International Journal of Industrial Engineering & Production Research (2018)

June 2018, Volume 29, Number 2
pp. 213 - 230

DOI: 10.22068/ijiepr.29.2.213 http://IJIEPR.iust.ac.ir/

Developing a Method for Reliability Allocation of Series-Parallel Systems by Considering Common Cause Failure

Maryam Mohammadi, Seyed Mohammad Mortazavi & Mahdi Karbasian*

Maryam Mohammadi, *Department of Industrial Engineering, Najafabad Branch, Islamic Azad University*
Seyed Mohammad Mortazavi, *Department of Industrial Engineering, Najafabad Branch, Islamic Azad University*
Mahdi Karbasian, *Department of Industrial Engineering, Malek Ashtar University of Technology,*

KEYWORDS

Reliability allocation;
Dependent failure;
Common cause failure;
Redundant system;
Series-parallel system;
Improvement prioritization

ABSTRACT

Reliability allocation has an essential connection to design for reliability and is an important activity in the product design and development process. In determining the reliability of subsystems or components on the basis of goal reliability, attention must be paid to failure effect, failure information, and improvement opportunities based upon real potentials for reliability improvement. In the light of the fact that ignoring dependent failures inflicts irreversible damage on systems, and that redundant systems are vulnerable to Common Cause Failure (CCF) as well as independent failure, attention must be paid not only to components' independent failure information, but also to CCF information in conducting reliability allocation for such systems. To consider improved failure rate alone cannot ensure the achievement of the goal reliability in question, because if the CCF occurrence exceeds a certain limit, the system's reliability will certainly fail to match the goal reliability. This paper is an attempt to develop a method for reliability allocation of series-parallel systems by considering CCF such that potentials and priorities of reliability improvement are taken into consideration. The proposed method consists of four stages: 1) adding a series component to the redundant system in order to investigate CCF, 2) conducting reliability allocation for series components and the redundant system, 3) conducting reliability allocation for redundant system components, and 4) analyzing the failure rate of system components. The proposed method is run for water pumping systems, and the results are evaluated. In this method, in addition to the improved failure rate of system components, the improved rate of CCF is computed, too. This proves to be instrumental and crucial for system designers in feasibility studies and conceptual design.

1. Introduction

Reliability allocation has an essential connection to design reliability and is considered a significant activity in the product design and development process. In order to achieve the goal reliability in a realistic fashion, it is necessary to investigate and evaluate the system's behavior, performance, and parameters using failure effects, failure information, and scope of reliability improvement. In fact, in determining the

* **Corresponding author:** ***Mahdi Karbasian***

Email: mkarbasi@mut-es.ac.ir
Received 19 November 2017; revised 15 April 2018; accepted 7 May 2018

reliability of systems or components on the basis of the goal reliability, it is essential to pay attention to opportunities on the basis of real potentials so as to improve reliability [1]. Reliability improvement is aimed at increasing it such that the smooth performance required by the system is ensured [2]. Due to the complexity of systems and their function conditions, their components are interdependent. This interdependency leads to dependent failures in systems, and ignoring such failures causes irreversible damage to them. Common Cause Failure (CCF) is a type of dependent failure that affects mainly redundant systems; in other words, in redundant systems, components undergo CCF as well as independent failure [3]. Therefore, it is important to consider CCF with regard to the reliability allocation of redundant systems.

Reliability allocation is a process which determines a system's allowable failure by taking the goal reliability into consideration. In the process of reliability allocation, first, the system is categorized into subsystems or components, and then the weight of each of components is determined under the impact of influencing factors or failure information. There are various ways to determine weights for reliability allocation. In these methods, the aim is to blend several factors in order to determine allocation weights. Afterwards, considering the goal reliability, the reliability of components is allocated.

Traditional methods include Aeronautical Radio Inc. (ARINC), Advisory Group on Reliability of Electronic Equipment (AGREE), feasibility-of-objectives (FOO), and weighted average method [4]. Some studies have investigated feasibility factors such as complexity, technology, operation time, environment and work conditions, safety, maintainability, availability, and costs. In one study, having selected feasibility factors [5] divided these factors into sub factors in order to compute them in a precise, practical fashion. This method is suitable, especially in stages where there is scant information regarding the amount of existing factors or where experts lack sufficient experience. [6] used the maximum entropy ordered weighted averaging (ME-OWA) method for weighted allocation, in which the optimal weighted vector is determined in maximum chaos, eliminating the deficiency of FOO method. In addition to using ME-OWA method, [7] investigated the indirect relationships between components using the decision-making trial and evaluation laboratory (DEMATEL) method. Besides, [8] added the minimum variance to the ME-OWA model and developed the maximum entropy minimum variance (MEMV-OWA) method. Finally, they computed the allocation weights using the analytical hierarchy process (AHP). Di Bona et al. [9] examined system components and factors as an AHP problem for a spatial case.

In all the aforementioned studies, feasibility factors were used as weights for reliability allocation, without paying attention to the potentials and feasibility of reliability improvement. In these papers, component reliability in series systems was determined by Eq. 1.

$$\mathrm{R}_i^* = (R^*)^{W_i} \quad or \quad \lambda_i^* = W_i \times \lambda^* \tag{1}$$

Several studies suggested reliability allocation with the use of mathematical models [10,11,12,13]. The studies attempted to minimize design costs under the limitations of reliability components. Studies, such as [14] and [15], investigated reliability allocation using the Bayesian network. Other studies, such as [16] and [17], investigated factors affecting reliability allocation using the fuzzy method.

