International Journal of Mathematical, Engineering and Management Sciences
Vol. 8, No. 4, 755-768, 2023
https://doi.org/10.33889/IJMEMS.2023.8.4.043

# Novel Heuristic Algorithm & its Application for Reliability Optimization

**Tripti Dahiya**
Department of Mathematics,
G.D. Goenka University, Gurgaon, India.
E-mail: triptidahiya69@gmail.com

**Nakul Vashishth**
Department of Mathematics,
G.D. Goenka University, Gurgaon, India.
E-mail: nakulsir@gmail.com

**Deepika Garg**
Department of Mathematics,
G.D. Goenka University, Gurgaon, India.
*Corresponding author*: deepika.garg@gdgu.org

**Avinash K. Shrivastava**
Department of Operations Management and Quantitative Techniques,
International Management Institute, Kolkata, West Bengal, India.
E-mail: kavinash1987@gmail.com

**P. K. Kapur**
Amity Center for Interdisciplinary Research,
Amity University, Noida, Uttar Pradesh, India.
E-mail: pkkapur1@gmail.com

(Received on November 18, 2022; Accepted on April 27, 2023)

**Abstract**
Heuristic algorithms are practical, easy to implement, and work fast to provide short-term, feasible solutions for any kind of problem within economical budgets as compared to other meta-heuristic algorithms. This paper presents a novel heuristic algorithm named the Dahiya-Garg Heuristic Algorithm (DG-Alg) to find the optimal solution for constrained reliability redundancy allocation optimization problems. The cornerstone of the novel DG-Alg is its novel selection factor, which is a mathematical formula that helps the heuristic algorithm search for optimal subsystems for reliability optimization. A novel formulated selection factor in DG-Alg has increased its effectiveness and efficiency. To analyze the performance of the proposed heuristic algorithm and the other three existing heuristic algorithms, they are applied to a problem taken from a pharmaceutical manufacturing plant named Yaris Pharmaceuticals. During the application of the heuristic algorithms, it was ensured that redundancy allocation was done within stipulated cost constraints. Further, a comparative analysis of the obtained results has been done to judge the performance of the proposed heuristic algorithm. It is deduced that the proposed heuristic algorithm gives optimized and computationally efficient results in comparison to the other existing heuristic algorithms.

**Keywords**- Reliability optimization, Reliability-redundancy, Allocation problem, Series system, Redundant component, Heuristic algorithm, Selection factor.

## 1. Introduction

Over the past few years, advancements in technology have led to massive growth in the process of industrialization. The complexity of the machinery has also increased to achieve the desired outputs in the manufacturing process. Efficiency is an important prerequisite for the expected life span of the machines.

The performance of a complex system is closely related to its reliability. However, it must also be taken into account that the failure of machines is an inherent event that is likely to happen. This has led to the concept of reliability engineering, which has the goal of attaining the demanded levels of reliability of complex systems in the process of planning, designing, and testing. The reliability of the system is increased by solving the Reliability Redundancy Allocation Problem (RRAP) under constraints such as weight, volume, and cost. A higher level of reliability in system structure can be achieved by using the minimum cost approach in RRAP. This can be done in two ways: either by swapping the existing units with much more reliable components or by employing components in parallel. However, swapping the existing units can stop the routine work of the system, thereby affecting the labour force employed on the system in addition to compromising their health and safety. Also, the production and delivery of services are affected. This is one of the reasons for the popularity of finding solutions for the cost constraint RRAP of a complex system in recent times. Redundancy allocation in complex systems has increased the reliability and quality of the system after imposing cost, weight, etc.-related constraints. In complex systems, while doing reliability optimization or maximizing the reliability of the system, the focus has to be on optimizing the reliability of subsystems that are not reliable enough for the proper functioning of the system. The reliability of the subsystems is increased either by attaching more reliable subsystems in parallel or by exchanging unreliable subsystems with more reliable subsystems.

## 2. Literature Survey

In the past few years, it has been seen that the popularity of Redundancy Allocation Problems (RAP) has increased in wide areas of the research field. Forcina et al. (2020) gave a systematic review on reliability redundancy allocation and proposed directions to pick out the optimal method for reliability allocation for the available resources, desired accuracy, and areas of application. Roa et al. (2020) proposed a meta-heuristic algorithm to find a solution for an allocation problem, i.e., the dispatching and relocation of an ambulance. Yeh (2019) proposed boundary swarm optimization to solve RRAP. Nath and Muhuri (2022) studied RRAP as a multi-objective optimization problem, further formulated a Multi-Objective Reliability Redundancy Allocation Problem (MORRAP), and provided solutions for it. Ouyang et al. (2018) studied the RRAP employing the improved Particle Swarm Optimization (PSO) method to judge the optimal design for the system under multiple constraints to enhance system reliability. Further, it has been found that design flexibility and switching reliability provide greater system reliability and optimal system design configuration, respectively. Sarwar et al. (2021) proposed two meta-heuristic algorithms named multi-objective PSO and multi-objective BAT algorithms to find the solution for multi-objective programming problems to decrease the cost and storage space. Wang et al. (2020) proposed a model of the multi-objective production system to solve RRAP. Zaretalab (2020) proposed a mathematical model to optimize the multiple RRAP. Kim (2018) studied the optimal design for system reliability in RAP of mixed components and introduced the idea of sequencing the optimal components for cold standby subsystems to enhance system reliability. Devi and Garg (2020) maximized the reliability of the system in solving an RRAP by employing two heuristic algorithms (HA), viz., Constraint Optimization Genetic Algorithm (COGA) and hybrid genetic-PSO. Chambari et al. (2021) introduced a bi-objective simulation optimization algorithm to find a solution for RAP with series-parallel systems. Garg and Sharma (2013) have maximized the reliability of the redundancy allocation non-linear constraint problem of a pharmaceutical plant with the help of a meta-heuristic algorithm for several constraints. Rakhi and Phauja (2020) presented a meta-heuristic algorithm to find the solution to RRAP that is re-engineered for different designs of the system. Mellal and Salhi (2022) used a multi-objective plant propagation algorithm to maximize reliability by solving the RAP of the system of a pharmaceutical plant. Garg (2015) proposed a meta-heuristic algorithm to solve constraints in RRAP.

