A multi objective optimization model for redundancy allocation problems in series-parallel systems with repairable components

Authors:

**Maghsoud Amiri (corresponding author) (**Department of Industrial Management, Faculty of Management and Accounting, Allameh Tabatabaei University, Tehran, Iran email:Amiri@atu.ac.ir)

**Mohammadreza Sadeghi** (Department of Industrial Management, Faculty of Management and Accounting, Allameh Tabatabaei University, Tehran, Iran; e-mail: m.r.sadeghi61@gmail.com)

**Ali Khatami Firoozabadi (**Department of Industrial Management, Faculty of Management and Accounting, Allameh Tabatabaei University, Tehran, Iran)

**Fattah Mikaeili (**Department of Industrial Management, Faculty of Management and Accounting, Allameh Tabatabaei University, Tehran, Iran)

**Abstract**

The main goal in this paper is to propose an optimization model for determining the structure of a series-parallel system. Regarding the previous studies in series-parallel systems, the main contribution of this study is to expand the redundancy allocation parallel to systems that have repairable components. The considered optimization model has two objectives: maximizing the system mean time to first failure and minimizing the total cost of the system. The main constraints of the model are: maximum number of the components in the system, maximum and minimum number of components in each subsystem and total weight of the system. After establishing the optimization model, a multi objective approach of Imperialist Competitive Algorithm is proposed to solve the model.

***Key words****: redundancy allocation problem; series-parallel system; repairable components; multi objective optimization; imperialist competitive algorithm*

**1. Introduction**

Development of a reliable system involves various complex and interrelated factors. The translation of overall system reliability into requirements at various subsystem levels, is an important task for those responsible for the design and development of reliable systems [1]. Enhancing the system reliability is one of the most attractive areas for system developers and using redundant components is one of the most frequent approaches in system design process. The series-parallel configuration is a kind of system design that resulted by using redundant components for each subsystem in a simple series system [2]. Figure 1 shows a simple series system and a series-parallel system design.

Series system

1

2

3

11

21

31

12

22

32

Series-parallel system

Figure 1: the difference between series systems and series-parallel systems

 Selecting the series-parallel configuration for using redundant component in order to enhance the system reliability, result in a challenge for the designers: decision making about the subsystem components by considering the available resources. This challenge was the main reason to start an interesting stream in the reliability optimization literature, called “redundancy allocation problems in series-parallel systems”. Since the first paper on redundancy allocation problem in series-parallel system by Fyffe et.al [1] many researchers have tried to develop this knowledge. Two main approaches in the development of redundancy allocation problem literature could be seen: 1-Proposing new method to solve the previous optimization models on redundancy allocation problems and 2- developing the new optimization models for redundancy allocation problems. Coelho[3] , Ramirez-Marquez et.al [4], Coit and Liu [5], Ouzineb et.al[6], Ramirez-Marquez and Coit [7], Yun and Kim [8], Nahas et al.[9], Kulturel-Konak et.al [10], Liang and Chen [11], Coit[12], Ha and Kuo [13], Yalaoui et.al [14], You and Chen[15] , Liang et.al [16], Juang et.al[17], Coit and Konak [18], Kumar et.al [19], Yeh [2], Wang and Watada [20] Kumar et.al[21] and Liu [22] are some of the studies on redundancy allocation problem in series-parallel system. Conducting a survey of redundancy allocation problems literature reveals that the repairable systems have not been involved in previous works. In this study the main goal is to expand the redundancy allocation problems in to repairable systems. The lack of studies for redundancy allocation problem in series-parallel system with repairable components and subsystems has been concluded in Kuo and Wan [23] after a complete survey on redundancy allocation problem literature.

There are two general problem classifications for redundancy allocation problems in series-parallel systems; for the first there are discrete component choices with known characteristics (cost, weight, etc.). Objective of these problems is to select which components should be used and their corresponding redundancy level. For the second, component reliability is treated as a design variable and component cost is a predefined increasing function of component reliability [5]. This paper pertains to the first type of problem.

*Availability* is the term which replaces *reliability* in repairable systems. Reliability of a system at time *t,* is defined as the probability that the system could performed its required function under a given condition for a stated time interval [0,t].[24] A failure in an un-repairable system before time *t* makes the system unreliable at that time. But for the repairable systems the *availability* is defined as the probability that the system could performed its required function under a given condition at time *t* regardless of its previous fails and repairs during [0,t]. For an un-repairable system *Mean Time to Failure (MTTF)* is defined as the average of system lifetime but in repairable systems *Mean Time to First Failure* *(MTTFF)*, the term that replaces MTTF, is equal to average time before the system fails for the first time; the repairable system could be repaired after the fail and restarts its function.