In some other studies, using risk priority number (RPN), the allocation weight is attributed to failure mode and effect analysis (FMEA). Studies, such as [18,19] and [20], multiplied severity by failure occurrence in order to compute RPN for reliability allocation. In these studies, criticality and allocation weights were determined through Eqs. 2.

$$C_i = \frac{1}{N_i}\sum_{j=1}^{N_i}\left(S_{ij} \times O_{ij}\right), \; i = 1,2,..,k \qquad \omega_i = 1 - \frac{C_i}{\sum_{i=1}^{k} C_i}, \; W_i = \frac{\omega_i}{\sum_{i=1}^{k} \omega_i} \tag{2}$$

In a study by Wang et al. [21], criticality was regarded as one of the seven comprehensive factors in reliability allocation. In [22] study, reliability allocation weight was computed by blending functional dependency and failure criticality. Besides, a new RPN-based approach to reliability allocation was introduced [4], in which exponential transformation function was considered in the place of 10-point ordinal severity rating. Moreover, allocation weights were determined through Eq. 3:

$$W_i = \frac{1/m\,\bar{s}_i\,F_i}{\sum_{i=1}^{k}(1/m\,\bar{s}_i\,F_i)} \qquad (3)$$

Yadav and Zhuang [1] considered weighted allocation for the amount of allocation rate improvement in a series system such that the amount of modified criticality weight was developed by taking into consideration nonlinear relationship for: 1) severity and failure effect, 2) effort for improvement and failure rate. Hence, the potential for failure rate was captured, and improved failure rates were computed. In [23] study, the degree of modified criticality was blended with functional dependency, and the new allocation weight was computed so as to determine the reliability of system components.

In a paper by Chen et al.[24], reliability allocation was carried out using a copula function. A copula function takes component interdependency into consideration, though it does not investigate a specific type of such interdependencies.

Table 1 presents a summary of the investigated papers in order to draw a comparison among previous studies.

Tab. 1. Comparison of factors and methods in reliability allocation

Factors & Methods	Feasibility Factors	Criticality Factors	Model	Bayesian Network	CCF
[10]			✓		
[11]			✓		
[7]	✓				
[12]			✓		
[14]				✓	
[4]		✓			
[1]		✓			
[8]	✓				
[25]				✓	
[9]	✓				
This paper		✓			✓

An investigation of the previous studies reveals that, in the field of reliability allocation, CCF, which is a type of dependent failure, has not been previously investigated. If the interdependencies are not taken into account, system design faces problems, and achievement of the goal reliability is not ensured. It should be noted that if CCF exceeds a certain limit, system reliability certainly will not reach goal reliability. Another gap in the previous studies is that they have not investigated reliability allocation for series-parallel systems according to real potential for reliability improvement and that they have addressed allocation reliability from the perspective of improvement only for series systems.

In this connection, the present paper introduces a new reliability allocation method for series-parallel systems by considering priorities, real potential for reliability improvement, and CCF to ensure systems' required performances. In order to investigate CCF, a component is added to the redundant system in a series fashion. Eight coupling factors are considered as failure modes in FMEA analysis for CCF component

in order to investigate the position of CCF in reliability allocation. In order to conduct reliability allocation, the modified criticality weight is allocated to the level of system's reliability improvement, and, after computing each component's level of reliability improvement, the final reliability of series components as well as that of the redundant system and its components is computed. The proposed method is run for water pumping systems, and the determined failure rates undergo investigation and comparison. As a result, this method ensures the achievement and analysis of the goal reliability through practical reliability allocation. Furthermore, in addition to computing the improved failure rate of system components, this method also computes the improved failure rate of CCF, which proves beneficial for system designers.
The present paper is structured as follows: Section 2 explains dependent failure, CCF, and coupling factors. Section 3 presents the reliability allocation method for series-parallel systems by considering CCF and real potential for reliability improvement of components. Section 4 illustrates the proposed method for water pumping systems and investigates failure rate of components. Moreover, in the end, the results are presented together with some suggestions for further research.

2. Common Cause Failure

When the components of a system fail, they do not invariably fail independently from one another; rather, these failures may be interdependent. Negative dependency failure and positive dependency failure are two types of dependent failures [26]. In positive dependency failure, if one component fails, the probability of failure of other components increases. In contrast, in negative dependency failure, the failure of one component reduces the probability of failure of other components. In reliability applications, failures are usually of the former type, of which one of the most common and most important varieties is CCF. It is the simultaneous failure of more than two components in a redundant system. A simultaneous failure is a failure that occurs at moment t or within a short-time interval (system mission interval) [27]. CCF may be the result of several types of dependencies among components, such as location and environmental dependency, physical dependency or human dependency. A group of components suffering from CCF is called a Common Cause Component Group (CCCG) (Fig. 1). In other words, a CCCG is a set of components tending to fail as a result of CCF [28]. Herein, there are two features to CCF: 1) *root cause*: it is a factor causing the failure of system components, and, in fact, it is an answer to the question as to *why components fail*?

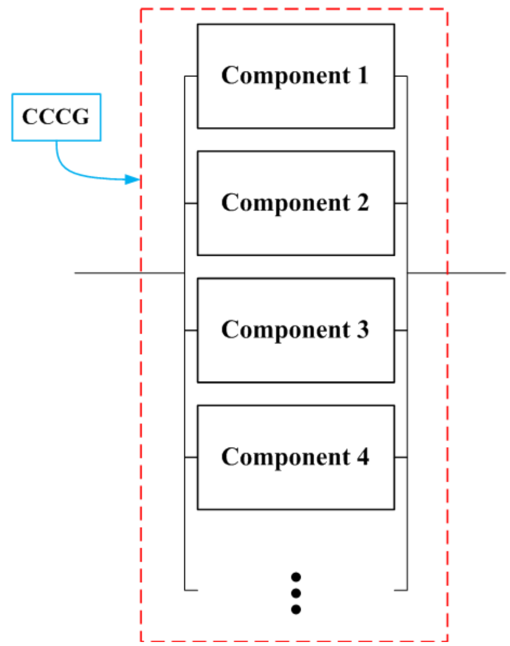

Fig. 1. Common cause component group (CCCG)

2) *Coupling factor*: The intrinsic interdependency within the system propagates failure among the components of a redundant system, and it is an answer to the question as to *why several components have been simultaneously affected and failed* [29]. Propagation of failure among redundant system component is caused by many components which prove too difficult to detect and identity. Using IEC61508 standard [30] and Unified Partial Method (UPM) [31], the factors leading to the propagation of failure in redundant systems components have been identified according to data resources and experiences of different industries. These factors are as follows:

- *Redundancy and diversity*: The number of redundant components and their diversity affects CCF events. As the diversity and redundancy among components in a CCCG increase, the probability of occurrence of CCF events decreases.

