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# Optimizing Reliability of Flow Networks Using RWGA Subject to Total Capacity Constraint

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**Abstract:** The study of capacity assignment problem for multistate network is an essential and helps in finding the best set of assigned capacities with maximum system reliability. Analyzing the network structure with respect to the system reliability helps in determining the critical nodes. Sufficient capacity should be assigned for each node in the flow network to keep the network operating normally in the case of failure due to maintenance at one or more nodes. Capacity assignment problem aims to decrease the number of critical nodes by searching for the minimum capacity with considering system reliability constraint, it is known as NP-hard problem. Therefore, this paper formulates the problem as multi-objective optimization problem and proposed an approach based on Random Weighted Genetic Algorithm to solve it. The main objective of the proposed approach is to minimize the total capacities and maximize system reliability. The obtained results of the studied cases prove the efficiency of the proposed approach to solve the capacity assignment problem in comparison with existing approaches.

**Keywords:** RWGA, flow network, capacity assignment problem, system reliability, multi- objective optimization

## 1 Introduction

Multistate network is represented in communication systems, transportation systems, manufacturing systems, electric power transmission systems, and many real-life systems [1,2,3,4]. Multistate network is a network in which its flow is stochastic because of having several capacities and may fail. The capacity of each arc or node is the maximum amount of flow that passes the arc or node per unit time [2]. The capacity must be optimally assigned for the network to still function in the case of arc failure or node failure [3]. The probability that the maximum flow of the network from source to sink is not less than given demand d is called system Reliability [4]. Reliability evaluation methods are based on minimal paths or minimal cuts [4,8,9,10]. A minimal path is a chain of directed arcs and nodes from source to sink which contains no cycle. Several minimum path vectors respect to system state d, called lower boundary points (LBPs) can be found. Then the union probability of all these LBPs is the network reliability [6,8]. So, the purpose of this article is discussed capacity assignment problem subject to reliability system. The capacity assignment and Reliability evaluation in stochastic flow network are known to be NP-hard [11,12]. The optimal capacity assignment is determined by genetic algorithm to obtain the maximum reliability and the minimum total capacity [13,14,15]. The maximum capacity of each node or arc is necessary for calculating the system reliability. the maximum capacity of each arc or node has been discussed by [16]. The study of structure for the network is an important for the capacity assignment method. It helps to determine critical arcs or nodes. The optimal solution for the capacity assignment problem is to decrease the number of critical arcs to minimize total capacity and maximize reliability. References [5,6] discussed the robust design problem for an SFN, proposed an algorithm to determine the minimum capacity assigned for each component to let the network functioning normally. A genetic algorithm (GA) is a heuristic search method used in optimization problems. GA approaches are based to solve reliability optimization [14]. GA is used to solve multi-objective optimization problems [15,17,18,19,20,21]. This paper examines

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multi-objective optimization problem, i.e. total capacities and system reliability. The Random Weighted Genetic Algorithm (RWGA) based-approach is used to solve the addressed problem by searching the optimal set of capacities with minimum total capacity and maximum system reliability. The rest of the paper is organized as follows: section 2 covers the notation. Section 3 describes the problem. Then, section 4 explains the problem formulation. Section 5 expounds RWGA approach. Section 6 presents the overall algorithm. Section 7 includes several examples demonstrate the usability of the proposed approach. Finally, section 8 draws conclusions.

## 2 Notation

| | |
|---|---|
| $\eta$ | Set of nodes. |
| £ | Set of arcs. |
| R | Reliability of arc or node. |
| np | Number of paths. |
| D | Given demand. |
| $\mathcal{F}$ | Flow vector. |
| X | Capacity vector. |
| $R_D$ | Reliability to demand. |
| MPs | Minimal paths |
| NEQ | Number of genes. |
| MG | Number of populations. |
| MaxGen | The maximum number of generations. |
| Pc | The rate of crossover. |
| Pm | The rate of mutation. |