The main goal in this paper is to optimize the redundancy allocation in a repairable series-parallel system; the main contribution of the paper is to encircle the reparability of the system components in the optimization process.

Structure of the paper is organized as follow: the availability calculation method in repairable systems is described in the second part. In the third part, the main assumptions of the repairable system, which should be considered for optimizing its components redundancies, are clarified. By considering the main assumptions of the system, in the fourth part, optimization model of the system is established. In the fifth part, the solution method for the optimization model is described and in the sixth part a real world case study is solved by the proposed model and solving approach, clarified in previous parts.

**2. Availability**

Calculating the availability of a repairable system is one of the interesting areas in repairable system. Since in this paper, the considered repair and failure rate for the components of series-parallel system are constant and failure and repair of the components have exponential distribution, a brief review of calculating the availability and MTTFF of these systems is presented in this part. The basic concept of Markove process is used to determine the availability of system. For more details about the availability calculation in repairable systems Birolini [24] and Billinton and Allan[25] could be studied.

Suppose that there is a system with an only one repairable component such, its failure rate is 𝜆 and its repair rate is µ; the state space diagram of the system could be established as Figure 2

State 0

Component operable

State 1

Component failed

𝜆

µ

Figure 2: the states of a repairable system with one component

When the system state is 0, it is capable of operation and is able to perform its function while in state 1 it is not able to do its function and should be repaired. Hence the availability of the system at time *t* is the probability of residing in the operable state (state 0) at time *t,* and the unavailability is the probability of residing in the failed state (state 1). Billinton and Allan[25] have driven EQ. 1 for these probabilities:

|  |  |
| --- | --- |
| EQ. 1 |   |

 and are the probability of residing in state 0 and state 1 respectively; and are the derivative of and with respect to *t*. EQ. 1 is comprised of a couple of differential equations. There are a various methods, by which, these differential equations could be solved. Using Laplace transforms, EQ. 2 could be concluded from EQ. 1:

|  |  |  |
| --- | --- | --- |
| EQ. 2 | a |   |
| b |   |

 and are the probability of residing system in each state of t=0 and is equal to 1. If the system starts its function correctly at t=0, then P0(0)=1 and P0(1)= 0 and EQ. 3 could be obtained from equation EQ. 2

|  |  |  |  |
| --- | --- | --- | --- |
| EQ. 3 | a |  |   |
| b |  |   |

Therefore, to calculate the availability of the system, firstly all the possible states of the system should be distinguished and the coefficient matrix in EQ. 1, called transaction matrix, should be established; then the differential equations should be solved. The transaction matrix is a square matrix and its dimensions are equal to number of states. After calculating the *Pi(t)*s, the availability of the system will be equal to the summation of *Pi(t)*sof the states in which the system performs its function correctly. Main challenge in calculating differential equations for a system is calculation volume required to solve the equations. Calculating the *Pi(t)*s of a repairable system is an attractive aspect of repairable systems: Bailey [26], Bhat [27], Grassmann [28], Sumita and Shanthikumar [29], Ross [30], Shaked and Shanthikumar [31], Shanthikumar and Yoon [32], Hoyland and Rausand [33], Moustafa [34], Moustafa [35], Zhang et.al [36], Azaron et.al [37], Li et.al [38] and Amiri and Ghassemi-Tari [39] are some of the studies which have proposes mathematical methods for calculating the *Pi(t)*s in repairable systems. In this paper the recommended mathematical method of Amiri and Ghassemi-Tari [39] is used to determine the availability of the system, therefore this method is clarified in more detail; more information about the method and its mathematical basis is available in Amiri and Ghassemi-Tari [39].

Establishing the transaction matrix of the system is the prerequisite of the performance indexes calculation for a repairable system. To establish the transaction matrix, firstly all the possible states of the system should be determined (like Figure 2). Then all the possible transactions between states should be detected. Note that the possible transactions are those with only one repair or fail between states transitions during their occurrences. The dimensions of the transaction matrix are equal to the number of states and each row or column is related to one of the states. The elements of the matrix are determined regarding the repair or failure rate of the transition between corresponding row and column. The summation of the elements in each row should be zero and regarding this consideration, the elements on the diagonal of the matrix could be calculated.

