $r \in \{1, 2, \dots, z\}$ , until the  $N$ th system's renovation,
- the distribution  $P(\ddot{N}(t, r) = N)$ ,  $N = 1, 2, \dots$ , of the optimal number  $\ddot{N}(t, r)$ ,  $r \in \{1, 2, \dots, z\}$  of system's renovations up to the moment  $t$ ,  $t \geq 0$ ,
- the expected value  $\ddot{H}(t, r)$  and the variance  $\ddot{D}(t, r)$  of the optimal number  $\ddot{N}(t, r)$ ,  $r \in \{1, 2, \dots, z\}$  of system's renovations up to the moment  $t$ ,  $t \geq 0$ ,
- the optimal steady availability coefficient  $\dot{A}(t, r)$ ,  $t \geq 0$ ,  $r \in \{1, 2, \dots, z\}$  of the system at the moment  $t$ ,

– the optimal steady availability coefficient  $\dot{A}(t, \tau, r)$ ,  $t \geq 0$ ,  $\tau > 0$ ,  $r \in \{1, 2, \dots, z\}$  of the system in the time interval  $\langle t, t + \tau \rangle$ ,  $\tau > 0$ .

The optimal renewal and availability characteristics of the exemplary system in the case when it is repairable and its time of renovation is non-ignored are presented in the “Results – non-ignored time” tab shown below.

N	Values
0	0.095908318587048
1	0.249342555383982
2	0.328100270939511
3	0.218698074211274
4	0.07375411090405
5	0.012546889098876
6	0.001072228036685
7	0.000045815848068
8	0.000000974380799
9	0.00000010271193
10	0.00000000053474
11	0.00000000000137
12	0

Choose the renovation type | Ignored time | Non-ignored time | Results - ignored time | **Results - non-ignored time**

the distribution function of the optimal time until the Nth exceeding the reliability critical state:

the expected value  and the variance of the optimal time

the distribution of the optimal number of exceeding the reliability critical state - table

the expected value  and the variance  of the optimal number of exceeding the reliability critical state

the distribution function of the optimal time until the Nth system's renovation

the expected value  and the variance  of the optimal time until the Nth system's renovation

the distribution of the optimal number of system's renovations

the expected value  and the variance of the optimal number of system's renovations

the optimal availability coefficient of the system at the moment t  in the time interval

Values of distribution of the optimal time until the *N*th exceeding reliability critical state and until the *N*th system's renovation are presented in first two tables. In the next two tables there are given values of distribution of the optimal number of system's renovation and the optimal number of exceeding the reliability critical state for fixed parameter *t*.

t	Values
0	0.000016118124899
1	0.000016188207249
2	0.000016258579036
3	0.000016329241384
4	0.000016400195424
5	0.00001647144229
6	0.00001654298312
7	0.000016614819057
8	0.000016686951246
9	0.000016759380838
10	0.000016832108988
11	0.000016905136854
12	0.000016978465601
13	0.000017052096394
14	0.000017126030406
15	0.000017200268812

t	Values
0	0.000015436442335
1	0.000015503704885
2	0.000015571245883
3	0.000015639066415
4	0.00001570716757
5	0.000015775550444
6	0.000015844216132
7	0.000015913165738
8	0.000015982400367
9	0.00001605192113
10	0.000016121729139
11	0.000016191825513
12	0.000016262211374
13	0.000016332887847
14	0.000016403856064
15	0.000016475117158
16	0.000016546672267

N	Values
0	0.098240863389695
1	0.253527475649781
2	0.329047604779527
3	0.214953115678213
4	0.070585118459535
5	0.011614702978496
6	0.000953564740319
7	0.000038873308073
8	0.000000783193852
9	0.000000007765402
10	0.00000000037754
11	0.00000000000009

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