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Reliability Assessment of Standby Component in Redundant system using Minimum Effort Optimization

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ABSTRACT: In systems comprising various subsystems, complexity plays a crucial role in reliability, this article offers a Minimum Effort Optimization (MEO) for the best distribution of redundancy and reliability in complex redundant systems, and the minimum effort method suggests improving the reliability of the first two components instead of improving the third component's reliability, and also define that concentrate on system reliability and cost, with the latter taking into account three factors: the cost of acquiring dependable but redundant components, the cost of developing components that require improvement, and the predicted failure costs of subsystems. This study tackles the problem of redundancy allocation and optimal dependability, which has always been handled separately. They provide a cost function that includes projected failure costs, reliability goals, and procurement, development, and improvement expenses. A reliability improvement rate is introduced to meet specific improvement targets, accounting for component reachability. Application frameworks are created for series and parallel systems, and illustrative examples demonstrate the effectiveness of the proposed method in assigning reliability requirements in the context of Minimum Effort Optimization.

KEYWORDS: component reliability, minimum effort method, redundant system, reliability, standby component

I. INTRODUCTION

In reliability analysis, a complex redundant system's overall properties, including dependability, must be translated into specifications for each of the many components that comprise the system. Reliability allocation is the process of allocating reliability needs to specific units in order to achieve the desired system reliability. The allocation of system reliability involves solving the basic inequality

$$f(R_1^*, R_2^*, R_3^*, \dots, R_n^*) \geq R^*$$

Theoretically, this equation has an endless number of solutions, assuming no limits on the allocation. Reliability would be more unrealistic, and that would be more subjective. These would be gained by field projects. We found that the minimum effort approach recommends lowering the failure rate of each subsystem by the same factors while increasing the dependability of the first two components to a point. However, it does not recommend enhancing the reliability of the third component. The reliability allocation program aids development staff in comprehending the fundamental reliability issues present in the design as well as the interaction between component, subsystem, and system reliabilities.

Notation

The following notation is used

1. $\Pr(e)$: Probability of event e
2. n : number of components in the system
3. p_i : the probability that component i functions
4. R : Reliability of a System
5. R^* : System reliability requirement.
6. R_n^* : n^{th} Subsystem reliability requirement.

1.1 Reliability Allocation Factors

In systems comprising various subsystems, complexity plays a crucial role in reliability. The reliability of a module depends heavily on its components; thus, failure rates are attributed to the sum of the constituent components' failure rates. Initially, it is reasonable to allocate failure rates based on the number of components. However, cost considerations are vital, as reliability improvement for expensive subsystems can be disproportionately high, making lower reliability allocations preferable for these modules. Components with a lengthy operational history may reach a reliability ceiling despite prior enhancements, while those with initially high reliability may still be improved cost-effectively. Engineering judgment is essential in determining the potential for improvement. Introducing redundancy can also enhance reliability, as demonstrated by the reduction in failure rates when components are used in active parallel redundancy. Maintenance impacts reliability, where well-maintained components generally exhibit higher availability. When apportioning reliability, the operational time of subsystems can be disregarded unless specific subsystems operate for shorter durations than the mission time, warranting a lower reliability allocation. Overall, reliability allocation is a complex interplay of component complexity, cost, potential for improvement, and operational context.