Suppose that the transaction matrix is shown by *Q*, an n×n square matrix, *Q* has n non-repeating eigenvalues; *V* is a matrix of eigenvectors of *Q* and *V-1* is the inverse of *V* and *d* is a diagonal eigenvalues of *Q* defined as follows:

|  |  |
| --- | --- |
| EQ. 4 |   |

Now *p(t)*, the state transient probability in the exponential Markov chain with the continuous time could be calculated by EQ. 5.

|  |  |
| --- | --- |
| EQ. 5 |   |

The probability of residing in state *i* (*i=1,2,…n)*, which shown by vector *Pn(t)*, could be derived by EQ. 6.

|  |  |
| --- | --- |
| EQ. 6 |   |

Where *Pn(0)* is the vector of probability of residing the system in state *i* (*i=*1,2,…n) at *t=0.* Using the elements in *Pn(t),* the availability of the system is the sum of the *Pi(t)*s (*i=*1,2,…n) of the states in which, system does its work correctly. If *B* is the set of functioning states then:

|  |  |
| --- | --- |
| EQ. 7 |   |

The availability of the system is defined as the probability of being in the operational mode (to be up) at time *t*, regardless of its historical failures and/or repairs. Another measure applicable for repairable system is *survivability function*. Survivability at time *t* determines the probability that a system does not leave the functioning states (does not fail) during the time interval (0,t][39] . To calculate the system survivability, the rows and columns related to down states (non-operational states) in the transaction matrix should be deleted; the resulted matrix is called *Q´*. The mathematical operations of EQ. 4 to EQ. 6 should be performed on matrix *Q´*. The survivability of the system at time *t,* which is shown by *Rs(t),* is equal to the summation of the *P­j(t)*s resulted by running EQ. 4 to EQ. 6 on *Q´*.

The mean time to first failure (MTTFF) of the system is the expected time to first failure of the system, which could be calculated by EQ. 8

|  |  |
| --- | --- |
| EQ. 8 |   |

 **3. System assumptions and model variables and parameters**

As mentioned, the main idea in this paper is to expand the redundancy allocation problem into the systems with repairable subsystems and components. The main assumptions of the considered system in this study are:

* Series-parallel system depicted in Figure 1 has *m* subsystems.
* There are *Oi* alternative components could be selected for *i*th subsystem; the decision maker should select one of the alternative components for each subsystem and its redundancy level.
* The failure and repair of each alternative component available for each subsystem has exponential distribution with fail rate and repair rate.
* The system conducts its function perfectly when each subsystem has at least one operable component. Therefore for each subsystem at least one component should be selected.
* The first goal in this study is to maximize the average time before the first failure of the system; the first failure of the system occurs when one of the subsystems fails completely. As Ramirez-Marquez et al. [4] implied the average time before the first failure of the system is equal to minimum of the subsystems MTTFFs. Hence the first goal in optimization process is to maximize the minimum of the subsystems MTTFFs.
* Each alternative component for subsystems has a specific cost. The second goal of the optimization is to minimize the system’s cost.
* Total weight of the system, the total number of system components and the components number of each subsystem has limitations.

Considering the above assumptions the parameters and variables of the optimization model are:

* xij: the number of selected component for *i*th subsystem from *j*th alternative (i= 1,2,…m),(j= 1,2,…Oi)
* : the failure rate of *j*th component for *i*th subsystem (i= 1,2,…m),(j= 1,2,…Oi)
* : the repair rate of *j*th component for *i*th subsystem (i= 1,2,…m),(j= 1,2,…Oi)
* m: the number of subsystems
* i: the index of subsystems
* j: the index of existing component types for each subsystem
* Oi: the number of existing component types for each subsystem
* Cij: the cost of *j*th component type for *i*th subsystem
* wij: the weight of *j*th component type for *i*th subsystem
* Ws: the total weight of system
* Cs: the total cost of system
* nmaxi: the maximum number of components for *i*th subsystem
* nmini: the minimum number of components for *i*th subsystem
* Ns: the maximum total number components of system

**4. Model construction**

According to the model assumptions and model variables and parameters, the details of the optimization model could be defined as below:

***Objective functions***

The first objective function of the optimization model is to maximize the minimum of subsystems MTTFFs; therefore the first objective function could be considered as EQ. 9:

|  |  |
| --- | --- |
| EQ. 9 |   |

When the MTTFFi is:

|  |  |
| --- | --- |
| EQ. 10 |   |

The second objective function is to minimize the total cost of subsystem; therefore the second objective function of optimization model is considered as EQ. 11:

|  |  |
| --- | --- |
| EQ. 11 |   |

***Model constraints***

The constraint indicates the weight of system in model:

|  |  |
| --- | --- |
| EQ. 12 |   |

The constraints that make it possible to select only one type of components for each subsystem:

|  |  |
| --- | --- |
| EQ. 13 |   |

The constraint of system total components:

|  |  |
| --- | --- |
| EQ. 14 |   |

The constraints of minimum and maximum number of components selected for each subsystem:

|  |  |
| --- | --- |
| EQ. 15 |   |

The constraints that determines the type and limits of variables:

|  |  |
| --- | --- |
|  EQ. 16  |   |

**5. Solving approach: Multi-objective Imperialist Competition Algorithm**

The main characteristic of the designed model in this paper, unlike the traditional optimization models, is the lack of a polynomial function between the first objective function (and the model variables (xij). For calculating the MTTFFs of subsystems, when the components are repairable, the mathematical method proposed by Amiri and Ghassemi-Tari [39] could be applied. On the other hand, one of the advantages of meta-heuristic algorithms is their applicability for solving the optimization models in which there are no polynomial function between objectives or constraints and the variables. Therefore in this paper one of the meta-heuristic algorithms is applied to solve the defined optimization model.

Imperialist Competition Algorithm (ICA) is one of the meta-heuristic algorithms, which has been applied for solving many optimization models since its introduction by Atashpaz-Gargary and Lucas.

In this work ICA is applied to solve the optimization method, clarified in previous sections. ICA, proposed by Atashpaz-Gargary and Lucas [40], is a Meta-heuristic algorithm applicable for solving the optimization models. This algorithm is inspired by the imperialistic competition. Like other evolutionary algorithm, ICA starts with an initial population. Population individuals, called country, are classified into two types: colonies and imperialists. An empire consists of an imperialist and some colonies. Imperialistic competition among these empires forms the basis of this evolutionary algorithm. During this competition, weak empires collapse and powerful ones take possession of their colonies. So, to prevent the collapse of an empire, during the progress of algorithm the imperialist countries try to make their colonies more powerful. Imperialistic competition hopefully converges to a state in which only one empire exists and its colonies are in the same position and have the same cost as the imperialist.

The first version of ICA was proposed for solving the optimization models with only one objective; however this algorithm was also applied in multi objective optimization models by many researchers. Abdi et.al [41], Abedinia et.al [42], Mohammadi et.al [43] and Ghanavati et.al [44] are some of the applications of ICA in solving the multi objective optimization. Some adjustments should be made in the original version of ICA to apply it in a multi objective optimization model. In this study these adjustments are done as follow:

**5.1. Countries structure**

The structure designed to depict the answers of a specific model could be unique. In ICA the structure of countries shows the circumstanceof defining the decision variables of the model. The role of countries structure is exactly like the role of chromosomes in genetic algorithm (GA). Regarding the model assumptions and its variables in this study, the structure of the countries is defined as Figure 3

...

Component type for the first subsystem

Number of component for the first subsystem

Component type for the *m*th subsystem

Number of component for the *m*th subsystem subsystem

Figure 3: the structure of the optimization problem’s answe

As shown in Figure 3, the answers of the optimization models are matrixes with two rows, the number of columns are equal to the number of subsystems. The elements of the first row illustrate the type of component, selected for the related subsystem. The element in second row of each subsystem column, verifies the number of selected components for related subsystem.

**5.2. Initial countries generation**

One of the main characteristics of the meta-heuristic algorithms is their random behavior in searching the feasible solution space. The start population of these algorithms is generated by stochastic process. Generating new population by current population is done by using the random numbers and parameters. In this study the first generation of countries is produced randomly; firstly all the matrixes of answers elements are established by random numbers between 0 and 1. Then, the first element of each column is multiplied by the number of existing component types for the related subsystem while the result is rounded to the first larger integer number. The second element of each column is multiplied by the maximum number of components could be selected for related subsystem while the result is rounded to the nearest integer number. The results are matrixes with integer elements, which culd be considered as countries and the start population of algorithm.

**5.3. Imperialists Selection**

After generating countries, a non-dominance technique and a crowding distance are used to select the imperialists. At first, the countries which are not dominated by other countries are selected; if the number of non-dominated countries is more than required imperialists, the countries with larger crowding distance are selected as imperialist countries between them. The remaining countries are considered as colonies, distributed among the imperialists with respect to imperialist power.