## 3 Description of problem

### 3.1 System reliability calculation

The system reliability $R_d$ is defined as the probability that the system satisfies the demand d that is

$$R_d = pr\ \{X|v(X)\ \geq d\} \tag{1}$$

To calculate $R_d$, a method is first to generate all lower boundary points for d. Suppose there are totally q lower boundary points for d: ($X_1$, $X_2$,. . . ., $X_q$). Where X= $(x_1\ ,x_2,\ldots,x_{np})$ , and there is $\mathcal{F}$=($f_1,f_2,f_3,\ldots..f_{np}$) which is feasible under X such that

$$x_i = \sum_{j=1}^{np}(f_j|\eta_i \in p_j) \leq M^{\mathrm{i}}\ for\ i = 1,2,\ldots..,neq \tag{2}$$

The flow vector $\mathcal{F}$ satisfies the demand d if and only if it satisfies constraints:

$$\sum_{j=1}^{np}(f_j|\eta_i \in p_j) \leq M^{\mathrm{i}}\ for\ i = 1,2,\ldots..,neq \tag{3}$$

$$\sum_{j=1}^{np} f_{\mathrm{j}} = d \tag{4}$$

So, to calculate $R_d$, the probability $Pr\{x_i\}$ of node $\eta_i$ should be defined by using the following equation:

$$Pr\{x_i = t\} = C_t^{m_i} r_i^t (1-r_i)^{m_i-t} \tag{5}$$

### 3.2 Capacity assignment

Capacity assignment is related with the analysis of a network structure. The analysis of a network structure is represented in defining the concept of node coverage and structural impact factor (SIF) $S_i$ for node $\eta_i$.

#### 3.2.1 Coverage

Let $\eta_i$, $\eta_j \in \eta$. $\eta_j$ is covered by $\eta_i$ if and only if $p_j \subseteq p_i$. That means there is no flow pass through $\eta_j$ when $\eta_i$ failed [5,6,22].

#### 3.2.2 SIF

The SIF for $\eta_i$ denoted by $s_i$, is given by**:**

$$s_i = \frac{||\{\eta_j|p_j \subseteq\ p_i\}||}{\rho} \tag{6}$$

Where, $\rho$ is the total number of nodes in the network [5,6, 22].

#### 3.2.3 Critical node

The $\eta_i$ is a critical node when $R_d$ is zero, [5,8,22].

## 4 Problem formulation

Let M = ($M^1$,$M^2$,. . . ,$M^{neq}$) as assigned capacities to the set of nodes ($\eta_1$, $\eta_2$, $\eta_3$,. . . , $\eta_{neq}$). The original mathematical formulation of the problem is:

$$Maximize\quad R_d(M) \tag{7}$$

$$Minimize\quad \mathcal{S}(M) \tag{8}$$

Where $R_d$ is the reliability for each assigned capacities under demand d, $\mathcal{S} = (\sum_1^{neq} M^i)$ and $M^i$ ranges from 1 to d except critical node, its $M^i$=d, [16].

To solve the problem is transformed into multi-objective minimization problem, [24,26], as follows:

$$Minimize\quad Ob_1 = 1 - R_d(M) \tag{9}$$

$$Minimize \quad Ob_2 = \mathcal{S}(M) \tag{10}$$

Also, the problem can be formulated as multi-objective maximization problem. Finally, the objective function can be formulated as follows:

$$Obj = w_1 * \mathrm{Ob}_1 + w_2 * \mathrm{Ob}_2 \tag{11}$$

Where, $w_1$ and $w_2$ are the corresponding weights for $\mathrm{Ob}_1$and $\mathrm{Ob}_2$ respectively. So, the problem is to minimize to objective function Obj.

## 5 The approach

In this section, the presented problem is a multi-objective optimization problem. So, we depended on multi-objective GA to solve it. The used approach relied to RWGA. The different components of RWGA based approach are presented in the following subsections:

### 5.1 Representation

If the network has neq number of nodes, then the chromosome M has neq field, each field (called gene) represents the maximum capacity for each node as shown in Fig. 1.

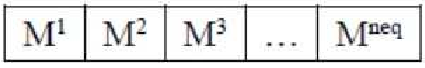

**Fig. 1:** Chromosomal representation

### 5.2 Initial population

Initial population is generated according to the following steps:

1.Determine genes $(M^i) = d$ for critical node.
2.Randomly generate a rest of genes of chromosome M in the initial population in the form:
M= $((M^1), (M^2), (M^3), \ldots, (M^{neq}))$ Where $M^i \in \{1,2,\ldots,d\}$; d is given demand.
3.Repeat steps from 1 to 3 to generate pop_size chromosome.