- *Separation*: Physical separation of components in a CCCG can reduce the probability of occurrence of CCF.
- *Understanding*: This indicates the maturity of CCCG technology. Factors, such as operational experience, novel technologies, technological complexity, and technology satisfaction, can be indicative of the technological maturity of redundant systems.
- *Analysis*: The use of instruments, such as FTA (Fault Tree Analysis), FMEA, and fishbone diagram, has a significant effect on failure propagation in CCCGs. If these instruments are used in a specialized fashion to analyze failures in a CCCG, the probability of occurrence of CCF is reduced.
- *Man-machine interface*: Man is one of the most important causes of propagation of failure in a CCCG. Human errors in system maintenance and operation lead to simultaneous failure of redundant system components.
- *Safety culture*: This is reflected in the training of company staff. If the company trains the staff on operating a redundant system, the probability of the occurrence of CCF events is diminished.
- *Environmental control*: It includes controlling the activities, equipment, and individuals directly related to CCCGs.
- *Environmental tests*: These tests are administered in order to design redundant systems or CCCGs in a more efficient way. They include shock, humidity, temperature, vibration tests, etc. If they are carried out in a specialized and persistent way, system design is improved, and, as a result, the probability of occurrence of CCF events is diminished.

3. Reliability Allocation

Use of failure analysis information during a FMEA process in reliability allocation helps to demonstrate system behavior and performance in a realistic fashion. Yadav and Zhuang [1] developed a modified approach to computing reliability allocation weights. They applied allocation weights to the level of failure rate improvement rather than goal failure rate, thus approaching reliability allocation from the perspective of improvement. A comprehensive idea held by design engineers is that a system component with a lower failure rate demands more efforts and expenditure in order to have improved reliability; hence, such a component has greater potential for improvement. Therefore, a nonlinear, indirect relationship has been illustrated between failure rate and effort for improvement. Besides, where the aim is to reduce severity rating from 10 or 9 (in comparison with the cases where the aim is to reduce severity rating from 5 or less), effort for improvement is more effective in reducing severity effects. These explanations suggest that there is a nonlinear relationship between the effect of improvement (degree of failure rate reduction) and severity rate. Therefore, modified criticality, where the potential is taken into consideration in order to improve reliability, is determined through Eqs. 4 and 5:

$$c_i = \frac{s_i}{e_i \times \delta_i} \tag{4}$$

$$W_i = \frac{c_i}{\sum_{i=1}^{n} c_i} \tag{5}$$

In what follows, the method proposed by the present study is presented for series-parallel systems by taking CCF into consideration.

3-1. The proposed method for reliability allocation

The purpose of reliability improvement is to increase reliability such that the system's required performances are ensured by taking CCF into consideration. Fig. 2 presents the stages of the proposed method.

Adding series component to the redundant system and investigating its failure modes (Section 3.1.1)

- Adding series component to CCF in relation to the redundant system
- Considering coupling factors as failure modes for CCF
- Investigating component failure modes, severity and failure occurrence probability

Reliability allocation of series components and redundant system (Section 3.1.2)

- Computing failure rate and reliability of components and the entire system
- Computing the level of reliability improvement of the entire system in relation to the goal reliability
- Investigating the degree of difficulty of reliability improvement of each component
- Computing modified criticality weight for the series component and redundant system
- Allocating criticality weight to the level of reliability improvement of the system
- Computing the improved reliability of series components and the redundant system

Reliability allocation of redundant system components (Section 3.1.3)

- Computing the improved reliability of redundant system components

Analyzing the failure rate of system components (Section 3.1.4)

- Computing and comparing the failure rate of components
- Presenting strategies to reduce the occurrence rate of CCF

Fig. 2. Proposed work process for reliability allocation

3-1-1. Adding the series component to the redundant system and investigating its failure modes

As mentioned previously, redundant failures are vulnerable to CCF as well as independent failure. Therefore, in the reliability allocation of redundant systems, attention must be paid not only to independent failure information of components, but also to CCF information. The consideration of an improved independent failure rate alone may not ensure the achievement of the desired R^* in the system, because if the occurrence of CCF exceeds a certain limit, system reliability will certainly not reach R^*. Hence, system designers need to know the improved failure rate of CCF. In order to take CCF into consideration in reliability allocation, a component is added to the redundant system in a series fashion. This component is regarded as the CCF component (Fig. 3).

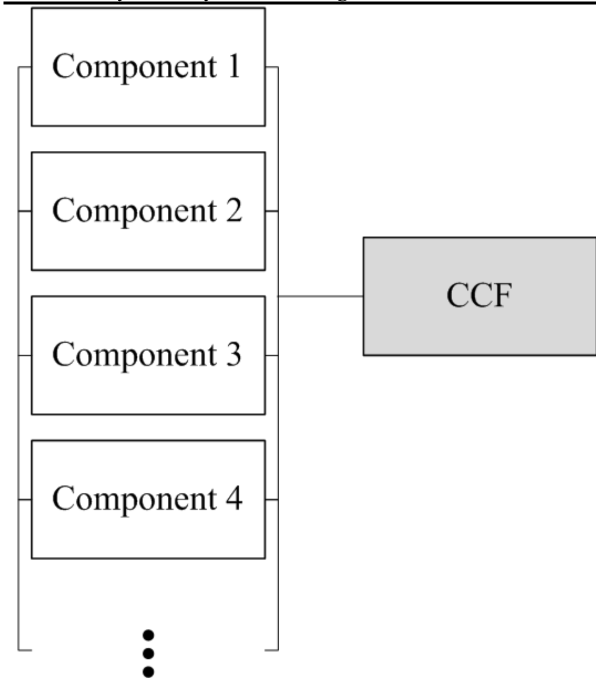

Fig. 3. Common cause failure component and redundant system

In case of failure occurrence in the CCF component, the entire redundant system breaks down simultaneously. After adding the CCF component to the system, the share of CCF in reliability allocation is investigated. The aforementioned eight coupling factors lead to the expansion and propagation of failure across redundant system components. These factors are used as failure modes in the analysis of FMEA for the CCF component. Severity and occurrence of each factor influence the failure rate of the CCF component. Consequently, by adding the CCF component to the system and by taking the eight coupling factors into consideration as failure modes for the CCF component, a share of reliability is allocated to CCF. In addition, failure modes, severity, and failure occurrence probability of other components are investigated, too.