II. LITERATURE REVIEW

In systems with components that have known reliability metrics but lack redundancy definitions, as well as those that require development or improvement, a novel approach for the best distribution of redundancy and reliability. Sharma, et al., (2010) and Kumar, et al., (2011) his article's goal was to introduce a novel method for addressing the issue of the best way to distribute redundancy and reliability when there is a combination of components that require development or improvement and components that have established reliability metrics but require redundancy definition [1] and [2]. Sharma, et al., (2012) define to put it another way, components that have been identified must have their minimum reliability requirements and the number of redundancies assigned to them specified [3]. Tyagi, et al., (2015), and Sharma, (2019) proposed factors for weighting components include failure severity, improvement effort, coupling strength, and fragility. The projected marginal contributions to CCF groups are used to calculate the failure severity. While a mathematical description for coupling strength is developed, reliability enhancement efforts are generalized using the alpha factor model [4] and [5]. Sharma, (2020), and Behera, et al., (2022) achieve certain improvement goals while taking component reachability into consideration, a reliability improvement rate is developed. For both parallel and series systems, application frameworks are developed, and illustrated examples show how well the suggested approach assigns dependability requirements in the context of CCF [6] and [7]. Dey, et al., (2022), Arun, et al., (2023) and Singh, et al., (2024) his paper discusses the allocation of reliability and redundancy in parallel-series systems to minimize costs. It establishes that optimal reliability allocation requires identical reliability among redundant components in a subsystem [8], [9] and [10]. Sharma, et al., (2024) and Sharma, et al., (2024) discuss an optimal algorithm, ECAY, is introduced for designing these systems, allowing for efficient reliability and redundancy allocation while targeting specific reliability levels. Benchmark comparisons show that ECAY outperforms LM-based algorithms, producing lower reliability costs and optimal redundancy levels across multiple stages of systems, all within reasonable computing times [11] and [12]. Kasana, et al., (2025), Sharma, et al., (2025) and Singh, et al., (2025) his study, a model calculates the minimal reliability required for several components to meet the overall dependability objective of a system. It includes a cost function for the optimization technique and a nonlinear programming formulation that tackles the allocation problem. The Flexible design is an approach that is a complex design [13], [14] and [15]. Parashar, et al., (2025), Verma, et al., (2025), Kaushik, et al., (2025) and Singh, et al., (2024) define the difficulties in reliability allocation analysis brought on by the intricacy of contemporary designs with high-performance integrated circuits are discussed in this work. It highlights the necessity of reevaluating reliability allocation techniques in order to appropriately distribute overall system reliability targets across different components [16], [17], [18] and [19] and also by Sharma, et al., (2025), Mishra, et al., (2025) and Sharma, et al., (2025) determining reliability needs requires early cooperation between design and reliability engineers. In order to divide system reliability requirements while taking into account hardware, software, and soft failures, the study evaluates existing allocation techniques, identifies their flaws, and suggests best practices [20], [21] and [22]. Kaushik, et al., (2026), Afoma et al., (2025), Naushad et al., (2025) and Acharya, et al., (2026) discuss new model for a two-unit standby system that categorizes the standby unit as hot, warm, or cold is presented in this work. The model affects the standby unit's operation in the event that the active unit fails by allowing it to stay in a cold state before changing to a warm one. The standby runs instantly if it is heated; if it is cold, it needs an emergency switch to warm, either instantly or with a specific likelihood [34], [23], [24] and [36].

The cost of purchasing redundant components with specified reliability, the expenses of creating or enhancing components, and the expected costs of subsystem failures based on redundancy are the three main macro-factors it takes into account. By estimating development costs and assessing the possible financial effects of failures, this framework facilitates the investigation of more economical design options that satisfy reliability requirements. Mudimannan, et al., (2025), Prasad, et al., (2025), Ajitha, et al., (2026) and Mittal, et al., (2026) with the exception of the standby unit's warm state duration, the study makes the assumption that most variables have generic distributions. Along with an improved cost function based on three control parameters, key dependability characteristics that are important to engineers and designers are derived, and the derived reliability behaviors are demonstrated by numerical data [25], [26], [27] and [28]. Abhyankar, et al., (2026), Sharma, et al., (2026) and Sharma, et al., (2022) define novel approach for reliability assessment and management of non-destructible different-component cold-standby redundant network systems is presented in this study. With lifetimes described as independent random variables with an Erlang distribution, the system enables backup components to function in the event that the primary fails [29], [30] and [31]. Sharma, et al., (2026), Samorlu, et al., (2026), Naushad, et al., (2026) and Samorlu, et al., (2026) discuss the projected lifetime is correlated with the rise in purchasing cost. In a directed stochastic network (E-network) that corresponds to the system's reliability graph, reliability is evaluated using the shortest path method. In the end, a multi-objective issue is developed and the surrogate worth trade-off approach is applied to find the best way to distribute reliability among system components [37], [32], [33] and [35]. Acharya, et al., (2026), Parashar, et al., (2026) and Sharma, et al., (2026) define the transform a delta-star structure into a star network to analyze an autonomous system. The technique facilitates the assessment of a bridge network's reliability by converting it into its series and parallel forms, despite introducing minimal error, which is considered negligible. The delta-star approach adeptly manages networks with multiple bridge topologies and accommodates devices with two mutually exclusive failure modes. Additionally, it simplifies complex durability block structures with two or three pieces of state equipment, allowing reliable network management even in the presence of minor inaccuracies [38], [39] and [40].

III. METHODOLOGY FOR MINIMUM EFFORT METHOD

We have described a method that has been proven to require minimum effort under certain assumptions to increase R_i to R_i^* obviously needs an effort which would be some function of the number of tests, amount of manpower applied to the task and so forth. Let the effort function $G(R_i, R_i^*)$ be a measure of the amount of effort needed to increase the reliability of i^{th} subsystem from R_i to R_i^* . Assuming that the nature of the effort function is the same for all subsystems, and consider the following steps:

1. The estimated or predicted reliabilities are arranged in an ascending order

$$\text{i.e., } R_1 \leq R_2 \leq \dots \leq R_m$$

2. The reliabilities of the first k components are increased to the same value R_0 . The reliabilities $R_{k+1}, R_{k+2}, R_{k+3}, \dots, R_m$ of the remaining $(m - k)$ subsystems are left unchanged.