### 5.3 Crossover

In the proposed GA, we used one-cut point crossover where two parents are selected based on Pc value to generate two offspring. Let parents (p1, p2) and $\mathcal{CP}$ be if the randomly selected crossover point. The crossover operation is presented in Fig. 2.

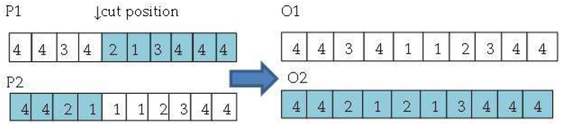

**Fig. 2:** Crossover process

### 5.4 Mutation

When crossover is finished, mutation takes place. Mutation is a random change to one gene. If this value of gene is B, its new value is selected randomly from the group 1,2,3,..., d-B as following figure:

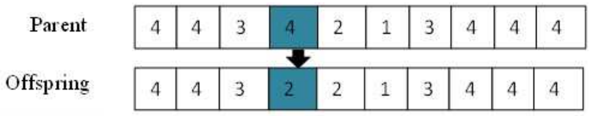

**Fig. 3:** Mutation process

### 5.5 Fitness evaluation

Let the values for the solutions be $R_d(i)$ in addition to $\mathcal{S}$(i) where (i=1,2,...,MG).

**Step1**. determine the normalized values of $R_d$, $\mathcal{S}$ as follows:

**Step1.1** Normalized value for $R_d(i)$:

$$\mathcal{N}Rd(i) = \frac{R_d\,(i)}{Max(R_d\,(1), R_d(2), \ldots, R_d\,(\mathrm{MG}))} \tag{12}$$

**Step1.2** Normalized value for $\mathcal{S}$(i)**:**

$$\mathcal{NS}(i) = \frac{Min(\mathcal{S}(1), \mathcal{S}(2), \ldots, \mathcal{S}\,(\mathrm{MG}))}{\mathcal{S}(i)} \tag{13}$$

**Step2.** Find the fitness value as follows:

**Step2.1** Randomly generate $U_L$ in [0,1] where L=1,2. Evaluate the weight from the following equation: $w_L = \frac{U_L}{\sum_{i=1}^{2} U_i}$ .

**Step2.2** Calculate the fitness as fit (i)=$w_1 * \mathcal{N}R_d(i) + w_2 * \mathcal{NS}(i)$.

**Step3.** Calculate the selection probability of each solution:

$$P(i) = \frac{(\mathrm{fit}(i) - f^{\min})}{\sum_{i \in MG} (\mathrm{fit}(i) - f^{\min})} \tag{14}$$

Where $f^{\min}$=min{fit(i), i ∈ MG}.

**Table 1:** The results for eight nodes network with d=4

| Run No. | M | $\mathcal{S}$ | $R_4$ |
|---|---|---|---|
| 1 | [4 4 3 3 4 3 2 4] | 27 | 0.468875 |
| 2 | [4 4 4 4 3 4 2 4] | 29 | 0.469880 |
| 3 | [4 4 3 4 2 2 3 4] | 26 | 0.468874 |
| 4 | [4 4 3 4 2 4 3 4] | 28 | 0.468875 |
| 5 | [4 4 3 1 1 3 2 4] | 22 | 0.466895 |
| 6 | [4 4 2 2 4 3 1 4] | 24 | 0.462061 |
| 7 | [4 4 2 1 2 2 4 4] | 23 | 0.462005 |
| 8 | [4 4 3 2 1 3 1 4] | 22 | 0.467255 |
| 9 | [4 4 3 3 1 2 1 4] | 22* | 0.467530 |

## 6 The overall algorithm

The steps of this algorithm are as follows:

Step 1. Input network information: MPs, neq, np, $r_i$ , d.
Step 2. Set the GA parameters: MG, MaxGen, Pc, Pm.
Step 3. Determine the critical nodes in the network.
Step 4. Generate the initial population including individuals ($M^1$,$M^2$,...,$M^{MG}$).
Step 5. For each individual, calculate the total capacity(M) and the network reliability $R_d$.
Step 6. Calculate fit(M) for each M in the current population.
Step 7. Calculate selection probability for each M in this population.
Step 8. Select two parents using the selection probability.Apply crossover and mutation on these parents to create offspring with Pc and Pm. Copy offspring to p+1.
Step 9. Set gen=gen+1; if gen <= MaxGen, go to Step 6, save the solution.
Step10. Report the best results found.