Several optimization techniques like heuristics, non-linear and linear programming, meta-heuristics, etc. are usually used to solve a wide variety of problems (Kumar et al., 2017; Ghosh et al., 2011; Hsieh, 2016; Feizabadi and Jahromi, 2017; Kim and Kim, 2017; Saleem et al., 2018; Devi and Garg, 2019; Peiravi et al., 2019) for reliability optimization in manufacturing plants. Golmohammadi et al. (2016) proposed a meta-heuristic algorithm to deal with the problem of optimization of storage location and vehicle routing, aiming to decrease the logistics cost. Babu et al. (2018) introduced a heuristic algorithm (HA) to deal with different kinds of scheduling problems in flexible manufacturing systems to minimize the makespan. Further, it has been found that the proposed heuristic algorithm provided a better optimal solution in less computational time. Kheirkhah and Ghajari (2018) proposed a three-phase heuristic algorithm to solve the problem of cellular manufacturing systems and production planning. Further, optimal solutions and computational efficiency were analyzed.

In mathematical optimization, the heuristic method possesses a slight advantage over other methods due to its simplicity, low computational time, and suitability for usage in complex and serial networks. Other popular features of the heuristic method include its ability to address multiple problems with non-linear and linear constraints and the provision of integer computerized solutions, which are mostly true optimums. However, the heuristic method may also provide near-optimum solutions in some cases. In recent years, the heuristic algorithm or method has been modified in search of better solutions for constraint RAP. Ardakani et al. (2020) solved a kind of RAP, i.e., a truck-to-door sequencing problem, with the help of a heuristic algorithm to minimize the makespan. Chowmali and Sukto (2021) proposed a heuristic algorithm named FJA-ALNS to deal with the problems of multi-compartment vehicle routing associated with fuel delivery and minimize the distance and number of vehicles. Agarwal and Gupta (2005) proposed a penalty function-based heuristic method to find the solution to the constraint RAP and searched feasible and infeasible regions for the optimal solution. Gazani and Niaki (2021) used a heuristic algorithm and a Genetic Algorithm (GA) to identify the optimal solution for a maximal-covering location problem. Hwan and Bong (1993) created a heuristic method to find solutions to the constraint RAP of complex systems that allowed deviation across bounded and infeasible regions and reduced the risk of stuck at the local optimum. Aggarwal (2019) presented a three-neighbourhood approach-based heuristic algorithm to find the solution to the RAP of complex systems and provided computationally efficient results. Devi and Garg (2017) obtained increased reliability for the cost constraint RAP of the manufacturing plant by using a heuristic algorithm and a GA. The Shi method (Dinghua, 1987) was developed to find the solution to constraint RAP in complex systems, aiming to increase system reliability. Kumar et al. (2010) introduced two heuristic methods to find the solution to the RAP in a complex system. The obtained results showed that the first method based on the nomination of the optimal path and then on the nomination of its optimal redundant component, performed better than Shi's method. Also, the second method based on the calculation of the sensitivity factor, is computationally efficient. Kumar et al. (2009) proposed a heuristic method to get the optimal solution to constraint RAP and analyzed the effect of the proposed heuristic algorithm with other existing heuristic methods. Garg et al. (2010) described and compared three heuristic algorithms, namely Shi's method and pro-Alg for finding the optimal solution to the constraint RAP of the pharmaceutical plant. These studies show that the RAP of complex systems can easily be solved to maximize system reliability by implementing effective selection or sensitivity factors in the algorithm.

It has been found during the literature survey that by developing and using an effective selection factor, the efficiency of the heuristic algorithm and the optimality of the problem is improved. In the present work, the focus is on proposing a heuristic algorithm with an effective novel selection factor that will make the search process more effective and efficient. In this paper, a heuristic algorithm is proposed. The novelty of the selection factor in the proposed algorithm has made a remarkable improvement in the reliability of the system. The novel selection factor is a mathematical formula that is the ratio of the change in a subsystem's reliability to the percentage of resources consumed, which will help the heuristic algorithm choose the optimal subsystem during redundancy allocation in the system so as to get an optimum solution. In order to prove the efficiency of the proposed heuristic algorithm, the proposed algorithm and the three other most efficient existing heuristic algorithms used by Garg et al. (2022) develops a new heuristic algorithm to achieve desired reliability, while solving constrained redundancy reliability optimization problems for complex systems using sets of minimal paths.

The rest of the manuscript is arranged as follows: in Section 3, the system of liquid medicine manufacturers is described. Further, the RAP of the liquid medicine manufacturing system at "Yaris Pharmaceuticals" is described, and assumptions made for the problem are given. In Section 4, methodologies named 'The Dahiya-Garg heuristic algorithm' and heuristic algorithms defined by Garg et al. (2010) are described. In Section 5, the results of the proposed problem are discussed and compared.

## 3. Problem Formulation

Yaris Pharmaceuticals is a good Manufacturing Practice certified pharmaceutical company situated in Himachal Pradesh. Yaris Pharmaceuticals has all the manufacturing sections like capsules, tablets, liquid medicines, ointments, dry syrup, and sachets. In this paper, the liquid medicine manufacturing section is considered a system. This section includes a detailed system description, notations, and assumptions made for the RAP.

### 3.1 System Description

The liquid manufacturing section of Yaris Pharmaceuticals consists of three main subsystems that are connected in series: named stirrer machines, colloid mill machine, and twin-head volumetric filling and sealing machine.