**5.4. Calculation of imperialists cost**

To calculate the cost of each imperialist, EQ. 17 is applied as follow:

|  |  |
| --- | --- |
|   | EQ. 17 |

Where is the normalized value of objective function *i* for imperialist *n*, andis the value of the objective function *i* for imperialist *n*. Also, and are the best, maximum and minimum values of *i*th objective function in each iteration, respectively. Finally, the normalized cost value of each imperialist () is obtained as below:

|  |  |
| --- | --- |
|   | EQ. 18 |

Where *r* is the number of objective functions. The power of each imperialist is calculated by EQ. 19, the colonies are distributed among the imperialists according to the power of each imperialist country.

|  |  |
| --- | --- |
|   | EQ. 19 |

Then, the initial number of colonies of an empire will be calculated as follow:

|  |  |
| --- | --- |
|   | EQ. 20 |

Where is the initial number of colonies of the *n*-th imperialist, and is the number of all colonies. of colonies are randomly selected and assign to the imperialists. Therefore, more powerful imperialist takes a greater number of colonies while imperialist with weaker power has less number.

**5.5. Total power for an empire**

The total power of an empire is mainly affected by the power of the imperialist country; however, the power of the colonies of an empire has an eligible effect on the total power of that empire. Therefore, the equation of the total power of an empire is calculated as below.

|  |  |
| --- | --- |
|   | EQ. 21 |

Where *TP of Empn* is the total power of the *n*th empire and is a positive number which is considered to be less than 1. The total cost of imperialists and colonies are calculated by EQ. 17 and EQ. 18. It is necessary to mention that the effect of colonies on an empire’s cost is related the value of ; therefore greater value of resulted in greater contribution of colonies in the total cost of an empire and vice versa.

**5.6. Searching solution space**

In this study the assimilation technique is applied for searching the solution space. After dividing colonies between imperialists, colonies are moved towards their related imperialist. This movement is shown in Figure 4, in which *d* is the distance between colony and imperialist, *x* is the amount of moving of colony towards the imperialist which has a uniform distribution between 0 and and is a number greater than 1. For moving colony towards imperialist in other direction, an angle,, is applied with a uniform distribution between and . It has been estimated that is the most proper value of .

Imperialist

New Position of Colony

Colony

Figure 4: Moving colonies toward the imperialists with a random angle

**6. Numerical case study**

In this part, regarding the alternative components for a system with 4 subsystems, the application result of optimization model and the solving approach for designed model is presented. The system has 4 subsystems with series-parallel configuration and the parameters of alternative components for each subsystem is depicted in Table 1

Table 1: subsystems alternative components

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| subsystem | Maximum number of components in subsystem | Minimum number of components in subsystem | Component types | Failure rate | Repair rate | Weight | Cost |
| 1 | 5 | 1 | 1 | 2 | 10 | 100 | 120 |
| 2 | 5 | 18 | 80 | 100 |
| 3 | 4 | 25 | 85 | 140 |
| 4 | 2 | 8 | 90 | 110 |
| 2 | 6 | 1 | 1 | 5 | 40 | 250 | 400 |
| 2 | 6 | 42 | 200 | 380 |
| 3 | 10 | 100 | 200 | 500 |
| 3 | 4 | 1 | 1 | 4 | 22 | 450 | 800 |
| 2 | 4 | 28 | 550 | 800 |
| 3 | 7 | 20 | 250 | 800 |
| 4 | 7 | 18 | 200 | 800 |
| 4 | 4 | 1 | 1 | 5 | 30 | 500 | 1200 |
| 2 | 7 | 35 | 500 | 1500 |
| 3 | 3 | 25 | 500 | 1500 |
| maximum number of total component in system = 20maximum weight of the system = 4500 |

After establishment of the optimization model with two objectives, maximizing the minimum of subsystems MTTFFs and minimizing the total cost of system, and the related constraints of system the model was solved by the ICA approach as clarified in previous part. For solving the optimization model firstly, the parameters of ICA approach should be defined. The definition of the ICA approach parameters was done by using the RSM method. The result of the parameters tuning by Expert Design software could bel seen in Table 2

Table 2: the parameters for ICA

|  |  |  |  |
| --- | --- | --- | --- |
| Parameters |  |  | Optimal value |
| *n-Pop* |  |  | 193 |
| *N-imp* |  |  | 5 |
| *PA* |  |  | 0.54 |
| *ξ* |  |  | 0.195 |
| *β* |  |  | 1.8 |

In Table 2, *n-pop ­*is the number of countries; the number of imperialist is *N-imp,* PA is the ratio demonstrating the probability of doing the assimilation for a colony towards its imperialist. *ξ* is the contribution of colonies in calculating the empires cost and *β* is the parameter defined in part 5.