3-1-2. Reliability allocation of series components and redundant system

In order to allocate reliability to the series-parallel system, first, the total weight of the redundant system is calculated from the sum of weights of redundant components. Having determined the weights of series components and redundant system using Eq. 5, these weights are normalized by a direct method, and the final weights are determined.

In so doing, reliability can be calculated through Eq. 6 for series-parallel systems with a constant failure rate and exponential lifetime distribution.

$$R_i = e^{-\lambda_i \times t}$$
$$R_{sys} = f(R_i) \quad (6)$$

Eqs. 7 and 8 are used to compute the level of reliability improvement. In this stage, weight allocation is carried out for the level of system reliability improvement, and the improved reliability of series components and redundant system is computed through Eq. 9.

$$\Delta R^* = \frac{R^*}{R_{sys}} \quad (7)$$
$$\Delta R_i^* = W_i \times \Delta R^* \quad (8)$$
$$R_i^* = \Delta R_i^* \times R_i \quad (9)$$

The factor of reliability improvement difficulty stands in opposition to the feasibility factor of increasing the reliability in Refs. [10] and [12]. Greater difficulty factors mean higher costs and greater difficulty in reliability improvement considering the factors influencing the component in question. This relationship is illustrated in Fig. 4. It can be seen that the lower level of feasibility causes cost function to approach infinity more sharply. In summary, feasibility can be computed in two methods: weighting factors and engineering judgment based on historical data. According to the paper by [1], in components with high failure severity and low initial failure rate, reliability improvement demands greater effort, hence greater difficulty in reliability improvement. Under such circumstances, a value higher than one is assigned to the difficulty factor so that the allocated failure rate does not become negative or the reliability of the component does not exceed one. For this purpose, in the present paper, expert judgment and the sum of these two factors have been considered as a criterion to account for reliability improvement difficulty.

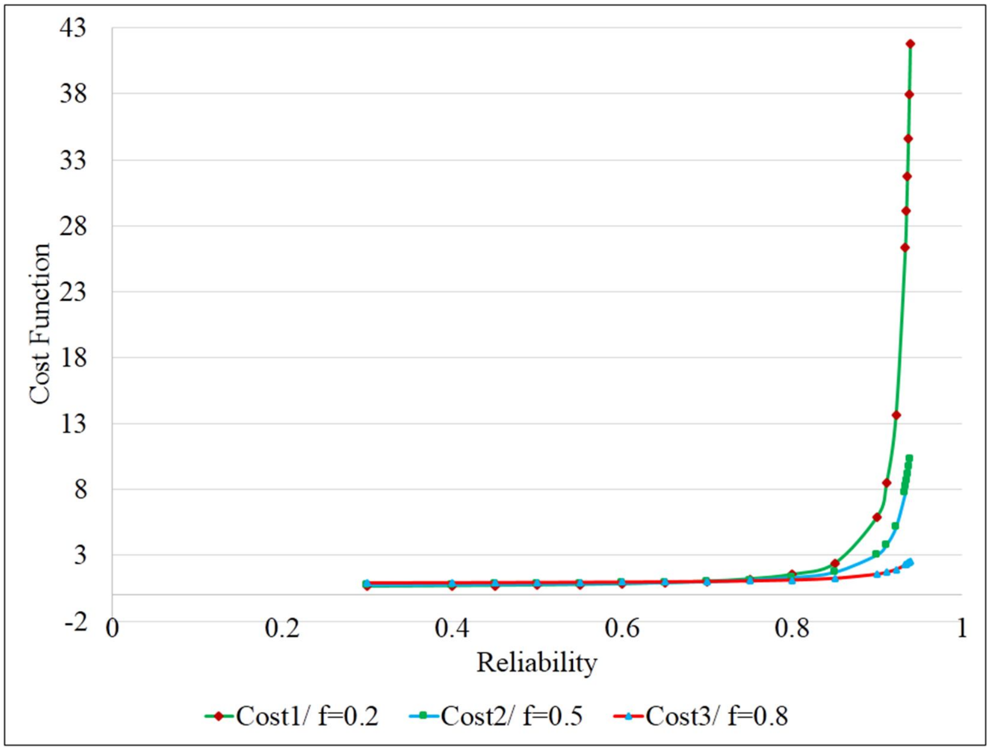

Fig. 4. Cost function versus reliability and effect of feasibility

3-1-3. Reliability allocation for redundant system components

Having computed the improved reliability of the redundant system, Eq. 10 is used to allocate reliability to each component of it. Fig. 5 shows the concept of component weights and redundant systems weight, too.