## 7 Examples

In this section, we present three examples to demonstrate the effectiveness of proposed approach. The GA parameters used are MG=20, MaxGen=100, Pc=0.95 and Pm=0.5.

### 7.1 Eight nodes network

This network includes 8 as nodes shown in Fig. 4. There are totally 8 MPs existed: $p_1 = \{\eta_1, \eta_2, \eta_4, \eta_8, \eta_{10}\}, p_2 = \{\eta_1, \eta_2, \eta_5, \eta_8, \eta_{10}\}, p_3 = \{\eta_1, \eta_2, \eta_6, \eta_8, \eta_{10}\}, p_4 = \{\eta_1, \eta_2, \eta_6, \eta_9, \eta_{10}\}, p_5 = \{\eta_1, \eta_3, \eta_6, \eta_8, \eta_{10}\}, p_6 = \{\eta_1, \eta_3, \eta_6, \eta_9, \eta_{10}\}, p_7 = \{\eta_1, \eta_3, \eta_6, \eta_9, \eta_{10}\}, p_8 = \{\eta_1, \eta_3, \eta_7, \eta_8\}$.

The available reliabilities of the nodes are 0.99, 0.98, 0.97, 0.98, 0.98, 0.99,0.97, 0.98, 0.97, 0.99. The demand for this example is set to 4. Table 1 shows the best M with its sum and R.

**Table 2:** Comparison results for the eight-node network

| Used approach | M | $\mathcal{S}$ | $R_4$ |
|---|---|---|---|
| Hamdy et al., [23] | [4 2 4 4 2 2 1 4] | 23 | 0.465164 |
| Proposed approach | [4 4 3 1 1 3 2 4]<br>[4 4 3 2 1 3 1 4]<br>[4 4 3 3 1 2 1 4] | 22 | 0.466895<br>0.467255<br>0.467530* |

**Table 3:** The results for ten-node network with d=4

| Run No. | M | $\mathcal{S}$ | $R_4$ |
|---|---|---|---|
| 1 | [4 4 2 4 2 2 3 4 2 4] | 31 | 0.922310 |
| 2 | [4 4 3 4 1 1 2 3 4 4] | 30 | 0.922544 |
| 3 | [4 4 2 1 2 1 3 4 4 4] | 29 | 0.922352 |
| 4 | [4 4 3 2 3 4 1 3 4 4] | 32 | 0.922722 |
| 5 | [4 4 4 1 1 1 3 3 3 4] | 28 | 0.922089 |
| 6 | [4 4 2 2 3 3 2 4 2 4] | 30 | 0.922315 |
| 7 | [4 4 2 2 1 2 2 3 3 4] | 27 | 0.922247 |
| 8 | [4 4 3 2 1 2 1 4 3 4] | 28 | 0.922618 |
| 9 | [4 4 3 3 1 3 3 4 2 4] | 31 | 0.922517 |
| 10 | [4 4 4 2 1 1 3 3 4 4] | 30 | 0.922716 |

Table 2 shows comparison results for the eight-node network between the proposed approach and Hamdy et al., [23].