**Figure 1.** Subsystems and their mediating factors.

In the manufacturing process of liquid medicines, there are definite inherent factors (like temperature, mixing time, shear rate, speed, etc.; see Figure 1) that affects the working of subsystems in the system. The process of manufacturing liquid medicines follows the following procedure.

In the first step, raw material is put into a stirrer-connected tank, which helps in mixing raw material at a certain temperature and time. In the next step, mixed raw materials in liquid form are shifted to a colloid mill machine to minimize the particle's size by considering the shear rate of the machine and the size of the droplet in the liquid solution. Finally, with the help of a twin-head volumetric filling & sealing machine, the prepared liquid solution is packed at a specific pace and volume. Subsystems of the liquid medicine manufacturing system are connected in series.

### 3.2 Assumptions

The assumptions made are the following:

(i) The system and its subsystems are coherent.

(ii) Path set, i.e., a set of subsystems, ensures that the working of all subsystems in the set along with the system is guaranteed.

(iii) The structure of subsystems other than the coherence property is not restricted.

(iv) Every constraint is an increasing function of $u_i$ with the addition of all the subsystems.

(v) Redundant components are restricted to the boundaries of the subsystem in the system.

(vi) System reliability $R_s$ is known in terms of the reliability of all the subsystems $R_i$.

### 3.3 Notations

| | |
|---|---|
| $u_i$ | $i^{th}$ Subsystem/component of the system. |
| $R_i(u_i)$ | Reliability of $i^{th}$ subsystem. |
| $Q_i(u_i)$ | Unreliability of $i^{th}$ subsystem. |
| $R_s(u)$ | Reliability of system. |
| $x_i$ | Total number of subsystems in $i^{th}$ subsystem $u(u_1, u_2, \dots, u_x)$. |
| $u^*(x_1, x_2, x_3)$ | Optimal solution. |
| $\Delta R_i$ | Reliability difference for $i^{th}$ subsystem on adding a redundant component. |
| $f^j(u_i)$ | Cost of $j^{th}$resource absorbed by $i^{th}$ subsystem. |
| $M_j$ | Maximum cost of resource $j$. |
| $x$ | Number of subsystems. |
| $y$ | Number of constraints. |
| $F_i$ | Selection factor. |

### 3.4 Redundancy Allocation Problem of Yaris Pharmaceuticals

In this paper, a liquid manufacturing system for Yaris Pharmaceuticals with three subsystems is considered. The system works only if all three subsystems are working accurately. Here, the objective is to increase the reliability, subject to cost constraints, of the liquid medicine manufacturing system by performing redundancy allocation. Therefore, the RAP for the liquid medicine manufacturing system is as follows:

Maximize

$$R_s(u) = \prod_{i=1}^{x} R_i(u_i) \tag{1}$$

Subject to cost constraint:

$$\sum_{i=1}^{x} f^1(u_i) * x_i \leq 335000 \tag{2}$$

$$R_i(u_i) = \left(1 - \left(Q_i(u_i)\right)^{x_i}\right) \tag{3}$$

where, $f^1(u_i)$ and $R_i(u_i)$ are cost and reliability of the $i^{th}$ subsystem, respectively. Here, we considered the cost constraint, i.e., $M_j$ =$M_1$ = Rs. 335000, (since the number of constraints is one, i.e., $y$ =1, therefore $j$=1), and obtained system reliability calculated using Equation (1) is: $R_s(u) = 0.7734$. The reliability and cost of each subsystem of the liquid medicine manufacturing system at Yaris Pharmaceuticals are tabulated in Table 1.

**Table 1.** Reliability and cost of subsystems of the system.

| Subsystem | $u_1$ | $u_2$ | $u_3$ |
|---|---|---|---|
| **Reliability of subsystem $R_i(u_i)$** | 0.9652 | 0.8261 | 0.97 |
| **Cost of subsystem $f^1(u_i)$** | 22444 | 85000 | 118000 |

## 4. Methodology

A heuristic algorithm is among the fastest, most precise, and most feasible approaches to deal with a problem. Here, four heuristic algorithms have been described to effectively find the optimal solution to a problem. The novel heuristic algorithm 'The Dahiya-Garg Heuristic Algorithm' will be referred to as 'DG-Alg'. The other three existing heuristic algorithms, i.e., 'algorithm 1', 'algorithm 2,' and 'algorithm 3,' used by Garg et al. (2010) will be referred to as 'GKP-Alg_1', 'GKP-Alg_2,' and 'GKP-Alg_3,' respectively. A comparative analysis of the performance of DG-Alg and other existing heuristic algorithms (GKP-Alg_1, GKP-Alg_2, and GKP-Alg_3) will be done from the obtained results. Defined heuristic algorithms differ in the formula of the selection factor and in the conditions for choosing the most unreliable subsystem. The common pseudo-code for all the heuristic algorithms is described in this section and also shown in Figure 2. Differences in the formula of the selection factor and unreliable conditions for the respective algorithms are defined in upcoming sub-sections.

*Heuristic Algorithm*

*Step 1*

Initialize $x_i = 1$; for $1 \leq i \leq x$.

*Step 2*

Calculate the reliability and selection factor for each subsystem using Equation (3) and the corresponding selection factor formula, respectively.

*Step 3*

Identify the subsystem that is most unreliable. Add one redundant component to that subsystem.

*Step 4*

Check for constraint violations on the addition of one redundant component.

1. If the constraint is violated, eliminate this subsystem for further consideration and then move to step 5.
2. If the constraint is not violated, then check to improve the limit of the subsystem's reliability by adding redundant
   - 2.1 If $\Delta R_i > 0.0001$, then go to step 2.
   - 2.2 If $\Delta R_i \leq 0.0001$, then remove that subsystem for further consideration, and then move to step 5.

*Step 5*

If all subsystems are eliminated for further consideration, then, $u^* = (x_1, x_2, x_3)$ is the optimal solution. Otherwise, move to step 2.