Like solving the other multi objective optimization models, the application of ICA for solving the model resulted in a pareto optimal answers. The pareto optimal answers contains the answers that was not dominated by the other answers. The pareto optimal answers for the optimization model of the considered system are depicted in Table 3.

**7. Conclusion**

The previous studies in redundancy allocation problems in series-parallel systems have not been considered the systems with repairable components. In this paper the main idea is to propose a multi objective approach for redundancy allocation problems in series-parallel systems with repairable components. The considered system in this study has components with constant failure and repair rate, therefore considering systems comprising of components without exponential distribution for theire repair and failure times could be a good challenge for future studies.

Table 3: the pareto optimal answers for optimization model resulted by using the ICA

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| No. | System structure | MTTFF | Cost | weight | No. | System structure | MTTFF | Cost | Weight |
| 1 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 3 | 1 | 2 | 1 | Component type |
| 1 | 1 | 1 | 1 | numbers |

 | 0.1667 | 2480 | 1250 | 2 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 3 | 1 | 2 | 4 | Component type |
| 1 | 1 | 1 | 1 | numbers |

 | 0.2 | 2500 | 1240 |
| 3 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 1 | 1 | 1 | 4 | Component type |
| 1 | 1 | 2 | 1 | numbers |

 | 0.25 | 3170 | 1540 | 4 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 1 | 1 | 1 | 4 | Component type |
| 1 | 2 | 2 | 1 | numbers |

 | 0.333 | 3970 | 1990 |
| 5 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 3 | 4 | 2 | 4 | Component type |
| 2 | 2 | 2 | 1 | numbers |

 | 0.5 | 4870 | 1890 | 6 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 3 | 1 | 2 | 4 | Component type |
| 2 | 2 | 2 | 2 | numbers |

 | 0.6282 | 4960 | 2480 |
| 7 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 1 | 4 | 2 | 2 | Component type |
| 2 | 2 | 2 | 2 | numbers |

 | 0.8163 | 4980 | 1960 | 8 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 3 | 2 | 1 | 2 | Component type |
| 2 | 2 | 2 | 2 | numbers |

 | 0.8772 | 5020 | 2760 |
| 9 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 3 | 2 | 2 | 4 | Component type |
| 2 | 2 | 2 | 2 | numbers |

 | 1.0815 | 5620 | 2680 | 10 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 3 | 4 | 2 | 4 | Component type |
| 2 | 2 | 3 | 2 | numbers |

 | 1.2245 | 5960 | 2180 |
| 11 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 3 | 2 | 2 | 4 | Component type |
| 2 | 3 | 3 | 2 | numbers |

 | 1,6754 | 6760 | 3430 | 12 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 3 | 1 | 2 | 4 | Component type |
| 2 | 3 | 3 | 2 | numbers |

 | 1.8590 | 6760 | 3130 |
| 13 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 3 | 1 | 2 | 4 | Component type |
| 3 | 3 | 3 | 2 | numbers |

 | 1.9354 | 7380 | 3630 | 14 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 1 | 4 | 2 | 4 | Component type |
| 3 | 3 | 3 | 3 | numbers |

 | 4.128 | 7470 | 2970 |
| 15 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 3 | 2 | 2 | 1 | Component type |
| 3 | 3 | 3 | 3 | numbers |

 | 4.3630 | 8370 | 4050 | 16 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 3 | 2 | 2 | 4 | Component type |
| 3 | 3 | 3 | 3 | numbers |

 | 5.7877 | 8430 | 4020 |
| 17 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 3 | 2 | 2 | 4 | Component type |
| 3 | 3 | 3 | 3 | numbers |

 | 6.4691 | 8460 | 4020 | 18 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 3 | 2 | 2 | 4 | Component type |
| 3 | 3 | 4 | 3 | numbers |

 | 6.5440 | 8780 | 4220 |
| 19 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 3 | 1 | 2 | 4 | Component type |
| 3 | 4 | 4 | 3 | numbers |

 | 7.8894 | 9580 | 4370 | 20 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 3 | 1 | 2 | 4 | Component type |
| 3 | 4 | 4 | 4 | numbers |

