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Integrated software tools supporting decision making on identification, prediction and optimization of complex technical systems operation, reliability and safety
Part 6
Integrated software tools application – Exemplary system operation cost analysis and maintenance optimization

Keywords

system operation process, optimization, cost analysis, corrective and preventive maintenance, software tools

Abstract

The integrated software tools are applied to the exemplary system operation cost analysis and maintenance optimization. Using the computer program CP 8.12 there is obtained the evaluation of the cost before and after the exemplary system operation process optimization and next the computer program CP 8.13 is applied for operation cost analysis of the improved exemplary system. The methods of corrective and preventive maintenance policy maximizing availability and minimizing renovation cost of the complex technical systems in variable operation conditions are illustrated for the analyzed exemplary system using equivalently the computer program CP 8.14 for maintenance policy maximizing system availability and CP 8.15 for minimizing system renovation cost.

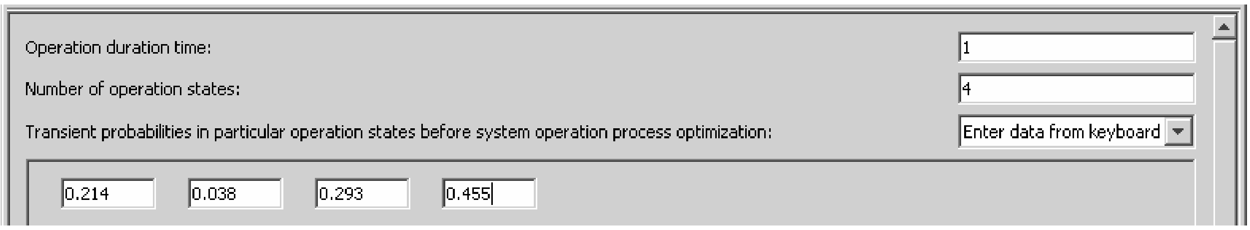
12. The exemplary system operation cost analysis

12.1. The exemplary system operation cost analysis before and after its operation process optimization

To determine the costs of the non-repairable and repairable exemplary system before and after the system operation process optimization we use the computer program CP 8.12 “Prediction of system operation cost” [8].

In order to do it the computer program is reading in:
- the time of the system operation process duration θ,
- the number of operation states of the system operation process ν,
- the transient probabilities in particular operation states before the system operation process optimization from Section 5 in [4],

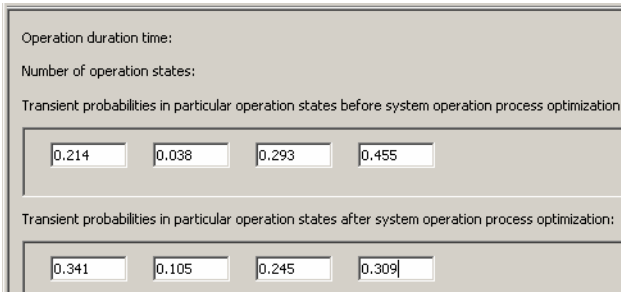
$p_1, \ p_2, \ \ldots, \ p_\nu,$



– the transient probabilities in particular operation states after the system operation process optimization

$\dot{p}_1, \ \dot{p}_2, \ldots, \ \dot{p}_\nu,$

from Section 8 in [5],



– the total number of the system components *n*,
– the system and components critical reliability state *r*,
– the mean value of the unconditional lifetime of the system in the reliability states subset not worse than the system critical reliability state *r* before its operation process optimization

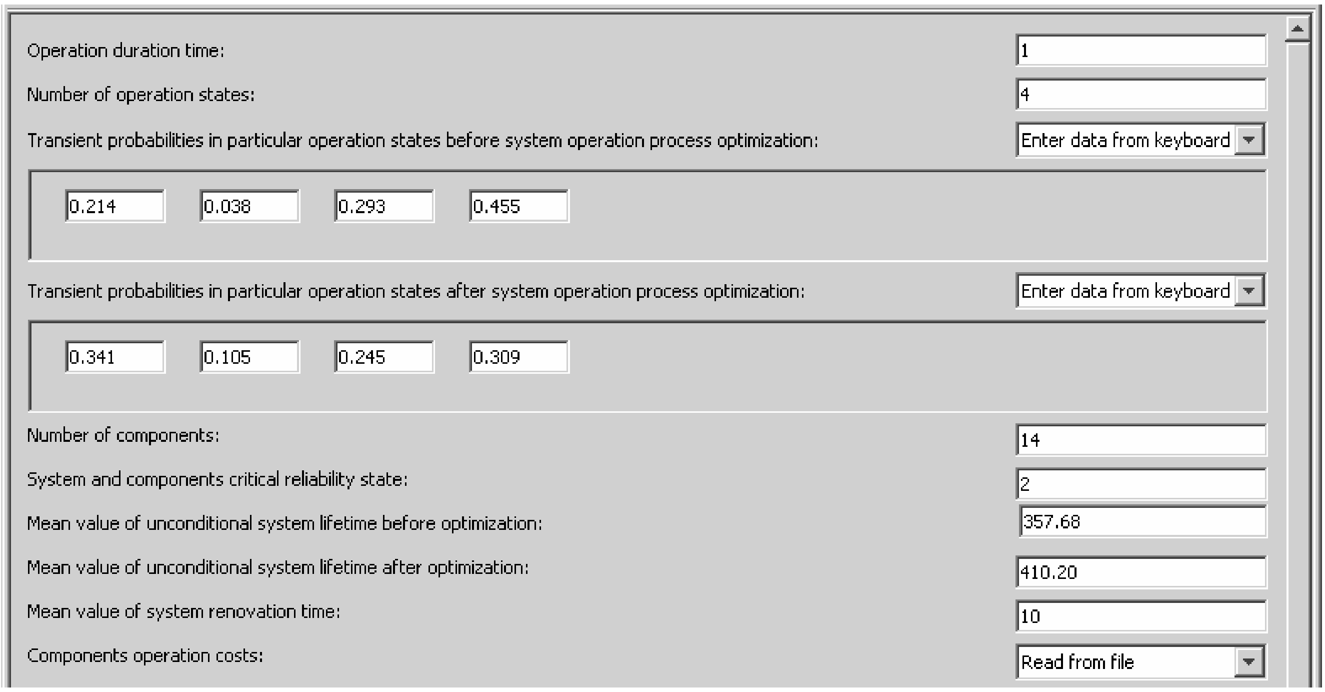
$\mu(r),$

– the mean value of the unconditional lifetime of the system in the reliability states subset not worse than the system critical reliability state *r* after its operation process optimization