*Step 6*

Finally, calculate the reliability of the system i.e., $R_s(u^*)$ using Equation (1).

### 4.1 Dahiya-Garg Heuristic Algorithm (DG-Alg)

Several heuristic algorithms were designed to improve the reliability of complex systems. Moreover, the effectiveness of heuristic algorithms fluctuates due to the selection factors that are used in them.

(i) In DG-Alg, the selection factor ($F_i$) is the ratio of change in the subsystem's reliability to the percentage of resources consumed.

$$F_{DG-Alg} = F_i = \frac{\substack{Difference\ of\ Subsystem\ reliability\ and \\ Change in\ subsystem\ reliability}}{percentage of resources consumed} = \frac{R_i - \Delta R_i}{\left(f^1(u_i)/_{M_1}\right)} \tag{4}$$

where, $\Delta R_i = (1 - Q_i(u_i)^2) - R_i(u_i)$ (5)

(ii) In DG-Alg, the subsystem with the maximum value of the selection factor is unreliable.

## 4.2 GKP-Alg_1

Under this algorithm, a subsystem with minimum reliability is chosen for redundancy allocation in order to improve the subsystem's reliability. The process continues till the cost constraint is not violated.

(i) In GKP-Alg_1, the selection factor ($F_i$) is considered as minimum stage reliability.
(ii) In GKP-Alg_1, a subsystem with a minimum value of selection factor is unreliable.

## 4.3 GKP-Alg_2

This algorithm focuses on the subsystem with the maximum value of the selection factor in order to do redundancy allocation. The process of redundancy allocation continues till the condition of the cost constraint is verified. The selection factor for this algorithm is given below.

(i) In GKP-Alg_2, the selection factor ($F_i$) is the ratio of the subsystem's reliability to the percentage of resources consumed.

$$F_{GKP-Alg\_2} = F_i = \frac{R_i(u_i)}{\left(f^1(u_i)/_{M_1}\right)} \tag{6}$$

(ii) In GKP-Alg_2, a subsystem with the maximum value of the selection factor is unreliable.

## 4.4 GKP-Alg_3

This algorithm chooses the subsystem with the maximum selection factor for redundancy allocation. The selection for this algorithm is given below.

(i) In GKP-Alg_3, the selection factor ($F_i$) is the ratio of change in subsystem reliability to the percentage of resources consumed.

$$F_{GKP-Alg\_3} = F_i = \frac{\Delta R_i}{\left(f^1(u_i)/_{M_1}\right)} \tag{7}$$

where, $\Delta R_i = (1 - Q_i(u_i)^{x_i+1}) - R_i(u_i)$ (8)

Here, $\Delta R_i$ will only be calculated by using Equation (8).

(ii) In GKP-Alg_3, a subsystem with the maximum value of the selection factor is unreliable.

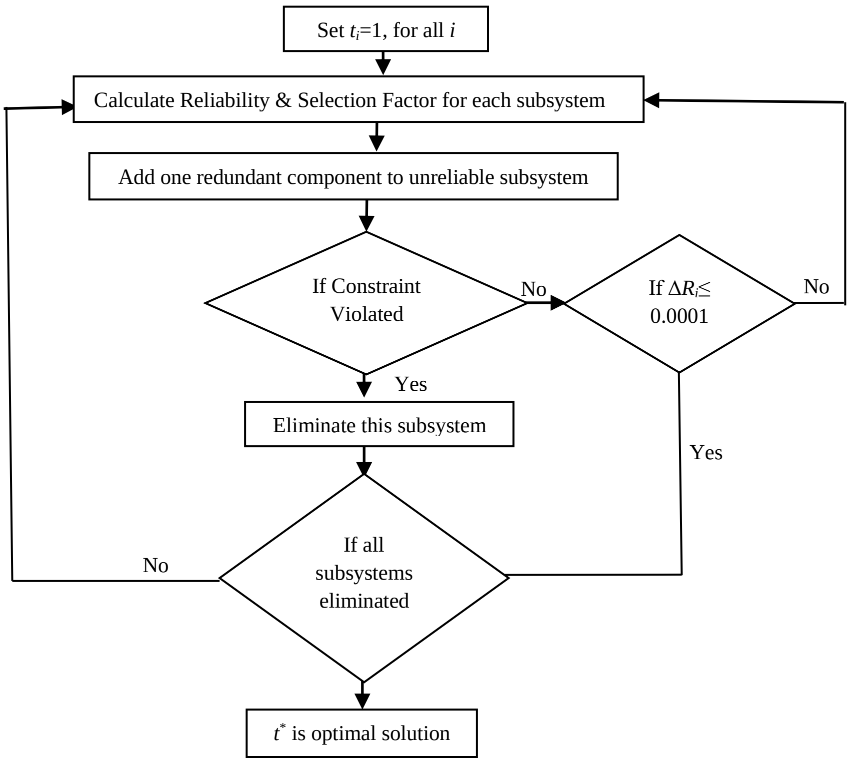


**Figure 2.** Flow chart for heuristic algorithm.

## 5. Results and Discussion

The performance of DG-Alg, GKP-Alg_1, GKP-Alg_2, and GKP-Alg_3 is detected with the help of the RAP described in Section 3.4. Obtained system reliability and redundancy allocation help to compare the performance of DG-Alg with the other three existing algorithms. In this section, the above-mentioned algorithms are applied to the RAP of Yaris Pharmaceuticals.

### 5.1 Application of Dahiya-Garg Heuristic Algorithm (DG-Alg)

In order to judge the effectiveness of DG-Alg, it is applied to defined RAPs by taking the initial allocation as (1,1,1). The selection factor of each subsystem is calculated, and the subsystem with the maximum selection factor is selected for further allocation. The process continues until either the cost constraint or desired limit of $\Delta R_i$ is violated. The application of DG-Alg to the proposed problem is described in Table 2.