$$(1 - R_{P_i}) = (1 - R_P^*)^{W_{P_i}} \tag{10}$$

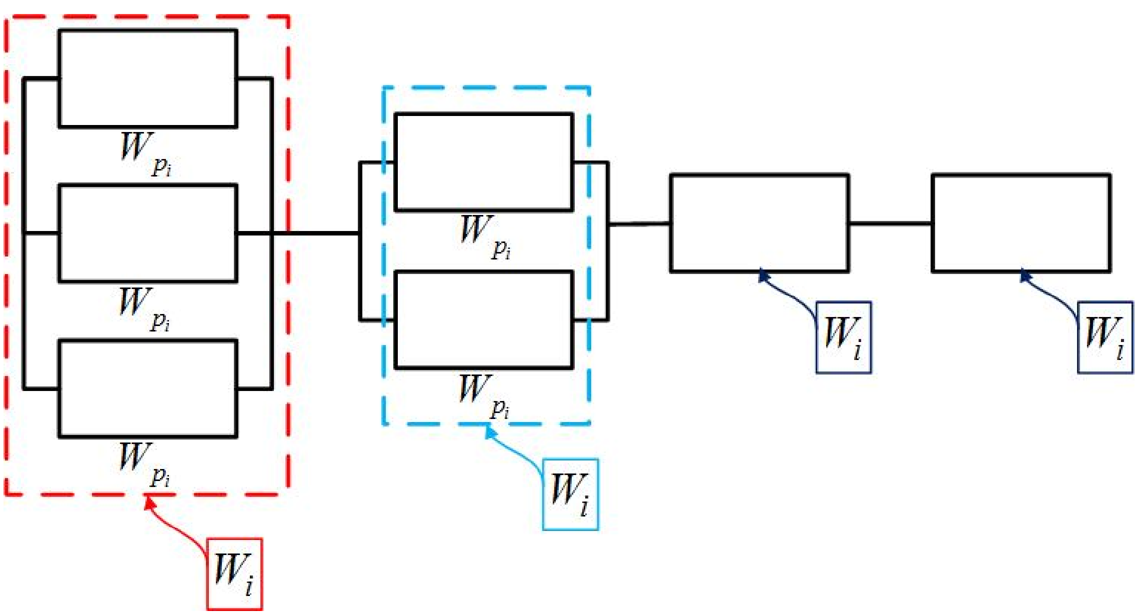

Fig. 5. Weights of components and redundant systems in a system

3-1-4. Analysis of failure rate of system components

In what follows, using reliability, the failure rates of all components are determined, investigated, and compared.

4. Case Study

Water pumps rank among the most essential machines in different industries. They are used in nuclear industries [32], cooling towers [33], water transfer pumps [34,35], etc. Due to the high sensitivity of such industries, two or more water pumps are used in parallel, thus building a redundant system which continues functioning in case of failure of one of the pumps. One of the crucial applications of water pumping redundant systems is the transfer of water from water purification plants to municipal areas. At each water pumping station, two pumps are used in parallel. These pumps are vulnerable not only to independent failure, but also to CCF. The other main components of this water pumping system are the valve, the check valve, and the electric panel. Engineers and designers have always paid attention to the reliability of water pump systems, and extensive activities have been carried out to improve the reliability of the subsystems and components of these systems. Reliability allocation is one of those activities, in which the goal reliability is determined for the water pumping system, and, in the light of failure information and other factors, the reliability of each component is allocated. Fig. 6 illustrates the water pumping system.

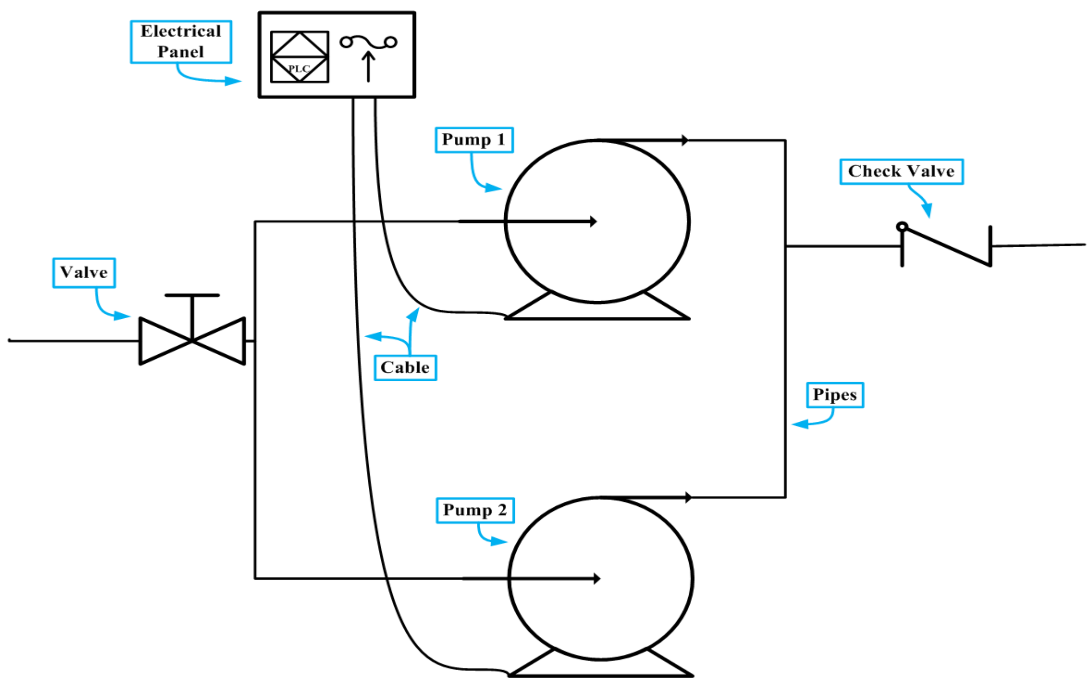

Fig. 6. Water pumping system

According to the proposed work process, as displayed in Fig. 7, CCF is added as a series component to the redundant system.