$\dot{\mu}(r),$

– the mean value of the system renovation time

$\mu_0(r),$



– the matrix of the operation costs $c_i(\theta, b)$, $i = 1,2,...,n$, $b = 1,2,...,v$, of the system single basic components E_i, $i = 1,2,...,n$, at the operation state z_b, $b = 1,2,...,v$, during the system operation time θ

$$[c_i(\theta,b)]_{n\times v} = \begin{bmatrix} c_1(\theta,1)\, c_1(\theta,2) \ldots c_1(\theta,v) \\ c_2(\theta,1)\, c_2(\theta,2) \ldots c_2(\theta,v) \\ \ldots \\ c_n(\theta,1)\, c_n(\theta,2) \ldots c_n(\theta,v) \end{bmatrix},$$

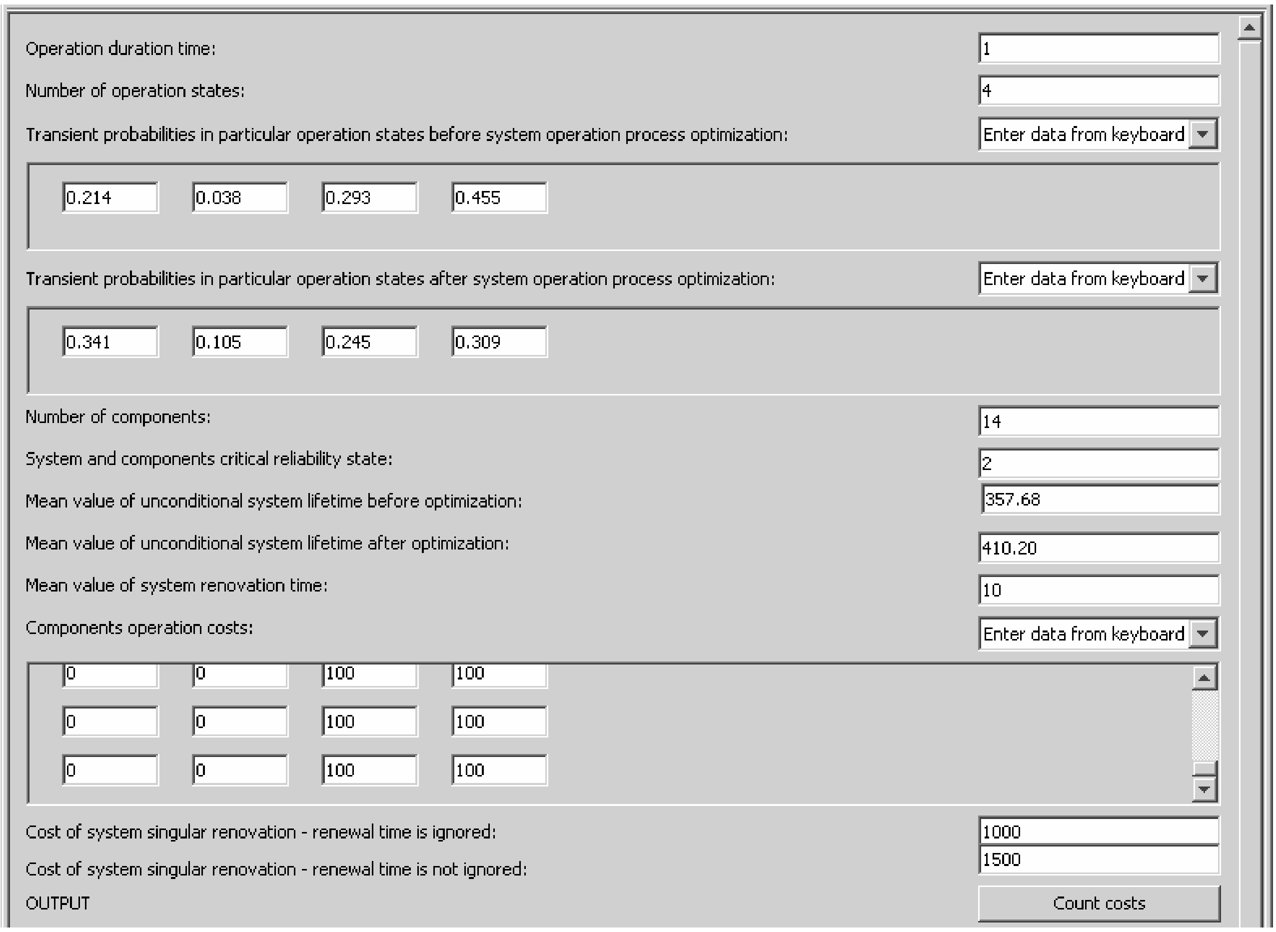
– the cost of the singular renovation of the repairable system with ignored time of renovation

c_{ig},

– the cost of the singular renovation of the repairable system with non-ignored time of renovation

c_{nig},

fixed in [11].



In Section 3 [3], it is fixed that the exemplary system is composed of $n = 14$ components and that the numbers of the system components operating in various operation states z_b, $b = 1,2,3,4$, are different. Namely, there are operating 6 system components at the operation states z_1, 8 system components at the operation states z_2 and 14 system components at the operation states z_3 and z_4. In the computer program window below there are given, according to the arbitrary assumption, the approximate mean operation cost of the single basic component of the considered exemplary system that is used during the operation time θ = 1 year, independently of the operation state z_b, $b = 1,2,3,4$.

The computer program is estimating the following operation costs of the complex technical systems [7], [10]:

– the total cost of the non-repairable system during the operation time θ, $\theta \geq 0$

$C(\theta)$,

– the total operation cost of the repairable system with ignored its renovation time during the operation time θ, $\theta \geq 0$

$C_{ig}(\theta)$,

– the total operation cost of the repairable system with not ignored its renovation time during the operation time θ, $\theta \geq 0$

$C_{nig}(\theta)$,

– the total optimal cost of the non-repairable system during the operation time θ, $\theta \geq 0$, after its operation process optimization

$\dot{C}(\theta)$,

– the optimal total operation cost of the repairable system with ignored its renovation time during the operation time θ, $\theta \geq 0$, after its operation process optimization

$\dot{C}_{ig}(\theta)$,

– the total optimal operation cost of the repairable system with non-ignored its renovation time during the operation time θ, $\theta \geq 0$, after its operation process optimization

$\dot{C}_{nig}(\theta)$.

After pressing the button "Count costs", the computer program is estimating operation costs of the system. Given, as a result, the characteristics of the exemplary system operation cost are shown below in the widow „OUTPUT".