**Table 2.** Results of the designed RAP using DG-Alg.

| **S. No.** | **Number of components in the subsystem** | | | **Consumed Resources** | **Subsystem Selection factor** | | |
|---|---|---|---|---|---|---|---|
| | $x_1$ | $x_2$ | $x_3$ | $\sum_{i=1}^{x} f^1(u_i) * x_i$ | $F_1$ | $F_2$ | $F_3$ |
| **1** | 1 | 1 | 1 | 225444 | 13.9054 | 2.6895 | 2.6712 |
| **2** | 2 | 1 | 1 | 247888 | 7.4452 | 2.6895 | 2.6712 |
| **3** | 3 | 1 | 1 | 270332 | # | 2.6895 | 2.6712 |
| **4** | 2 | 2 | 1 | 332888 | # | 1.8529 | 2.6712 |
| **5** | 2 | 2 | 2 | **450888?** | **#** | 1.8529 | ! |
| **6** | 2 | 3 | 1 | **417888?** | **#** | **!** | **!** |
| **7** | 2 | 2 | 1 | 332888 | Algorithm stops here | | |

! Indicate the removal of that subsystem for further consideration due to violation of cost constraint.
? Indicate the violation of cost constraint.
# Indicates the removal of that particular subsystem from further consideration as the desired limit of $\Delta R_i$ is violated.

Here, a violation of cost constraint has occurred at the 5$^{th}$ iteration. Redundancy allocation and reliability of the system for the defined problem obtained through Table 2 are $u^* = (2,2,1)$and$R_s(u^*) = 0.9690$, respectively. Employing DG-Alg, system reliability for the defined problem increases by 25.29%.

## 5.2 Application of GKP-Alg_1

GKP-Alg_1 is an algorithm in which the selection factor is based on minimum stage reliability. The initial allocation is taken as$(1,1,1)$. For further redundancy allocation, a subsystem with minimum reliability is chosen and the process of redundancy allocation continues until the cost constraint is not violated. The application of GKP-Alg_1 to the proposed problem is described in Table 3.

**Table 3.** Results of the designed RAP using GKP-Alg_1.

| S. No. | Number of components in subsystem | | | Consumed Resources | Subsystem Selection factor | | |
|---|---|---|---|---|---|---|---|
| | $x_1$ | $x_2$ | $x_3$ | $\sum_{i=1}^{x} f^1(u_i) * x_i$ | F$_1$ | F$_2$ | F$_3$ |
| **1** | 1 | 1 | 1 | 225444 | 0.9652 | 0.8261 | 0.97 |
| **2** | 1 | 2 | 1 | 310444 | 0.9652 | 0.9697 | 0.97 |
| **3** | 2 | 2 | 1 | 332888 | 0.9987 | 0.9697 | 0.97 |
| **4** | 2 | 3 | 1 | **417888?** | 0.9987 | **!** 0.97 | |
| **5** | 2 | 2 | 2 | **450888?** | 0.9987 | **!** | **!** |
| **6** | 3 | 2 | 1 | **355332?** | **!** | **!** | **!** |
| **7** | 2 | 2 | 1 | 332888 | Algorithm stops here | | |

! Indicate the removal of that particular subsystem from further consideration due to violation of cost constraint.
? Indicate the violation of the cost constraint.

Here, a violation of cost constraint has occurred at the 4$^{th}$ iteration. Redundancy allocation and reliability of the system for the defined problem obtained through Table 3 are $u^* = (2,2,1)$and $R_s(u^*) = 0.9405$, respectively. Employing GKP-Alg_1, system reliability for the defined problem increases by 21.60%.

## 5.3 Application of GKP-Alg_2

The GKP-Alg_2 is applied to the defined RAP by taking the initial allocation as $(1,1,1)$. The selection factor of each subsystem is calculated, and the subsystem with the maximum selection factor is selected for further allocation. The process continues until either the cost constraint or desired limit of $\Delta R_i$ is violated. The application of GKP-Alg_2 to the proposed problem is described in Table 4.

**Table 4.** Results of the designed RAP using GKP-Alg_2.

| S. No. | Number of components in the subsystem | | | Consumed Resources | Subsystem Selection factor | | |
|---|---|---|---|---|---|---|---|
| | $x_1$ | $x_2$ | $x_3$ | $\sum_{i=1}^{x} f^1(u_i) * x_i$ | F$_1$ | F$_2$ | F$_3$ |
| **1** | 1 | 1 | 1 | 225444 | 14.4071 | 3.2558 | 2.7538 |
| **2** | 2 | 1 | 1 | 247888 | 7.4533 | 3.2558 | 2.7538 |
| **3** | 3 | 1 | 1 | **270332#** | **#** | 3.2558 | 2.7538 |
| **4** | 2 | 2 | 1 | 332888 | **#** | 1.9108 | 2.7538 |
| **5** | 2 | 2 | 2 | **450888?** | **#** | 1.9108 | **!** |
| **6** | 2 | 3 | 1 | **417888?** | **#** | **!** | **!** |
| **7** | 2 | 2 | 1 | 332888 | Algorithm stops here | | |

! Indicate the removal of that particular subsystem from further consideration due to violation of cost constraint.
? Indicate the violation of the cost constraint.
# Indicate the removal of that particular subsystem from further consideration as the desired limit of $\Delta R_i$ is violated.

Here, a violation of cost constraint has occurred at the 5*th* iteration. Redundancy allocation and reliability of the system for the defined problem obtained through Table 4 are $u^* = (2,2,1)$ and $R_s(u^*) = 0.9394$, respectively. Employing GKP-Alg_2, system reliability for the defined problem increases by 21.46%.

## 5.4 Application of GKP-Alg_3

The selection factor of GKP-Alg_3 is dependent on the defined reliability change of the subsystem. In order to increase the reliability of the proposed RRAP, further redundancy allocation is preceded by the subsystem with the maximum selection factor. The iterative process keeps repeating until the cost constraint is not violated. The application of GKP-Alg_3 to the proposed problem is described in Table 5.