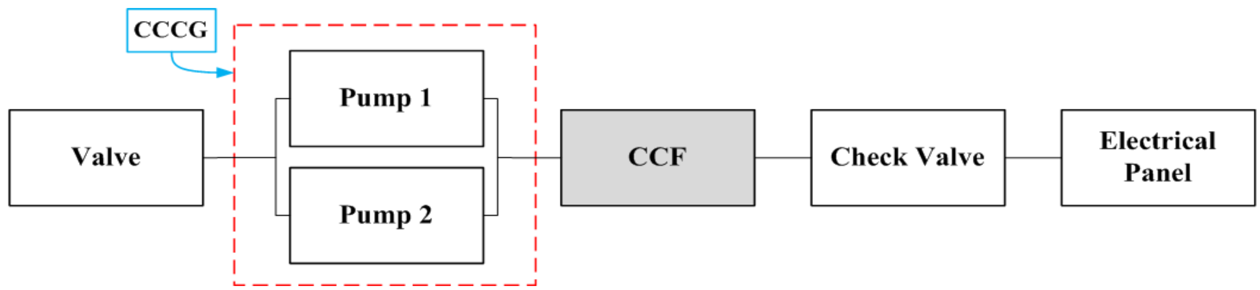

Fig. 7. Block diagram of water pumping system together with CCF component

Table 2 presents the failure modes as well as the severity and probability of failure occurrence for the components of water pumping system. According to this table, by assuming a mission time of 100 hours, the current reliability of each component has been computed. The figures related to the failure modes of system components have been derived from historical warranty data and on the basis of expert judgment. The figures related to the CCF component are derived from the current data on coupling factors; for instance, redundancy and diversity lead to simultaneous failure of components of redundant systems. The severity and occurrence of these factors can be determined in the FMEA process (in other words, the extent to which redundancy and diversity lead to simultaneous failure of the redundant system components as well as the severity of failure is determined). The same procedure is followed for other coupling factors, too.

Tab. 2. Failure modes and current reliability of components

i	Component	FMs	S_{ij}	O_{ij}	λ_{ij}	λ_i	R_i
1	Pump 1	FM1	6	1	0.0000988	0.0029866	0.7418146
		FM2	5	1	0.0000988		
		FM3	6	4	0.0009956		
		FM4	5	3	0.0004609		
		FM5	4	1	0.0000988		
		FM6	3	3	0.0004609		
		FM7	6	2	0.0002133		
		FM8	5	3	0.0004609		
		FM9	6	1	0.0000988		
2	Pump 2	FM1	6	1	0.0000988	0.0029866	0.7418146
		FM2	5	1	0.0000988		
		FM3	6	4	0.0009956		
		FM4	5	3	0.0004609		
		FM5	4	1	0.0000988		
		FM6	3	3	0.0004609		
		FM7	6	2	0.0002133		
		FM8	5	3	0.0004609		
		FM9	6	1	0.0000988		
3	CCF	FM1	9	4	0.0009956	0.0020306	0.8162254

		FM2	7	2	0.0002133		
		FM3	9	1	0.0000988		
		FM4	8	2	0.0002133		
		FM5	6	1	0.0000988		
		FM6	5	2	0.0002133		
		FM7	5	1	0.0000988		
		FM8	4	1	0.0000988		
4	valve	FM1	8	1	0.0000988	0.0014314	0.8666357
		FM2	7	3	0.0004609		
		FM3	8	1	0.0000988		
		FM4	8	3	0.0004609		
		FM5	5	2	0.0002133		
		FM6	6	1	0.0000988		
5	Check valve	FM1	7	1	0.0000988	0.0011838	0.8883546
		FM2	7	2	0.0002133		
		FM3	7	3	0.0004609		
		FM4	5	1	0.0000988		
		FM5	5	1	0.0000988		
		FM6	6	2	0.0002133		
6	Panel	FM1	6	1	0.0000988	0.0012826	0.8796242
		FM2	6	2	0.0002133		
		FM3	8	3	0.0004609		
		FM4	7	1	0.0000988		
		FM5	4	1	0.0000988		
		FM6	5	1	0.0000988		
		FM7	7	2	0.0002133		

Afterwards, considering the system structure, R_{sys} is computed using Eq. 6 R^* is considered equal to 0.9. Values of difficulty of reliability improvement are given on the basis of failure severity, improvement efforts, and expert judgment. The level of reliability improvement of the entire system is computed through Eq. 7, and, considering the weight of modified criticality W_i , the degree of system improvement is allocated to the series components and the redundant system. Table 3 presents the calculation results.

$$R_{sys} = \big(1-(1-R_4)(1-R_5)\big) \times R_1 \times R_2 \times R_3 \times R_6 = 0.51590 \quad (11)$$

$$\Delta R^* = \frac{0.9}{0.5159056} = 1.7445 \quad (12)$$

Tab. 3. Allocated reliability to series components and redundant system

i	Component	$\bar{S}_i$	E_i	s_i	e_i	δ_i	c_i	W_i	ΔR_i^*	R_i^*
	Redundant system							0.06315	1.0358	0.96672
1	Pump 1	121.51	0.0581	0.0398	0.1539	5	0.0517			
2	Pump 2	121.51	0.0581	0.0398	0.1539	5	0.0517			

3	CCF	1339.4	0.0619	0.4382	0.1641	5	0.5340	0.32638	1.1992	0.97879
4	Valve	601.85	0.0654	0.1969	0.1734	3	0.3786	0.23137	1.1374	0.98572
5	Check Valve	270.43	0.0673	0.0885	0.1784	2	0.2480	0.15155	1.0880	0.96652
6	Panel	601.85	0.0665	0.1969	0.1763	3	0.3723	0.22756	1.1350	0.99837
Total							1.6362	1.00000	1.7445	0.90000

Table 4 presents modified criticality W_{P_i} for redundant system components. In this table, two parallel components are measured in relation to each other, and the weights are normalized directly. Considering that R_P^* =0.96672, the improved reliability of redundant components is computed through Eq. 10.

Tab. 4. Allocated reliability to components of redundant system

Component of redundant system	c_i	W_{P_i}	$R_{P_i}^*$
Pump 1	0.0517	0.50000	0.81757
Pump 2	0.0517	0.50000	0.81757
Total	0.1034	1.00000	0.96672

In this stage, the reliability of all components is computed. Table 5 presents the improved failure rate and improvement level.