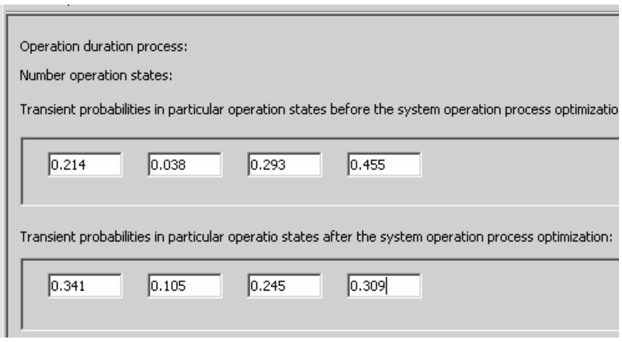
– the time of the system operation process duration θ,
– the number of the operation states of the system operation process ν,
– the transient probabilities in particular operation states before the system operation process optimization

$p_1,\ p_2,\ \ldots,\ p_\nu,$

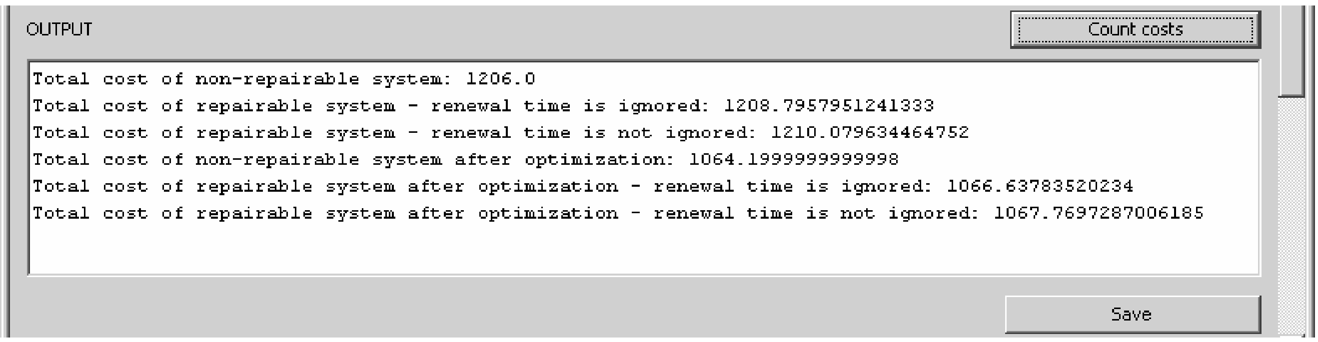
– the transient probabilities in particular operation states after the system operation process optimization

$\dot{p}_1,\ \dot{p}_2,\ \ldots,\ \dot{p}_\nu,$

from results of Section 5 [4] and Section 8 [5],



– the total number of the system components *n*,
– the system and components critical reliability state *r*,



12.2. Operation cost analysis of the improved exemplary system

To determine the costs of the non-repairable and repairable improved exemplary system with reserve and improved components before and after this system operation process optimization we use the computer program CP 8.13 "The computer program for prediction of operation cost of complex technical systems with reserve and improved components".
The computer program is reading in [9]:

– the mean value of the unconditional lifetime of the non-repairable system with non-improved components in the reliability states subset not worse than the system critical reliability state *r* before its operation process optimization

$\mu^{(0)}(r)$,

– the mean value of the unconditional lifetime in the reliability states subset not worse than the system critical reliability state r of the non-repairable system with its components hot single reservation before its operation process optimization

$\mu^{(1)}(r)$,

– the mean value of the unconditional lifetime in the reliability states subset not worse than the system critical reliability state r of the non-repairable system with its components cold single reservation before its operation process optimization

$\mu^{(2)}(r)$,

– the mean value of the unconditional lifetime in the reliability states subset not worse than the system critical reliability state r of the non-repairable system with its components improved by the reduction of their rates of departures from the reliability state subsets before its operation process optimization

$\mu^{(3)}(r)$,

– the optimal mean value of the unconditional lifetime of the non-repairable system with non-improved components in the reliability states subset not worse than the system critical reliability state r after its operation process optimization

$\dot{\mu}^{(0)}(r)$,

– the optimal mean value of the unconditional lifetime in the reliability states subset not worse than the system critical reliability state r of the non-repairable system with its components hot single reservation after its operation process optimization

$\dot{\mu}^{(1)}(r)$,

– the optimal mean value of the unconditional lifetime in the reliability states subset not worse than the system critical reliability state r of the non-repairable system with its components cold single reservation after its operation process optimization

$\dot{\mu}^{(2)}(r)$,

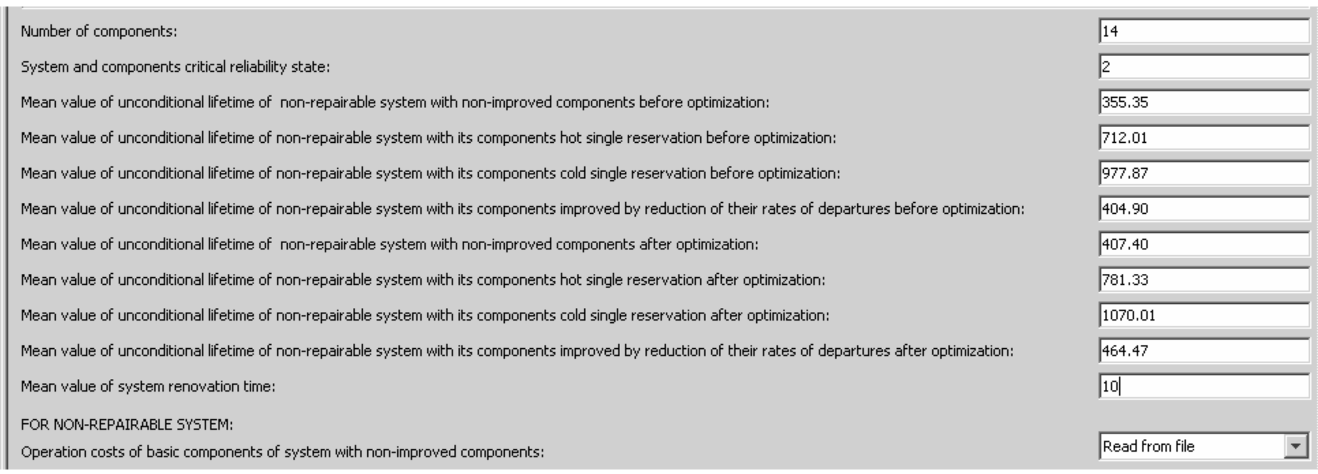
– the optimal mean value of the unconditional lifetime in the reliability states subset not worse than the system critical reliability state r of the non-repairable system with its components improved by the reduction of their rates of departures from the reliability state subsets after its operation process optimization

$\dot{\mu}^{(3)}(r)$,

– in the case of a repairable system with non-ignored renovation time the mean value of the system renovation time