 | 11.5181 | 9700 | 4460 |

**References**

1. Fyffe, D.E., Hines, W.W., Lee., N.K.,*"System Reliability Allocation and a Computational Algorithm"*, IEEE Transactions on Reliability, Vol.17, 1968, pp. 64-69.
2. Yeh, W., "*A two-stage discrete particle swarm optimization for the problem of multiple multi-level redundancy allocation in series systems*", Expert Systems with Applications, Vol.36, 2009, pp. 9192–9200.
3. Coelho, L.D.S., "*Reliability–redundancy optimization by means of a chaotic differential evolution approach*", Chaos, Solitons and Fractals, Vol.41, 2009, pp.594–602.
4. Ramirez-Marquez, J.E., Coit, D.W., Konak, A., "*Redundancy allocation for series-parallel systems using a max-min approach*", IIE Transactions, Vol. 36, 2004, pp.891-898.
5. Coit, D.W., Liu, J., "*System reliability optimization with k-out-of n subsystems*", International Journal of Reliability, Quality and Safety Engineering, Vol. 7, 2000, 129-142
6. Ouzineb, M., Nourelfath, M., Gendreau, M., "*An efficient heuristic for reliability design optimization problems*", Computers & Operations Research, Vol. 37, 2010, pp.223-235.
7. Ramirez-Marquez, J.E., Coit, D.W., "*A heuristic for solving the redundancy allocation problem for multi-state series-parallel systems*", Reliability Engineering and System Safety, Vol.83, 2004, pp.341–349.
8. Yun, W.Y., Kim, J.W., "*Multi-level redundancy optimization in series systems*", Computers & Industrial Engineering, Vol.46, 2004, pp. 337–346.
9. Nahas, N., Nourelfath, M., Ait-Kadi, D., "*Coupling ant colony and the degraded ceiling algorithm for the redundancy allocation problem of series–parallel systems*", Reliability Engineering and System Safety,Vol**.** 92, 2007, pp. 211–222.
10. Kulturel-Konak, S. , Smith, A.E., Coit, D.W., "*Efficiently Solving the Redundancy Allocation Problem Using Tabu Search*", IIE Transactions, Vol.35,2003, pp.515-
11. Liang, Y.C., Chen, Y.C., "*Redundancy allocation of series-parallel systems using a variable neighborhood search algorithm*", Reliability Engineering and System Safety, Vol.92, 2007, pp. 323–331.
12. Coit, D.W., "*Maximization of System Reliability with a Choice of Redundancy Strategies*", IIE Transactions, Vol.35, 2003, pp.535-543.
13. Ha, C., Kuo, W., "*Reliability redundancy allocation: An improved realization for nonconvex nonlinear programming problems*", European Journal of operation research. Vol. 171, 2006, pp.24–38.
14. Yalaoui, A., Chu, C., Chatelet, E., "*Reliability Allocation Problem in Series-Parallel System*". Reliability Engineering and System Safety***.***Vol.90, 2005, pp.55-61.
15. You, P.S., Chen, T.C., "*An efficient heuristic for series-parallel redundant reliability problems*", Computers & Operations Research. Vol. 32, 2005, pp.2117–2127.
16. Liang, Y.C.,Lo, M.H., Chen, Y.C., "*Variable neighborhood search for redundancy allocation problems*",IMA Journal of Management Mathematics**,** Vol.18, 2007, pp.135−155.
17. Juang, Y.S., Lin, S.S., Kao, H.P., "*A knowledge management system for series-parallel availability optimization and design*", Expert Systems with Applications, Vol,34, 2008, pp. 181-193.
18. Coit, D.W., Konak, A., "*Multiple Weighted Objectives Heuristic for the Redundancy Allocation problem*", IEEE Transactions on reliability, Vol.55, 2006, pp.551-566.
19. Kumar, R., Izui, K., Masataka, Y., Nishiwaki, S.,"*Multilevel Redundancy Allocation Optimization Using Hierarchical Genetic Algorithm*", IEEE Transactions on reliability, Vol. 57, 2008, pp. 650-661.
20. Wang, S., Watada, J., "Modeling redundancy allocation for a fuzzy random parallel series system", *Journal of Computational and Applied Mathematics*, Vol. 232, 2009, pp.539-557
21. Kumar, R., Izui, K., Yoshimura, M., Nishiwaki, S., "*Optimal multilevel redundancy allocation in series and series–parallel systems*", Computers & Industrial Engineering, Vol.57, 2009, pp. 169-180.
22. Liu, G.S., "*A combination method for reliability-redundancy optimization*", Engineering Optimization, Vol. 38, 2006, pp.485-499.
23. Kuo, W., Wan, R., "Recent Advances in Optimal reliability Allocation". IEEETransactions on system, man and cybernetics- part a: system and humans, Vol.37, 2007, pp.143-156.