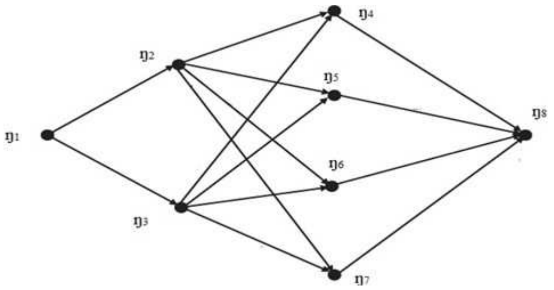

**Fig. 4:** Eight nodes network

### 7.2 Ten nodes network

This network includes 10 as nodes shown in Fig. 5. There are totally 7 MPs existed: $p_1 = \{\eta_1, \eta_2, \eta_4, \eta_8, \eta_{10}\}, p_2 = \{\eta_1, \eta_2, \eta_5, \eta_8, \eta_{10}\}, p_3 = \{\eta_1, \eta_2, \eta_6, \eta_8, \eta_{10}\}, p_4 = \{\eta_1, \eta_2, \eta_6, \eta_9, \eta_{10}\}, p_5 = \{\eta_1, \eta_3, \eta_6, \eta_8, \eta_{10}\}, p_6 = \{\eta_1, \eta_3, \eta_6, \eta_9, \eta_{10}\}, p_7 = \{\eta_1, \eta_3, \eta_6, \eta_9, \eta_{10}\}$.

The available reliabilities of the nodes are 0.99, 0.98, 0.97, 0.98, 0.98, 0.99,0.97, 0.98, 0.97, 0.99. The demand for this example is set to 4. Table 3 shows the best M with its sum and R.

**Table 4:** Comparison results for the ten-node network

| Used approach | M | $\mathcal{S}$ | $R_4$ |
|---|---|---|---|
| Chen and Lin [16] | [4 4 4 2 2 3 3 4 4 4] | 34 | 0.922643 |
| Hamdy et al. [23] | [4 4 1 3 1 4 1 3 3 4] | 28 | 0.922734 |
| Proposed approach | [4 4 3 2 1 2 1 4 2 4]<br>[4 4 3 2 1 2 1 4 3 4] | 27<br>28 | 0.922411<br>0.922618 |

Table.4 shows the comparison results for the ten-node network between the proposed approach, Ln and Chen [16], and Hamdy et al., [23].

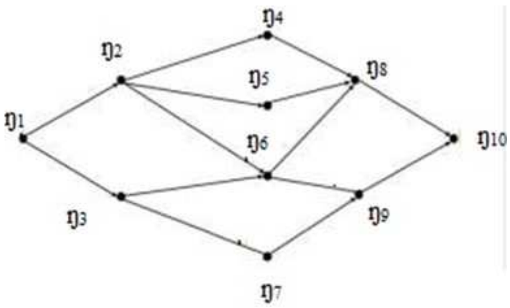

**Fig. 5:** Ten nodes network

### 7.3 Thirteen-node network

This network includes 30 as nodes shown in Fig. 6 . There are totally 6 MPs existed:
$p_1 = \{\eta_1, \eta_2, \eta_4, \eta_6, \eta_8, \eta_{10}, \eta_{12}, \eta_{14}, \eta_{16}, \eta_{18}, \eta_{20}, \eta_{22}, \eta_{24}\}$.
$p_2 = \{\eta_1, \eta_3, \eta_5, \eta_7, \eta_9, \eta_{11}, \eta_{13}, \eta_{15}, \eta_{17}, \eta_{19}, \eta_{21}, \eta_{23}, \eta_{24}\}$.
$p_3 = \{\eta_1, \eta_2, \eta_4, \eta_6, \eta_8, \eta_{10}, \eta_{25}, \eta_{27}, \eta_{28}, \eta_{29}, \eta_{14}, \eta_{16}, \eta_{18}, \eta_{20}, \eta_{22}, \eta_{24}\}$.
$p_4 = \{\eta_1, \eta_2, \eta_4, \eta_6, \eta_8, \eta_{10}, \eta_{25}, \eta_{27}, \eta_{28}, \eta_{30}, \eta_{15}, \eta_{17}, \eta_{19}, \eta_{21}, \eta_{23}, \eta_{24}\}$.
$p_5 = \{\eta_1, \eta_3, \eta_5, \eta_7, \eta_9, \eta_{11}, \eta_{26}, \eta_{27}, \eta_{28}, \eta_{30}, \eta_{15}, \eta_{17}, \eta_{19}, \eta_{21}, \eta_{23}, \eta_{24}\}$.
$p_6 = \{\eta_1, \eta_3, \eta_5, \eta_7, \eta_9, \eta_{11}, \eta_{26}, \eta_{27}, \eta_{28}, \eta_{29}, \eta_{14}, \eta_{16,}, \eta_{18}, \eta_{20}, \eta_{22}, \eta_{24}\}$.