Tab. 5. Result of proposed method for failure rate of components

Component	λ_i	λ_i^*	$\lambda_i - \lambda_i^*$	Improvement Percent
Pump 1	0.0029866	0.0020142	0.0009724	0.097
Pump 2	0.0029866	0.0020142	0.0009724	0.097
CCF	0.0020306	0.0002144	0.0018162	0.182
Valve	0.0014314	0.0001439	0.0012875	0.129
Check Valve	0.0011838	0.0003405	0.0008433	0.084
Panel	0.0012826	0.0000163	0.0012663	0.127

Fig. 8 draws a comparison between improved failure rate and initial failure rate. Fig. 9 presents the level of improvement of each component. Because failing to consider dependent failures leads to irreversible damage, attention must be paid to independent failure as well as CCF information in reliability allocation for redundant systems. For the pump in question, if the aim is to achieve reliability of 0.9, the CCF rate must undergo a reduction of 0.18% and reach 0.0002144.

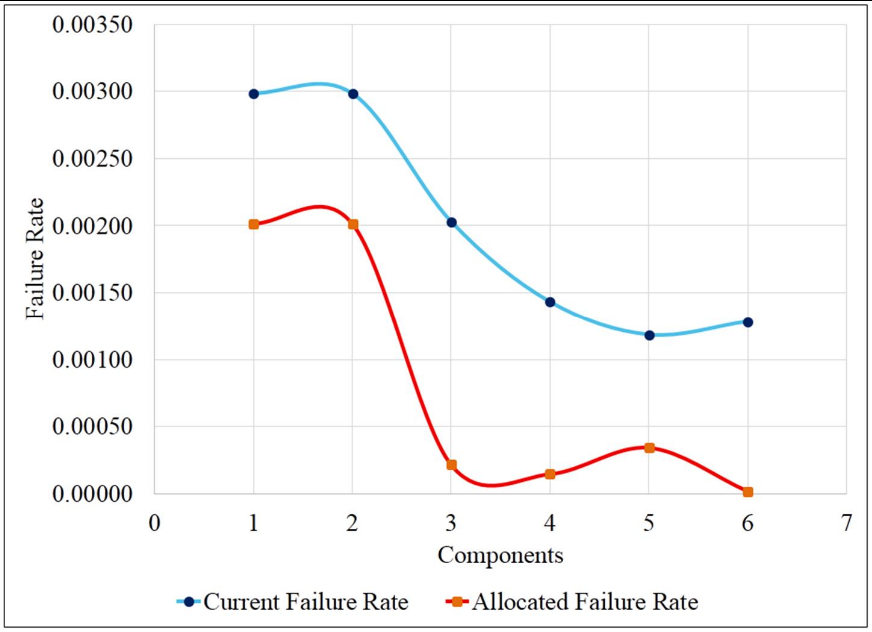

Fig. 8. Comparison of components failure rate

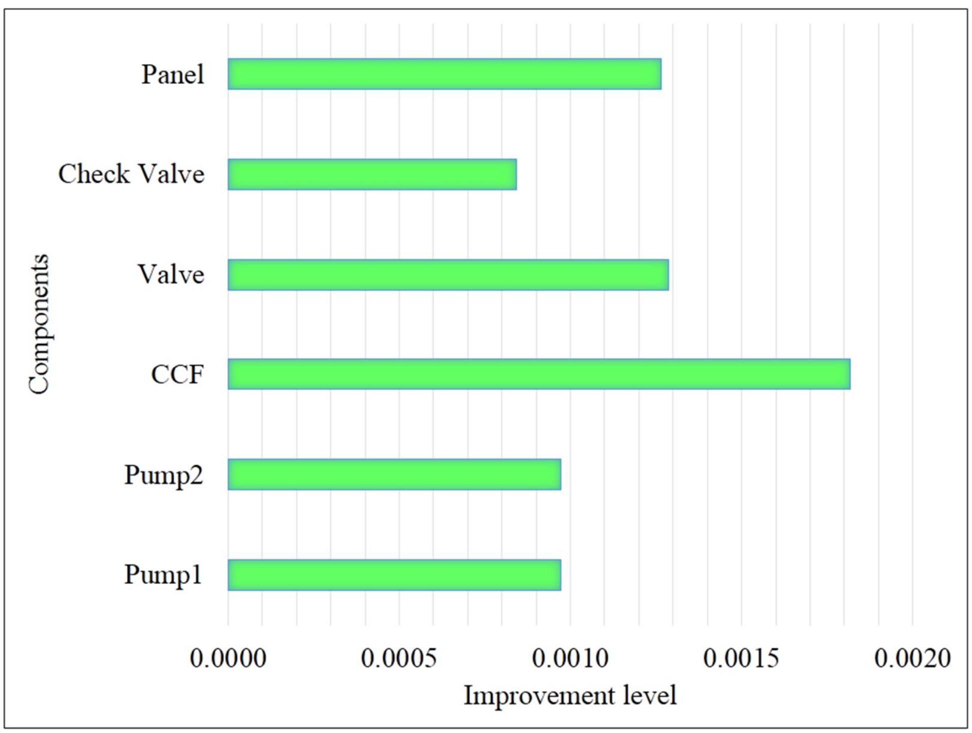

Fig. 9. Improvement level of components failure rate

Table 6 displays the failure rate of system components without considering the CCF component in the system. Fig. 10 presents the results. As expected of the results, by considering CCF, failure rate of components should be improved more than that without considering CCF. Fig. 11 presents the level of reliability improvement.