$\mu_0(r)$,

from results of Section 11 in [5] and [11],



Number of components:	14
System and components critical reliability state:	2
Mean value of unconditional lifetime of non-repairable system with non-improved components before optimization:	355.35
Mean value of unconditional lifetime of non-repairable system with its components hot single reservation before optimization:	712.01
Mean value of unconditional lifetime of non-repairable system with its components cold single reservation before optimization:	977.87
Mean value of unconditional lifetime of non-repairable system with its components improved by reduction of their rates of departures before optimization:	404.90
Mean value of unconditional lifetime of non-repairable system with non-improved components after optimization:	407.40
Mean value of unconditional lifetime of non-repairable system with its components hot single reservation after optimization:	781.33
Mean value of unconditional lifetime of non-repairable system with its components cold single reservation after optimization:	1070.01
Mean value of unconditional lifetime of non-repairable system with its components improved by reduction of their rates of departures after optimization:	464.47
Mean value of system renovation time:	10
FOR NON-REPAIRABLE SYSTEM:	
Operation costs of basic components of system with non-improved components:	Read from file

i) for a non-repairable system:

– the matrix of the operation costs $c_i^{(0)}(\theta,b)$, $i=1,2,...,n$, $b=1,2,...,v$, of the system single basic components E_i, $i=1,2,...,n$, with non-improved components at the operation state z_b, $b=1,2,\ldots,\nu$, during the system operation time θ

$$[c_i^{(0)}(\theta,b)]_{n\times\nu}=\begin{bmatrix} c_1^{(0)}(\theta,1)\, c_1^{(0)}(\theta,2)\ldots c_1^{(0)}(\theta,\nu) \\ c_2^{(0)}(\theta,1)\, c_2^{(0)}(\theta,2)\ldots c_2^{(0)}(\theta,\nu) \\ \ldots \\ c_n^{(0)}(\theta,1)\, c_n^{(0)}(\theta,2)\ldots c_n^{(0)}(\theta,\nu) \end{bmatrix},$$

– the matrix of the operation costs $c_i^{(1)}(\theta,b)$, $i=1,2,...,n$, $b=1,2,...,v$, of the system single basic components E_i, $i=1,2,...,n$, with a hot single reservation of components in the operation state z_b, $b=1,2,...,v$, during the system operation time θ

$$[c_i^{(1)}(\theta,b)]_{n\times\nu}=\begin{bmatrix} c_1^{(1)}(\theta,1)\, c_1^{(1)}(\theta,2)\ldots c_1^{(1)}(\theta,\nu) \\ c_2^{(1)}(\theta,1)\, c_2^{(1)}(\theta,2)\ldots c_2^{(1)}(\theta,\nu) \\ \ldots \\ c_n^{(1)}(\theta,1)\, c_n^{(1)}(\theta,2)\ldots c_n^{(1)}(\theta,\nu) \end{bmatrix},$$

– the matrix of the operation costs $c_i^{(2)}(\theta,b)$, $i=1,2,...,n$, $b=1,2,...,v$, of the system single basic components E_i, $i=1,2,...,n$, with a cold single reservation of components in the operation state z_b, $b=1,2,...,v$, during the system operation time θ

$$[c_i^{(2)}(\theta,b)]_{n\times\nu}=\begin{bmatrix} c_1^{(2)}(\theta,1)\, c_1^{(2)}(\theta,2)\ldots c_1^{(2)}(\theta,\nu) \\ c_2^{(2)}(\theta,1)\, c_2^{(2)}(\theta,2)\ldots c_2^{(2)}(\theta,\nu) \\ \ldots \\ c_n^{(2)}(\theta,1)\, c_n^{(2)}(\theta,2)\ldots c_n^{(2)}(\theta,\nu) \end{bmatrix},$$

– the matrix of the operation costs $\bar{c}_i^{(2)}(\theta,b)$, $i=1,2,...,n$, $b=1,2,...,v$, of the system single reserve components E_i, $i=1,2,...,n$, with a cold single reservation of components in the operation state z_b, $b=1,2,...,v$, during the system operation time θ

$$\bar{c}_i^{(2)}[(\theta,b)]_{n\times\nu}=\begin{bmatrix} \bar{c}_1^{(2)}(\theta,1)\, \bar{c}_1^{(2)}(\theta,2)\ldots \bar{c}_1^{(2)}(\theta,\nu) \\ \bar{c}_2^{(2)}(\theta,1)\, \bar{c}_2^{(2)}(\theta,2)\ldots \bar{c}_2^{(2)}(\theta,\nu) \\ \ldots \\ \bar{c}_n^{(2)}(\theta,1)\, \bar{c}_n^{(2)}(\theta,2)\ldots \bar{c}_n^{(2)}(\theta,\nu) \end{bmatrix},$$

– the matrix of the operation costs $c_i^{(3)}(\theta,\rho(r),b)$, $i=1,2,...,n$, $b=1,2,...,v$, of the system single basic components E_i, $i=1,2,...,n$, with improved components in the operation state z_b, $b=1,2,...,v$, during the system operation time θ

$$[c_i^{(3)}(\theta,b)]_{n\times\nu}=\begin{bmatrix} c_1^{(3)}(\theta,1)\, c_1^{(3)}(\theta,2)\ldots c_1^{(3)}(\theta,\nu) \\ c_2^{(3)}(\theta,1)\, c_2^{(3)}(\theta,2)\ldots c_2^{(3)}(\theta,\nu) \\ \ldots \\ c_n^{(3)}(\theta,1)\, c_n^{(3)}(\theta,2)\ldots c_n^{(3)}(\theta,\nu) \end{bmatrix},$$

ii) for a repairable system with ignored renovation time:

– the cost of the singular renovation of the repairable system with ignored renovation time with non-improved components is

$c_{ig}^{(0)}$,

– the cost of the singular renovation of the repairable system with ignored renovation time with a hot single reservation of components is

$c_{ig}^{(1)}$,

– the cost of the singular renovation of the repairable system with ignored renovation time with a cold single reservation of components is

$c_{ig}^{(2)}$,

– the cost of the singular renovation of the repairable system with ignored renovation time with improved components by reduction the rates of departures from the reliability state subsets

$c_{ig}^{(3)}$,

iii) for a repairable system with non-ignored renovation time:

– the cost of the singular renovation of the repairable system with non-ignored renovation time with non-improved components is

$c_{nig}^{(0)}$,

– the cost of the singular renovation of the repairable system with non-ignored renovation time with a hot single reservation of components is

$c_{nig}^{(1)}$,

– the cost of the singular renovation of the repairable system with non-ignored renovation time with a cold single reservation of components is

$c_{nig}^{(2)}$,

– the cost of the singular renovation of the repairable system with non-ignored renovation time with improved components by reduction the rates of departures from the reliability state subsets

$c_{nig}^{(3)}$.

In the window below there are given, arbitrary assumed [11], the approximate mean operation cost of the single basic, reserve and improved components of the considered exemplary system that are used during the operation time θ = 1000 days.