**Table 5.** Results of the designed RAP using GKP-Alg_3.

| S. No. | Number of components in each subsystem | | | Consumed Resources | Subsystem Selection factor | | |
|---|---|---|---|---|---|---|---|
| | $x_1$ | $x_2$ | $x_3$ | $\sum_{i=1}^{x} f^1(u_i) * x_i$ | $F_1$ | $F_2$ | $F_3$ |
| **1** | 1 | 1 | 1 | 225444 | 0.5051 | 0.5563 | 0.0826 |
| **2** | 1 | 2 | 1 | 310444 | 0.5051 | 0.6646 | 0.0826 |
| **3** | 1 | 3 | 1 | **395444?** | 0.5051 | **!** | 0.0826 |
| **4** | 2 | 2 | 1 | 332888 | 0.5188 | **!** | 0.0826 |
| **5** | 3 | 2 | 1 | **355332?** | **!** | **!** | 0.0826 |
| **6** | 2 | 2 | 2 | **450888?** | **!** | **!** | **!** |
| **7** | 2 | 2 | 1 | 332888 | Algorithm stops here | | |

! Indicate the removal of that particular subsystem from further consideration due to violation of cost constraint.

Here, a violation of cost constraint has occurred at the 3*rd* iteration. Redundancy allocation and reliability of the system for the defined problem obtained through Table 5 are $u^* = (2,2,1)$ and $R_s(u^*) = 0.9676$, respectively. Employing GKP-Alg_3, system reliability for the defined problem increases by 25.10%.

In order to improve the reliability of the system, redundancies have been allocated to the subsystems while applying DG-Alg, GKP-Alg_1, GKP-Alg_2 and, GKP-Alg_3 to the proposed problem. As a result, the redundancy obtained for subsystems, viz., stirrer, colloid mill, and filling machine, is (2, 2, 1) which is the same for all four algorithms, is shown graphically in Figure 3.

System reliability obtained by DG-Alg, GKP-Alg_1, GKP-Alg_2, and GKP-Alg_3 is 0.9690, 0.9405, 0.9394, and 0.9676, respectively. In spite of getting the same redundancy allocation, i.e., (2, 2, 1), in the cases of DG-Alg, GKP-Alg_1, GKP-Alg_2, and GKP-Alg_3, system reliability varies in all four cases, as shown in Figure 4. Varying system reliabilities are obtained due to the selection factors $F_{DG\text{-}Alg}$, $F_{GKP\text{-}Alg\_1}$, $F_{GKP\text{-}Alg\_2}$ and $F_{GKP\text{-}Alg\_3}$ of the respective algorithms taken in this paper. It clearly states that the selection factor plays a vital role in improving the reliability of the system.