Tab. 6. Result of components failure rate with CCF and without CCF

Component	Pump 1	Pump 2	CCF	Valve	Check valve	Panel
λ_i^* Without CCF	0.0020785	0.0020785	-	0.0002175	0.0003888	0.0000888
λ_i^* With CCF	0.0020142	0.0020142	0.0002144	0.0001439	0.0003405	0.0000163

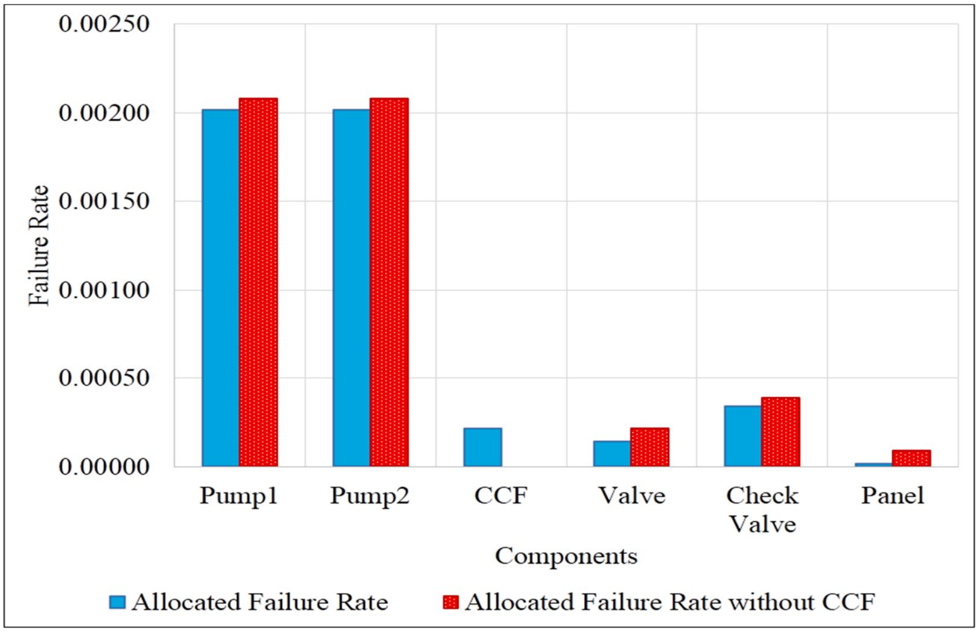

Fig. 10. Comparison of allocated failure rate with CCF and without CCF

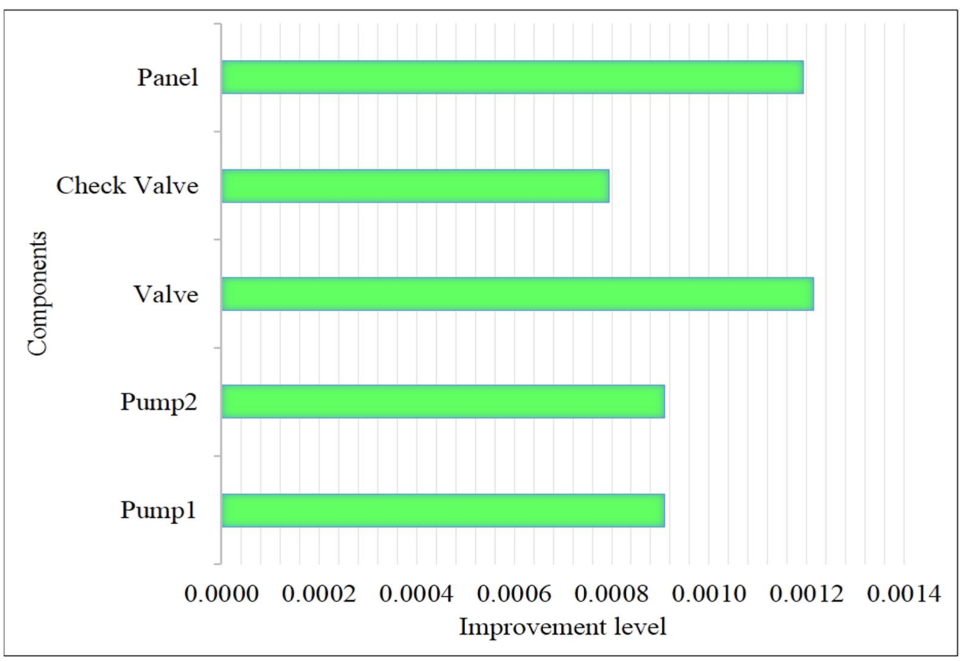

Fig. 11. Improvement level of components failure rate without CCF

Coupling factors are investigated in order to reduce CCF occurrence. In this respect, the following measures can be taken:

- increasing the redundancy and diversity of pumps and using pumps made by various companies in the system
- separating the redundant system components as much as possible (installing them in different places)
- minimizing human errors through training and controlling the activities, equipment, and individuals operating in the redundant system
- using FMEA and fishbone diagram in order to reduce CCF occurrence
- minimizing human interaction with the water pumping redundant system by enhancing the technologies and using modern equipment
- continuously controlling the vibration and temperature of the water pumping redundant system, and using proper maintenance in cases where vibration and temperature exceed the permitted limit so as to prevent the simultaneous failure of water pumps

5. Conclusion

Redundant systems may undergo CCF as well as independent failure. Hence, it is crucial to take CCF into consideration in the reliability allocation of redundant systems so as to achieve goal reliability. In order to investigate CCF, a series component was added to the redundant system. By considering coupling factors as failure modes of the CCF component, a method was developed for reliability allocation of series-parallel system, which accounted for opportunities of reliability allocation. After applying the proposed method to a pumping system, the results underwent investigation. This reliability allocation method ensures the achievement of R^* in a practical fashion. In addition to computing the improved failure rate of system components, the improved failure rate of CCF is computed, too. This proves instrumental and necessary for system designers in the stages of feasibility study and conceptual design. The CCF component enjoys the highest reliability improvement. This means that in order to achieve R^* intended by the designer, intrinsic factors leading to system failure must be analyzed, because if CCF exceeds a certain limit, the system reliability will certainly fail to reach R^*. The proposed model provides greater flexibility for design engineers who seek to identify improvement opportunities and to regulate reliability objectives in connection with the feasibility of improvement of reliability, degree of criticality, and CCF. Load share is another variety of independent failures which impinges upon some redundant systems. It is recommended that future studies incorporate CCF and also load share into the reliability allocation of redundant systems. For mechanical equipment, considering the presence of parts such as O-rings which are made of polymers, other probability distributions, such as Weibull, are valid. In this condition, reliability allocation can be carried out on the basis of the Weibull failure rate function. Besides, by taking CCF into consideration, other factors, such as feasibility factors, can be used to compute allocation weights.

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