– the total operation cost of the non-repairable system with a cold single reservation of components during the operation time θ, $\theta \ge 0$

$C^{(2)}(\theta)$,

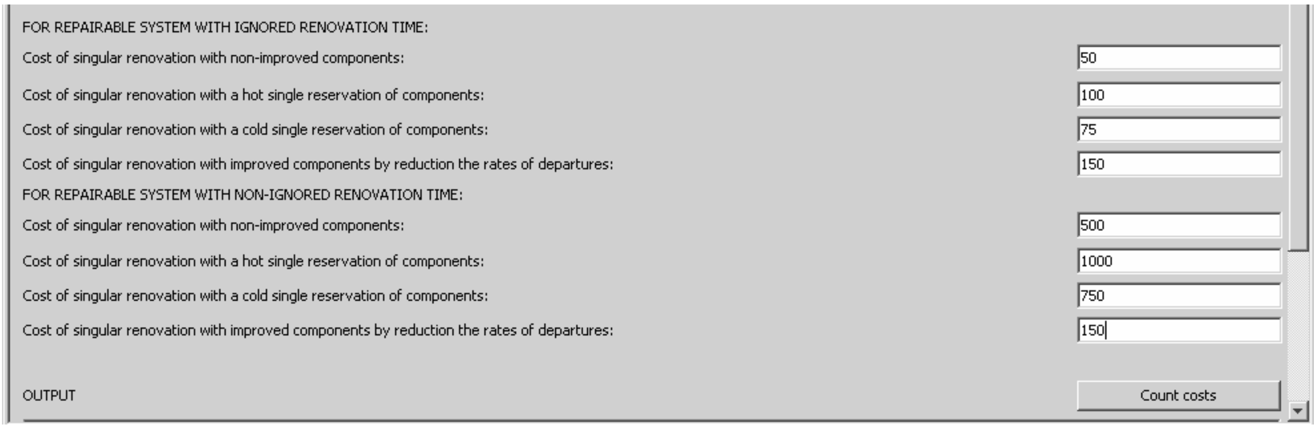
– the total operation cost of the non-repairable system with improved components by reduction their rates of departures from the reliability state subsets during the operation time θ, $\theta \ge 0$

$C^{(3)}(\theta, \rho(r))$,

ii) for a repairable system with ignored renovation time:

– the total operation cost of the repairable system with ignored renovation time with non-improved components during the operation time θ, $\theta \ge 0$

$C_{ig}^{(0)}(\theta)$,



The computer program is estimating the following operation costs of the complex technical systems [10]:

a) before the system operation process optimization

i) for a non-repairable system:

– the total operation cost of the non-repairable system with non-improved components during the operation time θ, $\theta \ge 0$

$C^{(0)}(\theta)$,

– the total operation cost of the non-repairable system with a hot single reservation of components during the operation time θ, $\theta \ge 0$

$C^{(1)}(\theta)$,

– the total operation cost of the repairable system with ignored renovation time with a hot single reservation of components during the operation time θ, $\theta \ge 0$

$C_{ig}^{(1)}(\theta)$,

– the total operation cost of the repairable system with ignored renovation time with a cold single reservation of components during the operation time θ, $\theta \ge 0$

$C_{ig}^{(2)}(\theta)$,

– the total operation cost of the repairable system with ignored renovation time with components improved by reduction their rates of departures during the operation time θ, $\theta \geq 0$

$C_{ig}^{(3)}(\theta, \rho(r))$,

iii) for a repairable system with non-ignored renovation time:

– the total operation cost of the repairable system with non-ignored renovation time with non-improved components during the operation time θ, $\theta \geq 0$

$C_{nig}^{(0)}(\theta)$,

– the total operation cost of the repairable system with non-ignored renovation time with a hot single reservation of components during the operation time θ, $\theta \geq 0$

$C_{nig}^{(1)}(\theta)$,

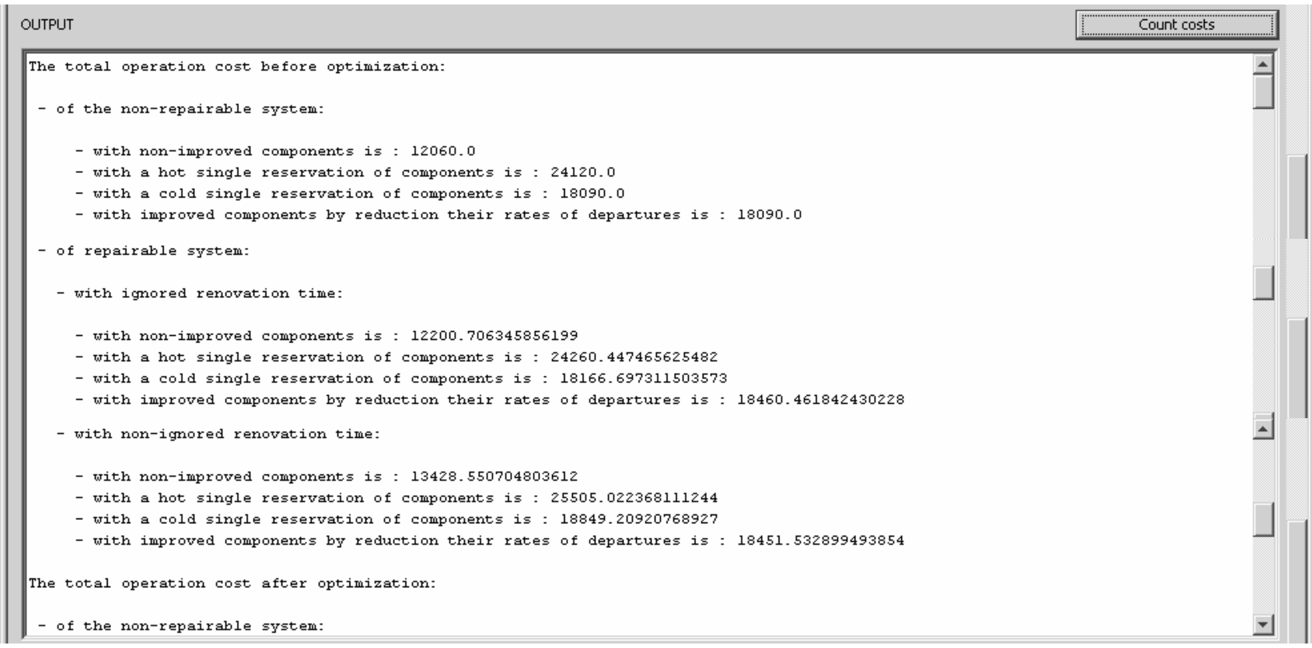
– the total optimal operation cost of the non-repairable system with a hot single reservation of components during the operation time θ, $\theta \geq 0$
$\dot{C}^{(1)}(\theta)$,

– the total optimal operation cost of the non-repairable system with a cold single reservation of components during the operation time θ, $\theta \geq 0$

$\dot{C}^{(2)}(\theta)$,

– the total operation cost of the repairable system with non-ignored renovation time with a cold single reservation of components during the operation time θ, $\theta \geq 0$

$C_{nig}^{(2)}(\theta)$,



b) after the system operation process optimization

i) for a non-repairable system:

– the total optimal operation cost of the non-repairable system with non-improved components during the operation time θ, $\theta \geq 0$

$\dot{C}^{(0)}(\theta)$,

– the total operation cost of the repairable system with non-ignored renovation time with improved components by reduction the rates of departures in the reliability state subsets during the operation time θ, $\theta \geq 0$

$C_{nig}^{(3)}(\theta, \rho(r))$,

– the total optimal operation cost of the non-repairable system with improved components by reduction their rates of departures from the reliability state subsets during the operation time θ, $\theta \geq 0$

$\dot{C}^{(3)}(\theta, \rho(r))$,

ii) for a repairable system with ignored renovation time:

– the total optimal operation cost of the repaired system with ignored renovation time with non-improved components during the operation time θ, $\theta \geq 0$

$\dot{C}^{(0)}_{ig}(\theta)$,

– the total optimal operation cost of the repaired system with ignored renovation time with a hot single reservation of components during the operation time θ, $\theta \geq 0$

$\dot{C}^{(1)}_{ig}(\theta)$,

– the total optimal operation cost of the repairable system with ignored renovation time with a cold single reservation of components during the operation time θ, $\theta \geq 0$

$\dot{C}^{(2)}_{ig}(\theta)$,

– the total optimal operation cost of the repairable system with ignored renovation time with improved components by reduction the rates of departures during the operation time θ, $\theta \geq 0$

$\dot{C}^{(3)}_{ig}(\theta, \rho(r))$,

iii) for a repairable system with non-ignored renovation time:

– the total optimal operation cost of the repairable system with non-ignored renovation time with non-improved components during the operation time θ, $\theta \geq 0$

$\dot{C}^{(0)}_{nig}(\theta)$,

– the total optimal operation cost of the repairable system with non-ignored renovation time with a hot single reservation of components during the operation time θ, $\theta \geq 0$

$\dot{C}^{(1)}_{nig}(\theta)$,

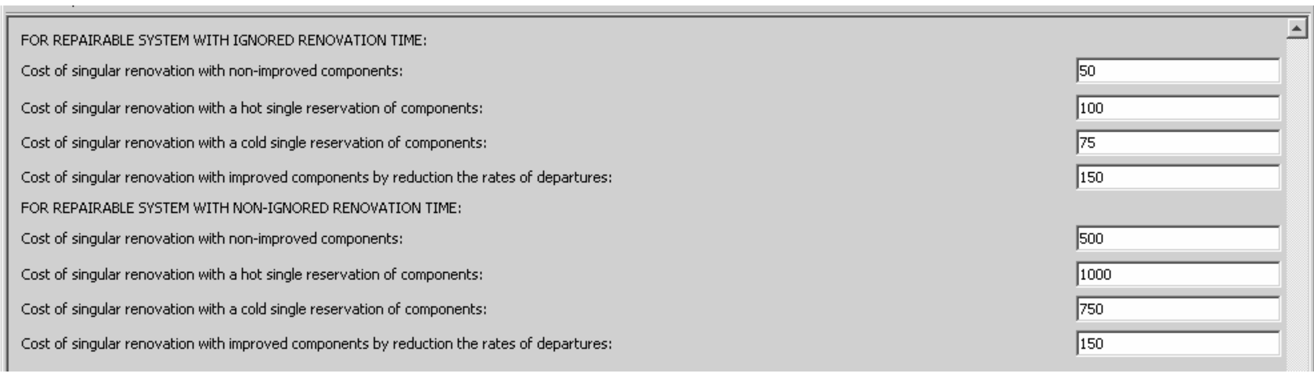
– the total optimal operation cost of the repairable system with non-ignored renovation time with a cold single reservation of components during the operation time θ, $\theta \geq 0$

$\dot{C}^{(2)}_{nig}(\theta)$,

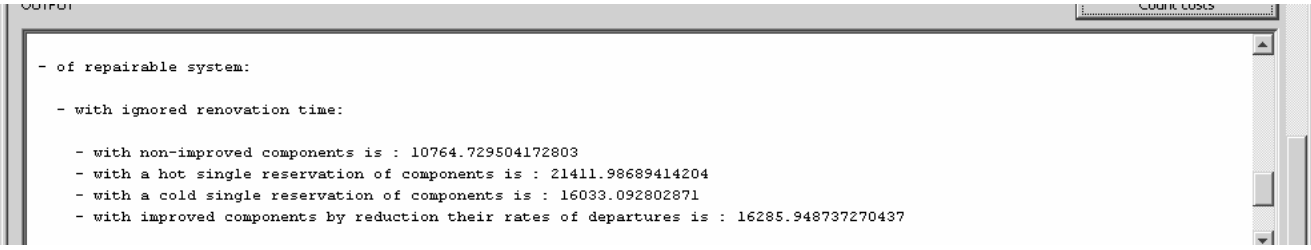
– the total optimal operation cost of the repairable system with non-ignored renovation time with improved components by reduction the rates of departures in the reliability state subsets during the operation time θ, $\theta \geq 0$

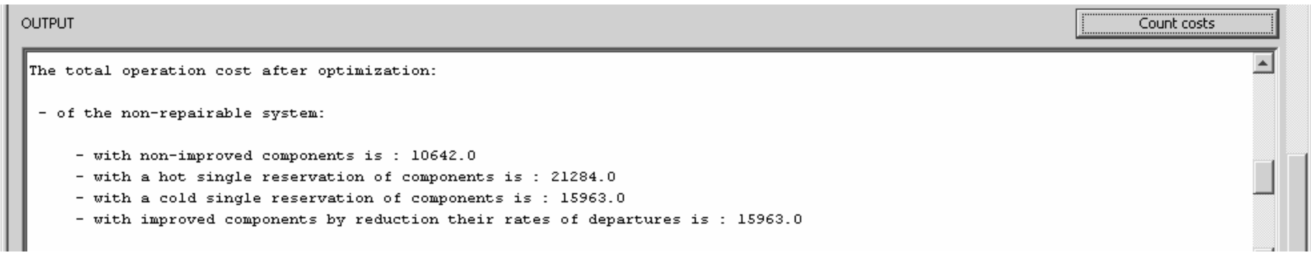
$\dot{C}^{(3)}_{nig}(\theta, \rho(r))$.