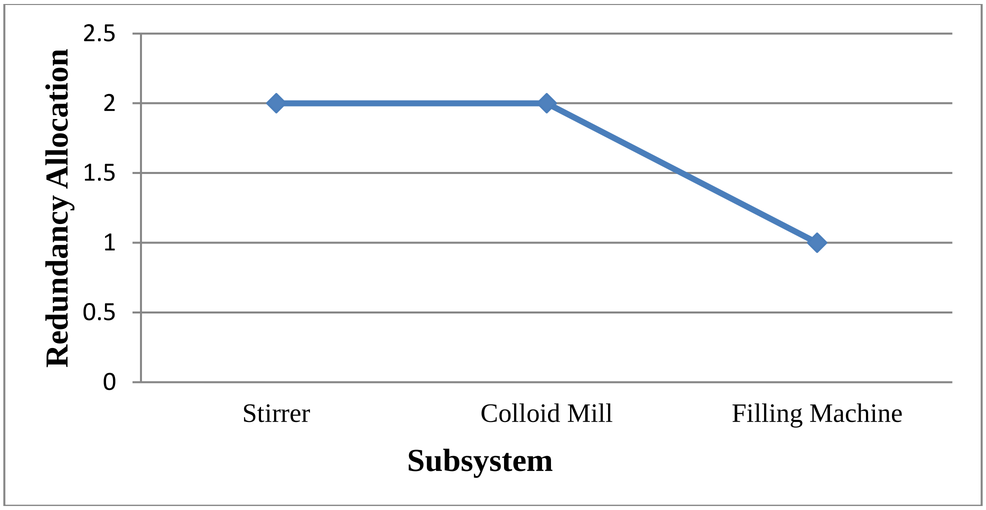


**Figure 3.** Redundancy allocation using DG-Alg, GKP-Alg_1, GKP-Alg_2 and GKP-Alg_3.

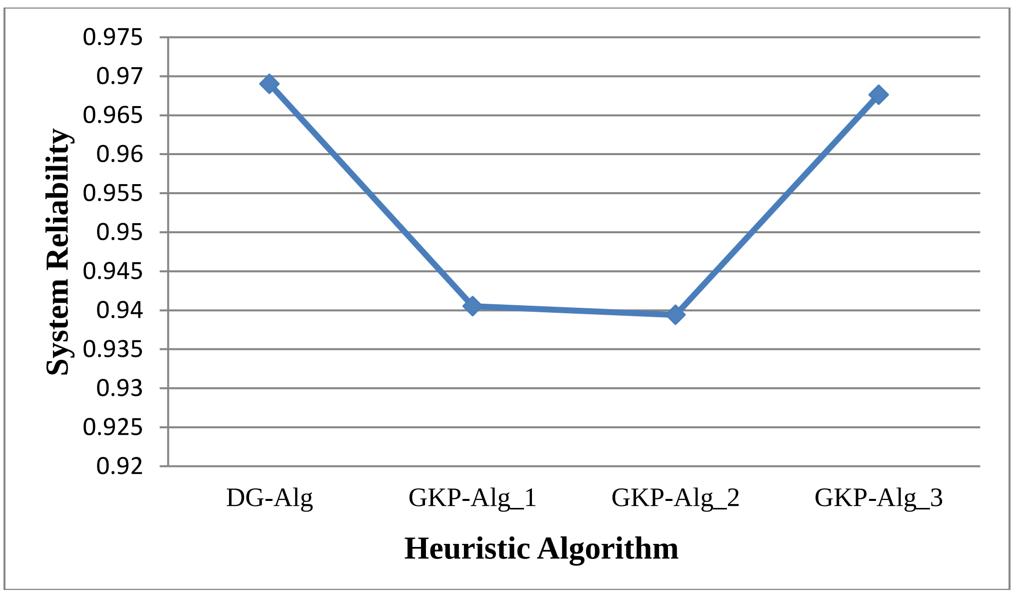


**Figure 4.** System reliability w.r.t. DG-Alg, GKP-Alg_1, GKP-Alg_2 and GKP-Alg_3.

## 6. Limitations of Work

Due to the increased reliance on approximation and estimation, the major limitation of the proposed research work is the requirement of certain mathematical theoretical assumptions. So that, one is able to find the best or most efficient optimal solution to the mathematical problems at a faster rate. In addition, the proposed method has been applied to a small sample size, obtained from a manufacturing plant, to avoid the possibility of inaccurate decisions and inadequate data leading to imprecise solutions. Major reasons for this issue could be the limited availability of complete and accurate data with respect to running conditions, stability, troubleshooting, and maintenance of the machinery in manufacturing plants.

## 7. Conclusion and Future Research Direction

This paper introduces a new heuristic algorithm named DG-Alg to solve constraint redundancy reliability optimization problems. In this paper, a novel heuristic and three existing heuristic algorithms (DG-Alg, GKP-Alg_1, GKP-Alg_2 and GKP-Alg_3, respectively) are applied to the stated problem of a pharmaceutical manufacturing system in order to maximize system reliability, under the given cost constraint. Further, comparative analysis among the considered algorithms has been done to validate the performance of DG-Alg. System reliability was 0.7434, and after applying DG-Alg, GKP-Alg_1, GKP-Alg_2, and GKP-Alg_3, system reliability becomes 0.9690, 0.9405, 0.9394, and 0.9676, respectively. On conducting a comparative analysis of the performances of algorithms, it is observed that DG-Alg provides maximum system reliability, i.e., 0.9690. Also, DG-Alg increases the reliability of the liquid manufacturing system at Yaris Pharmaceuticals to its maximum, i.e., by 25.29%.

The proposed research techniques can be further extended for finding optimal solutions in a broad category of optimization problems that may be de facto practical, real-world, and authenticated. Integration of proposed heuristic problems with meta-heuristics can yield better dividends in terms of quick convergence towards optimal solutions to reliability redundancy problems of complex systems with better credibility, improved efficiency, and a lesser penalty in terms of failure rate under both single and multiple constraints like cost, risk, weight, etc. This technique, when applied in conjunction with meta-heuristic techniques, can be well exploited and can become a valuable asset for seeking rapid and dependable solutions to challenging real-time problems; as ineffective maintenance management strategies in the manufacturing process can result in undesirable losses and the inability to provide reliable and quality-finished products.

#### Conflict of Interest

The authors confirm that there is no conflict of interest to declare for this publication.

#### Acknowledgements

This research did not receive any specific grants from funding agencies in the public, commercial, or not-for-profit sectors. The authors thank the editor and anonymous reviewers for their valuable suggestions to improve the quality of this work.

## References

Agarwal, M., & Gupta, R. (2005). Penalty function approach in heuristic algorithms for constrained redundancy reliability optimization. *IEEE Transactions on Reliability*, *54*(3), 549-558.

Aggarwal, S. (2019). Heuristic algorithm for optimal redundancy allocation in complex systems: A 3-neighborhood approach. *Journal of Quality in Maintenance Engineering*, *25*(1), 54-64.

Ardakani, A., Fei, J., & Beldar, P. (2020). Truck-to-door sequencing in multi-door cross-docking system with dock repeat truck holding pattern. *International Journal of Industrial Engineering Computations*, *11*, 201-220.

Babu, K., Babu, V., & Medikondu, N. (2018). Implementation of heuristic algorithms to synchronized planning of machines and AGVs in FMS. *Management Science Letters*, *8*(6), 543-554.

Chambari, A., Azimi, P., & Najafi, A.A. (2021). A bi-objective simulation-based optimization algorithm for redundancy allocation problem in series-parallel systems. *Expert Systems with Applications*, *173*, 114745. https://doi.org/10.1016/j.eswa.2021.114745.

Chowmali, W., & Sukto, S. (2021). A hybrid FJA-ALNS algorithm for solving the multi-compartment vehicle routing problem with a heterogeneous fleet of vehicles for the fuel delivery problem. *Decision Science Letters*, *10*(4), 497-510.

Devi, S., & Garg, D. (2017). Redundancy-allocation in Neel metal products limited. *Indian Journal of Science and Technology*, *10*(30), 1-5.

Devi, S., & Garg, D. (2019). Reliability analysis of manufacturing plant via fault tree analysis. *Journal of Advances and Scholarly Researches in Allied Education*, *16*(5), 256-259.

Devi, S., & Garg, D. (2020). Hybrid genetic and particle swarm algorithm: redundancy allocation problem. *International Journal of System Assurance Engineering and Management*, *11*, 313-319.

Feizabadi, M., & Jahromi, A.E. (2017). A new model for reliability optimization of series-parallel systems with non-homogeneous components. *Reliability Engineering & System Safety*, *157*, 101-112.

Forcina, A., Silvestri, L., Di Bona, G., & Silvestri, A. (2020). Reliability allocation methods: A systematic literature review. *Quality and Reliability Engineering International*, *36*(6), 2085-2107.