The available reliabilities of the nodes are 0.99, 0.88, 0.93, 0.91, 0.91, 0.89, 0.87, 0.91, 0.90, 0.90, 0.93, 0.92,0.88, 0.88, 0.87, 0.92, 0.92, 0.93,0.90,0.90,0.91, 0.87, 0.87, 0.99, 0.89,0.93, 0.90, 0.93, 0.87, 0.89. The demand for this example is set to 4. Table 5 shows the best M with its sum and $R_4$.

**Table 5:** The results for thirty-node network with d=4

| ***No.*** | **M** | $\mathcal{S}$ | $R_4$ |
|---|---|---|---|
| 1 | [443424144323333 343334444223144] | 95 | 0.357216 |
| 2 | [443414242331314 344434444413214] | 92 | 0.233499 |
| 3 | [441444244423443 344333444323114] | 97 | 0.531814 |
| 4 | [442444244334244 313242444123114] | 90 | 0.315481 |
| 5 | [442434244421214 331324444432123] | 88 | 0.120285 |
| 6 | [441414144413432 324232444214111] | 82* | 0.248654 |
| 7 | [442434242312134 244244444341422] | 91 | 0.202882 |
| 8 | [441444342444422 432433444413311] | 94 | 0.262730 |
| 9 | [441444443313233 244432444411434] | 95 | 0.245519 |
| 10 | [444424143344131 4141324441122231] | 83 | 0.136830 |

**Table 6:** Comparison results for the thirty-node network

| Used approach | M | $\mathcal{S}$ | $R_4$ |
|---|---|---|---|
| Hamdy et al. [23] | [4 2 3 3 3 2 3 2 2 3 3 2 1 4 2 2 3 4 4 3 2 3 4 4 4 3 3 2 1] | 85 | 0.109870 |
| Proposed approach | [4 4 1 4 1 4 1 4 4 4 1 3 4 3 2 3 2 4 2 3 2 4 4 4 2 1 4 1 1 1] | 82 | 0.248654 |

Table.6 presents comparison results for the ten-node network between the proposed approach and Hamdy et al. [23].

## 8 Conclusion

This research presented capacity assignment problem subject to reliability and total capacity constraints. The problem treated as multi-objective optimization problem and an approach based on RWGA was developed for solving it. It is used to obtain the optimal solution characterized by maximal reliability and minimal total capacity. Our results for ten-node network are compared with the results of Chen and Lin's approach [16], and Hamdy *et al.* [23]. Our results are better than Chen and Lin [16] for all objectives, but the same results for Hamdy *et al.* [23] with little difference in reliability value. Also, the results of eight-node and thirty-node network are compared with the results Hamdy *et al*, [23]. The results of proposed approach are better than Hamdy *et al*,[23] for all objectives.

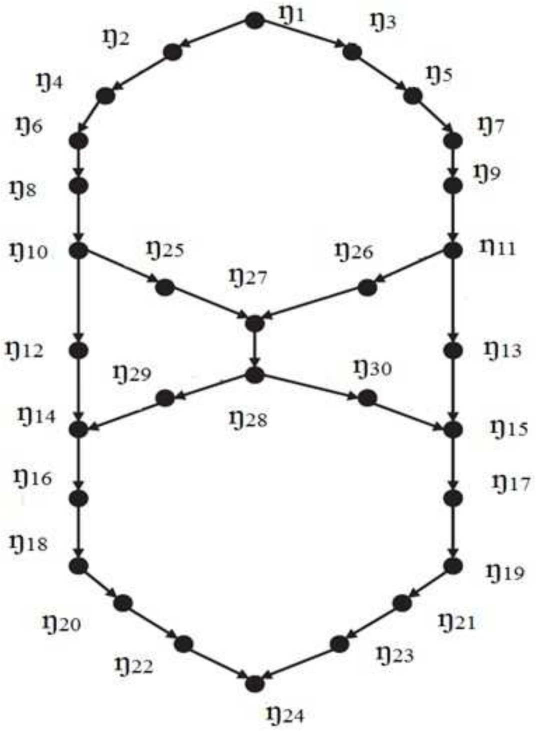

**Fig. 6:** Ten nodes network

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