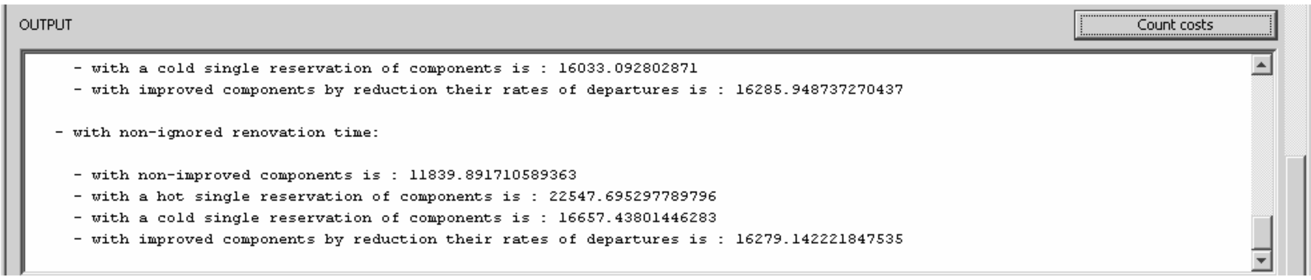
The results of the program for the operation cost analysis of the improved exemplary system are presented in the following two windows.



FOR REPAIRABLE SYSTEM WITH IGNORED RENOVATION TIME:	
Cost of singular renovation with non-improved components:	50
Cost of singular renovation with a hot single reservation of components:	100
Cost of singular renovation with a cold single reservation of components:	75
Cost of singular renovation with improved components by reduction the rates of departures:	150
FOR REPAIRABLE SYSTEM WITH NON-IGNORED RENOVATION TIME:	
Cost of singular renovation with non-improved components:	500
Cost of singular renovation with a hot single reservation of components:	1000
Cost of singular renovation with a cold single reservation of components:	750
Cost of singular renovation with improved components by reduction the rates of departures:	150







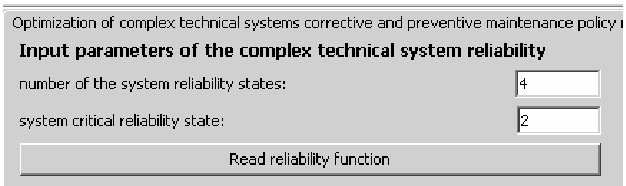
13. The exemplary system corrective and preventive maintenance policy optimization

13.1. Maintenance policy maximizing system availability

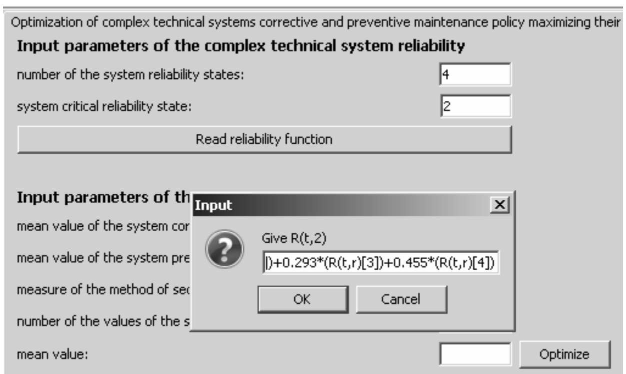
To optimize the exemplary system corrective and preventive maintenance policy maximizing its availability, we use the computer program CP 8.14 “Optimization of system corrective and preventive maintenance policy maximizing their availability”. The computer program allows to determine [1] the optimal value of the system preventive maintenance period of time that maximizes the availability coefficient of this system using the method of secants, in the case when such optimal value exists. Otherwise, in the case when there is no optimal value of the preventive maintenance period of time that maximizes the system availability coefficient, the computer program allows to determine the values of the system availability coefficient for the fixed values of the preventive maintenance period of time.

To make the optimization the complex technical system corrective and preventive maintenance policy maximizing its availability, the computer program is loaded following input reliability parameters:

– the number of the system reliability states,
– the system critical reliability state *r*,



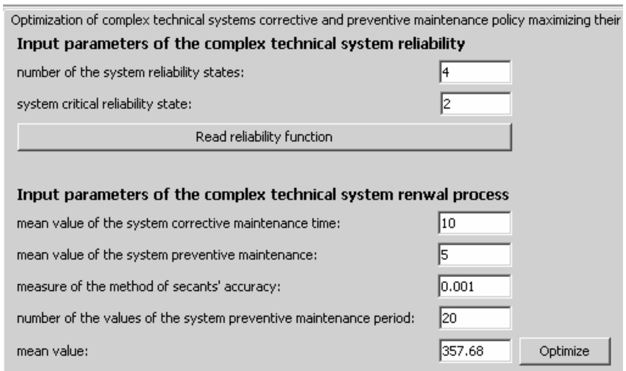
– the r-th coordinate $\boldsymbol{R}(t,r)$, $t \geq 0$, of the system unconditional reliability function $\boldsymbol{R}(t,\cdot)$, determined in Section 6 [4],



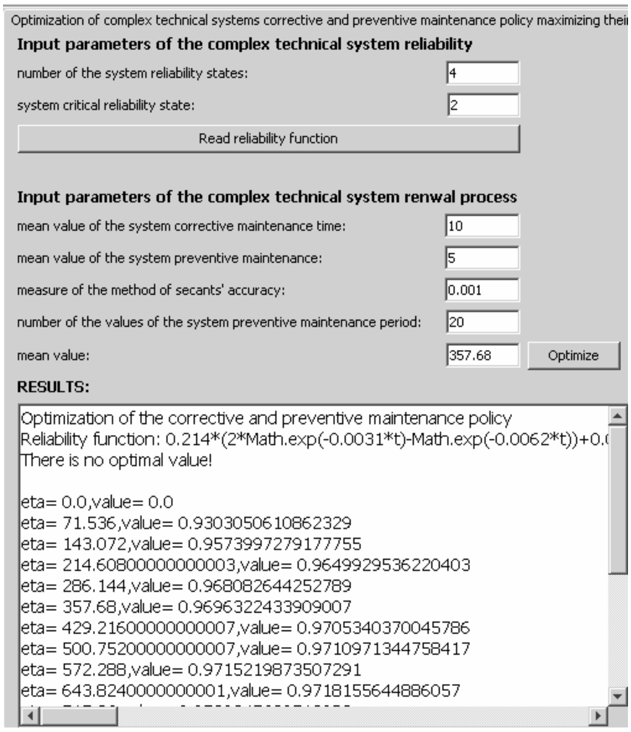
The computer program is loaded the following input renewal parameters [11]:

– the mean value $\mu_0(r)$ of the system corrective maintenance (renovation) time,

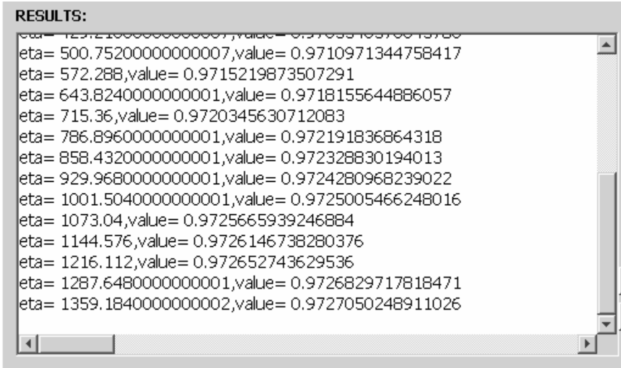
– the mean value $\mu_1(r)$ of the system preventive maintenance (renovation) time,
– the measure ε of the method of secants' accuracy,
– the number κ of the values of the system preventive maintenance period for which we find the values of the availability coefficient of the system,
– the values η_1, η_2, ..., η_κ of the system preventive maintenance period for which we find the values of the availability coefficient.