Garg, D., Kumar, K., & Pahuja, G.L. (2010). Redundancy-allocation in pharmaceutical plant. *International Journal of Engineering Science and Technology*, *2*(5), 1088-97.

Garg, D., Dahiya, T., & Shrivastava, A.K. (2022). Developing a new heuristic algorithm for efficient reliability optimization. *International Journal of Information Technology*, *14*(5), 2505-2511.

Garg, H. (2015). An approach for solving constrained reliability-redundancy allocation problems using cuckoo search algorithm. *Beni-Suef University Journal of Basic and Applied Sciences*, *4*(1), 14-25.

Garg, H., & Sharma, S.P. (2013). Reliability-redundancy allocation problem of pharmaceutical plant. *Journal of Engineering Science and Technology*, *8*(2), 190-198.

Gazani, M., & Niaki, S. (2021). The capacitated maximal covering location problem with heterogeneous facilities and vehicles and different setup costs: An effective heuristic approach. *International Journal of Industrial Engineering Computations*, *12*(1), 79-90.

Ghosh, T., Sengupta, S., Chattopadhyay, M., & Dan, P. (2011). Meta-heuristics in cellular manufacturing: A state-of-the-art review. *International Journal of Industrial Engineering Computations*, *2*(1), 87-122.

Golmohammadi, A., Bonab, S., & Parishani, A. (2016). A multi-objective location routing problem using imperialist competitive algorithm. *International Journal of Industrial Engineering Computations*, *7*(3), 481-488.

Hsieh, Y.C. (2016). A two-phase linear programming approach for redundancy allocation problems. *Yugoslav Journal of Operations Research*, *12*(2), 227-236.

Hwan, J.K., & Bong, J.Y. (1993). A heuristic method for solving redundancy-optimization problems in complex systems. *Institute of Electrical and Electronics Engineers (IEEE) Transaction on Reliability*, *42*(4), 572-578.

Kheirkhah, A., & Ghajari, A. (2018). A three-phase heuristic approach to solve an integrated cell formation and production planning problem. *Uncertain Supply Chain Management*, *6*(2), 213-228.

Kim, H. (2018). Maximization of system reliability with the consideration of component sequencing. *Reliability Engineering & System Safety*, *170*, 64-72.

Kim, H., & Kim, P. (2017). Reliability–redundancy allocation problem considering optimal redundancy strategy using parallel genetic algorithm. *Reliability Engineering & System Safety*, *159*, 153-160.

Kumar, P., Chaturvedi, D.K., & Pahuja, G.L. (2009). Heuristic algorithm for constrained redundancy reliability optimization and performance evaluation. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, *223*(4), 381-386.

Kumar, A., Garg, D., & Goel, P. (2017). Mathematical modeling and profit analysis of an edible oil refinery industry. *Airo International Research Journal*, *12*, 1-8.

Kumar, P., Chaturvedi, D.K., & Pahuja, G.L. (2009). Heuristic algorithm for constrained redundancy reliability optimization and performance evaluation. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, *223*(4), 381-386.

Kumar, P., Chaturvedi, D.K., & Pahuja, G.L. (2010). Heuristic methods for solving redundancy allocation in complex systems. *International Journal of Reliability and Safety*, *4*(2-3), 285-298.

Mellal, M.A., & Salhi, A. (2022). System reliability-redundancy allocation by the multiobjective plant propagation algorithm. *International Journal of Quality & Reliability Management*, *39*(4), 902-909.

Nath, R., & Muhuri, P.K. (2022). Evolutionary optimization based solution approaches for many objective reliability-redundancy allocation problem. *Reliability Engineering & System Safety*, *220*, 108190.

Ouyang, Z., Liu, Y., Ruan, S.J., & Jiang, T. (2019). An improved particle swarm optimization algorithm for reliability-redundancy allocation problem with mixed redundancy strategy and heterogeneous components. *Reliability Engineering & System Safety*, *181*, 62-74.

Peiravi, A., Karbasian, M., Ardakan, M.A., & Coit, D.W. (2019). Reliability optimization of series-parallel systems with K-mixed redundancy strategy. *Reliability Engineering & System Safety*, *183*, 17-28.

Rakhi, Pahuja, G.L. (2020). Solving reliability redundancy allocation problem using grey wolf optimization algorithm. In *Journal of Physics: Conference Series* (Vol. 1706, No. 1, p. 012155). IOP Publishing. Coimbatore, India.

Roa, J., Escobar, J., & Moreno, C. (2020). An online real-time matheuristic algorithm for dispatch and relocation of ambulances. *International Journal of Industrial Engineering Computations*, *11*(3), 443-468.

Saleem, E.A.A., Dao, T.M., & Liu, Z. (2018). Multiple-objective optimization and design of series-parallel systems using novel hybrid genetic algorithm meta-heuristic approach. *World Journal of Engineering and Technology*, *6*(03), 532-555.

Sarwar, F., Ahmed, M., & Rahman, M. (2021). Application of nature inspired algorithms for multi-objective inventory control scenarios. *International Journal of Industrial Engineering Computations*, *12*(1), 91-114.

Dinghua, S. (1987). A new heuristic algorithm for constrained redundancy-optimization in complex systems. *IEEE Transactions on Reliability*, *36*(5), 621-623.

Wang, W., Lin, M., Fu, Y., Luo, X., & Chen, H. (2020). Multi-objective optimization of reliability-redundancy allocation problem for multi-type production systems considering redundancy strategies. *Reliability Engineering & System Safety*, *193*, 106681.

Yeh, W.C. (2019). A novel boundary swarm optimization method for reliability redundancy allocation problems. *Reliability Engineering & System Safety*, *192*, 106060.

Zaretalab, A., Hajipour, V., & Tavana, M. (2020). Redundancy allocation problem with multi-state component systems and reliable supplier selection. *Reliability Engineering & System Safety*, *193*, 106629.