24. Birolini, A., "*Reliability engineering theory and practice****.*** *3rd edition*", Springer,1999.
25. Billinton, R., Allan, R., "*Reliability evaluation of engineering system: concept and techniques*", Plenum press,1983.
26. Bailey, N.T.J., "*A continuous time treatment of a single queue using generating functions*", [Journal of the Royal Statistical Society: Series B](http://onlinelibrary.wiley.com/journal/10.1111/%28ISSN%291467-9868), Vol.16, 1954, pp. 288-291.
27. Bhat, U.N., "*Transient behavior of multi-server queues with recurrent input and Exponential service times*", Journal of Applied probability, Vol.5, 1968, pp.158-168.
28. Grassmann, W., "*Transient solutions in Markovian queues*", European Journal of Operation Research, Vol.1, 1977, pp.396-402.
29. Sumita, U., Shanthikumar, J.G., "*Software reliability model with multiple-error introduction and removal*", IEEE Transactions on reliability Vol.35, 1986, pp.459-463.
30. Ross, M., "*Approximating transition probabilities and mean accupation times in continuous-time markov chain*", probability in the Engineering and informational science, Vol.1, 1990, pp.251-264.
31. Shaked, M., Shanthikumar, J.G ., "*Temporal stochastic convexity and concavity*", Stochastic processes and their applications, Vol. 27, 1988, pp.1-20, (1988).
32. Shanthikumar, J. G., Yoon, B.S. "*Bounds & Approximations for the Transient behavior of continues-time markov-chains*", *Probability in the Engineering & Information sciences,*Vol.3, 1992,pp.175-198.
33. Hoyland, A., Rausand, M., "System reliability theory models and statistical methods", The Norwegian Institute of Technology , John Wiley & Sons Inc. 1994.
34. Moustafa, M.S., "*Transient analysis of reliability with and without repair for k-out-of-N: G system with two failure modes*", Reliability Engineering and system safety, Vol. 53, 1996, pp.31-35.
35. Moustafa, M. S., "*Transient analysis of reliability with and without repair for k-out-of-N: G systems with M failure modes*", Reliability Engineering and system safety,Vol. 59,1998, pp.317-320.
36. Zhang, Y.L., Zou, M.J., Yam, R.C.M., "*reliability analysis of a circular consecutive-2-out-of-n:F repairable system with priority in repair*", Reliability Engineering & System Safety, Vol.68, 2000, pp.113-120.
37. Azaron, A., Katagiri, H., Kato, K., Sakawa, M., "*Reliability evaluation of multi-component cold-standby redundant systems*", Applied Mathematics and computation, Vol.173, 2006, pp. 137-149.
38. Li, X., Zuo, M.J., Yam, R.C.M., "*reliability analysis of a repairable k-out-of-n system with some components being suspended when the system is down*", Reliability Engineering & System Safety, Vol.91, 2006, pp.305-310.
39. Amiri, M., Ghassemi-Tari, F., "*A methodology for analyzing the transient availability and survivability of a system with repairable components*". Applied Mathematics and Computation***.*** Vol. 184, 2007, pp. 300-307.
40. Atashpaz-Gargari, E., Lucas, C*.,* "*Imperialist Competitive Algorithm: An Algorithm for Optimization Inspired by Imperialistic Competition*", IEEE Congress on Evolutionary Computation (CEC 2007), 2007, pp 4661-4667.
41. Abdi, B., Mozafari, H., Ayob, A., Kohandel, R., " *Imperialist Competitive Algorithm for Multiobjective optimization of Ellipsoidal Head of Pressure Vessel* ", Applied Mechanics and Materials, Vol. 110-116, 2012, pp. 3422-3428.
42. Abedinia, O., Amjady, N., Kiani, K., Shayanfar, H.A., Ghasemi, A., "*Multiobjective* *Environmental and Economic Dispatch Using Imperialist Competitive Algorithm*", International Journal on Technical and Physical Problems of Engineering, Vol.4, 2012, pp.63-70.
43. Mohammadi, M., Tavakkoli-Moghaddam, R., Rostami, H.,"*A multi-objective imperialist competitive algorithm for a capacitated hub covering location Problem*", International Journal of Industrial Engineering Computations, Vol.2, 2011, 671–688.
44. Ghanavati, M., Gholamian, M.R., Minaei, B., Davoudi, M., "*An Efficient Cost Function For Imperialist Competitive Algorithm To Find Best Clusters*", Journal of Theoretical and Applied Information Technology, Vol.20, 2011, pp.22-31.