To start the optimization, the button "Optimize" should be pressed. According to the procedure of optimization [7] when the the mean value of the system corrective maintenance (renovation) time is less or equal to the mean value of the system preventive maintenance (renovation) time, then there is no optimal value, what is signed in the field of results.

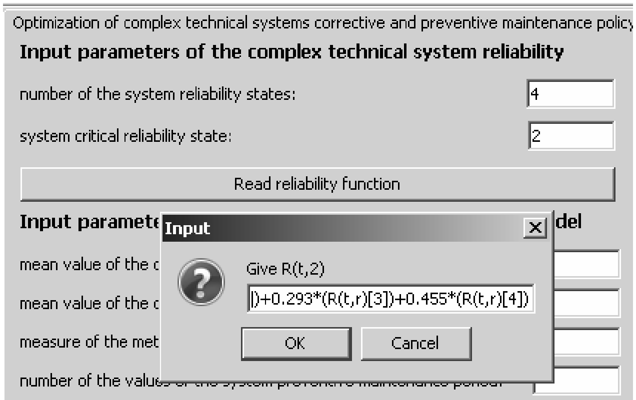


When the optimal value exists, program gives the appropriate message in result window, with particular value of maximal availability coefficient and value of optimal period.



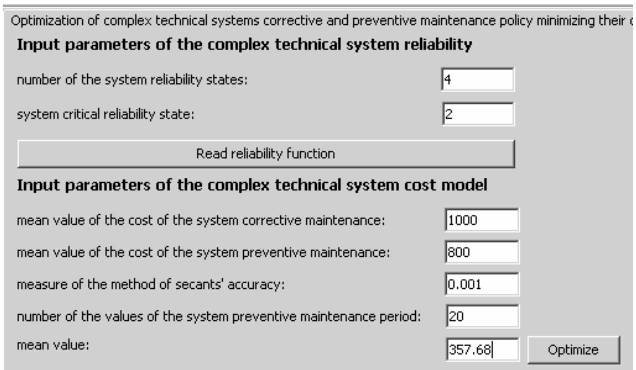
13.2. Maintenance policy minimizing system renovation cost

To optimize the exemplary system corrective and preventive maintenance policy minimizing its cost of renovation, we use the computer program CP 8.15 "Optimization of system corrective and preventive maintenance policy minimizing their cost of renovation". The computer program allows to determine [2] the optimal value of the system age at which the system successive preventive renovation is performed that minimizes the cost of the system renovation per unit of time using the method of secants, in the case when such optimal value exists. Otherwise, in the case when there is no optimal value of the system age at which the system successive preventive renovation is performed that minimizes the cost of the system renovation per unit of time, the program allows to determine the values of the system operation cost for the selected fixed values of the system age at which the system successive preventive renovation is performed.
The computer program is loading the following input parameters for the complex technical system reliability:
– the number of the system reliability states,
– the system critical reliability state r,
– the r-th coordinate $\boldsymbol{R}(t,r)$, $t \ge 0$, of the system unconditional reliability function $\boldsymbol{R}(t,\cdot)$, determined in Section 6 [4],



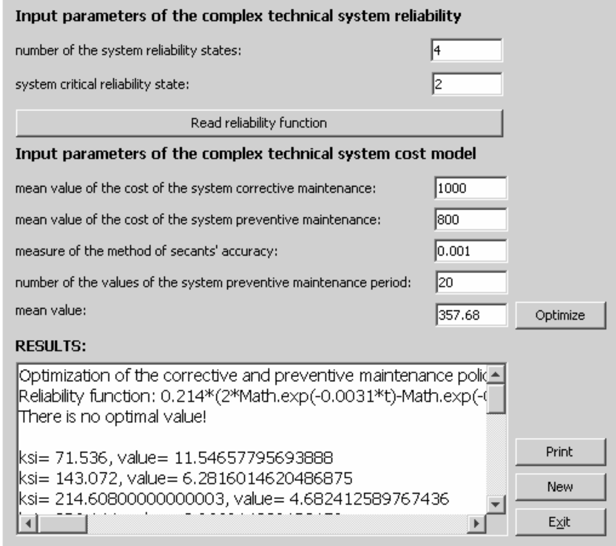
The computer program is loading the following input parameters for cost model of complex technical system [11]:

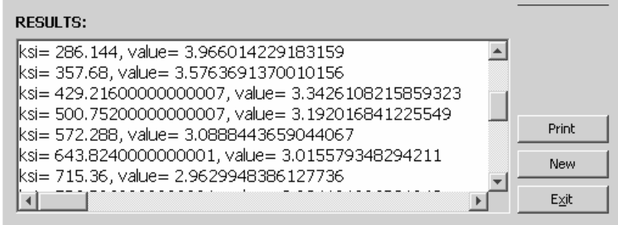
- the mean value $c_0(r)$ of the cost of the system corrective maintenance (renovation),
- the mean value $c_1(r)$ of the cost of the system preventive maintenance (renovation),
- the measure ε of the method of secants accuracy,
- the number κ of the values of the system age for which we find the values of the cost of the system renovation per unit time,
- the values ς_1, ς_2, ..., ς_κ of the system age for which we find the values of the cost of the system renovation per unit time.

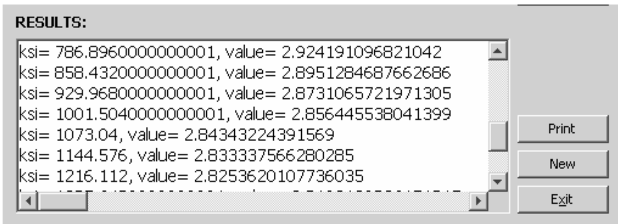


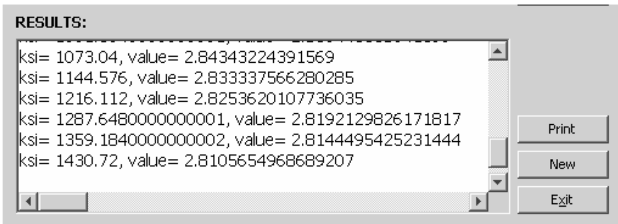
To start the optimization procedure [7], the button "Optimize" should be pressed. According to the procedure of optimization when the mean value of the cost of the system corrective maintenance is less or equal to mean value of the cost of the preventive maintenance, there is no optimal value and the message about it is given in the window with results.

Another message is given when there is the optimal value, with this value and minimal cost of renovation.









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