3. The number k is the maximum value of j , such that $R_j < \left[\frac{R^*}{\prod_{i=j+1}^{m+1} R_i} \right]^{1/j} = r_j$, where $R_{m+1} = 1$

a) Calculated of $\left[\frac{R^*}{R_2 R_3 \dots R_m} \right]^{1/1} = r_1$, if $R_1 < r_1$, then R_1 will have to be increased to the value of R_0 .

b) Again Calculated of $\left[\frac{R^*}{R_3 R_4 \dots R_m} \right]^{1/2} = r_2$, if $R_2 < r_2$, then R_1 and R_2 both will have to be increased to a common value. The procedure is continued as long as $R_j < r_j$ the value of R_0 .

4. The value of R_0 , the allocated reliability for first k units, is determined as

$$R_0 = \left[\frac{R^*}{\prod_{i=k+1}^{m+1} R_i} \right]^{1/k}, \quad \text{where } R_{m+1} = 1$$

IV. RESULTS AND DISCUSSION

4.1 Numerical Computations through Minimum Effort Method

Discuss a desirable reliability of the system be $R^* = 0.55$, we consider a system consists of three units connected in series with respective reliability $R_1 = 0.60, R_2 = 0.70$ & $R_3 = 0.80$ for respectively components c_1, c_2 & c_3

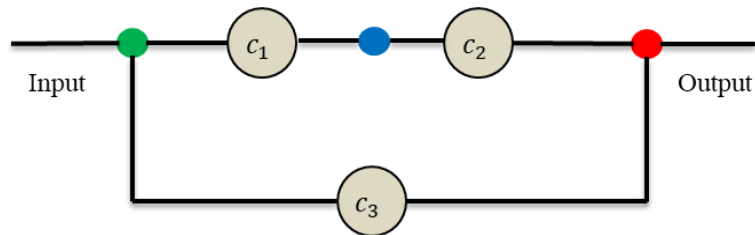


Figure 1: Mixed Parallel-series diagram

The component reliabilities are correctly arranged as follows

$$r_1 = \left[\frac{R^*}{R_2 R_3} \right]^{1/1} \cong 0.628 > R_1$$

$$r_2 = \left[\frac{R^*}{R_3} \right]^{1/2} \cong 0.829 > R_2$$

$$r_3 = [R^*]^{1/3} \cong 0.819 > R_3$$

$$\text{So, } R_0 = \left[\frac{0.55}{0.829} \right]^{1/2} \cong 0.814$$

Hence $R_1^* = R_2^* = 0.814$ and $R_3^* = R_3 = 0.819$

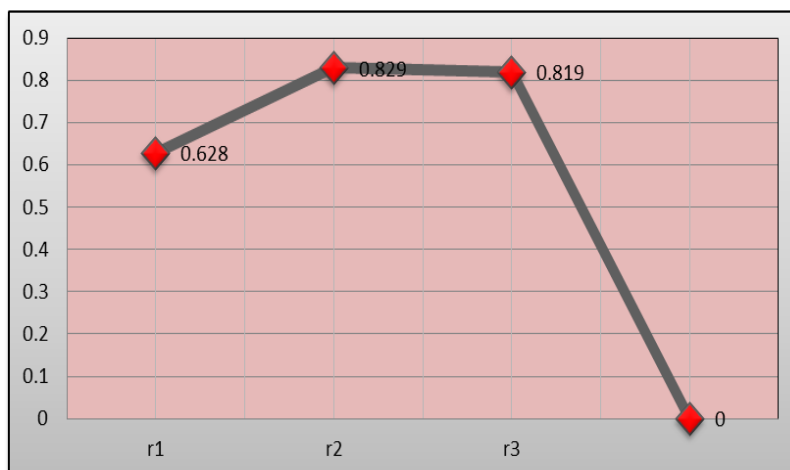


Figure 2: Component Reliability

V. CONCLUSION AND SCOPE

Reliability engineers are required to assess the system's dependability during a product's design phase. When the estimated dependability is insufficient, the challenge of how to achieve a reliability objective for the system emerges. This therefore becomes a reliability allocation problem at the component level. The advantage of the reliability allocation program guarantees appropriate design manufacturing methods and testing producers, and the scope of the design engineer is required to consider reliability equally with other system parameters. The minimum effort method suggests improving the reliability of the first two components instead of improving the third component's reliability.

In the future, reliability is frequently assigned to subsystems whose projected or anticipated reliability values are unknown. Considering elements like complexity, cost, state of the art, maintenance, and operating duration makes sense. A series logic diagram is assumed in this section. When a subsystem's modules are connected in parallel to offer redundancy, the parallel unit is regarded as a single entity for reliability allocation purposes. This strategy enables us to maintain the validity of the validity of the validity of the validity of the series structure.

Author Contribution

C K Sharma; Methodology, and data conceptualization, Ruchi; Literature Review, Result Discussion; conclusion and Drafting

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Conflicts Of Interest

There is no conflict of interest.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

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