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ARTICLES

RELIABILITY ALLOCATION CONSIDERING RISK INDICATORS AND THEIR UNCERTAINTIES THROUGH PROBABILISTIC COMPOSITION OF PREFERENCES

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ABSTRACT. In the development of new designs for systems or improvement of existing ones, the search for effective methods of reliability allocation is fundamental to achieve the minimum requirements. The different allocation methods can involve the consideration of many criteria. Among these criteria, some are quantitative, and others are qualitative, but in both cases, there will be uncertainties associated with the metrics. This article presents an approach based on the probabilistic composition of preferences to allocate the reliability of subsystems considering the uncertainties associated with each criterion considered. The results obtained with application to a case described in the literature demonstrate the efficacy of the proposed approach to deal with this class of problems.

Keywords: probabilistic composition of preferences, reliability allocation, FMEA.

1 INTRODUCTION

In the past 20 years, many approaches have been proposed for reliability allocation involving systems. Various factors can be considered to establish a minimum reliability requirement for the design of a system (Wang et al. 2001). During this period, the increase in competitiveness, safety requirements and productivity have been pressuring organizations to invest in the development of increasingly reliable systems (Yadav et al. 2003). In the conceptual design phases, efforts and possible modifications cause, in terms of costs, less significant impacts than alterations of designs already conceived (Blanchard 2008).

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In the conceptual design phase, no matter how much information exists on similar designs, the development is replete with subjectivity associated with the opinions of specialists, mainly related to analyses of failure and risks, which are essential steps for understanding the potential ways that components can fail (Yadav et al. 2003). In this context, different approaches have been proposed.

Wang et al. (2001) presented a “comprehensive” procedure for reliability allocation based on seven criteria, weighted by pairwise analysis between subsystems. Yadav et al. (2003) proposed an approach based on a set of fuzzy inference rules to establish indices of increased reliability of subsystems. Yadav et al. (2003) proposed an approach in a Bayesian framework combining information obtained from the failure mode and effect analysis (FMEA) with data from manufacturers. This approach also involves the planning of verification tests to reach the desired reliability level. In turn, Yadav et al. (2006) proposed an approach based on a three-dimensional design analysis that observes functional aspects, mission time and physical structure. This three-dimensional decomposition entails the development of FMEA and functional diagrams to support the establishment of reliability targets to be attained. Based on this decomposition, the criticality indices, obtained via FMEA, and information from the manufacturer, among other sources, are combined to establish the weights for allocation among the failure rates of the components of a system considering the failure time modeled in advance for a distribution that will be updated. Yadav (2007) extended the developments of Yadav et al. (2006) to consider an analytic hierarchy process (AHP) for establishing the weights for the distribution of the reliability allocation among subsystems. Finally, Yadav & Zhuang (2014) investigated the limitations associated with the criticality index associated with FMEA to propose a modified index. In their proposal, they established a nonlinear relationship between the variation of the failure rate and the effort undertaken to achieve this variation in terms of its reduction. According to this relation, the lower the failure rate is, the greater the effort will be to improve it, i.e., to reduce it even more, as depicted in Figure 1.

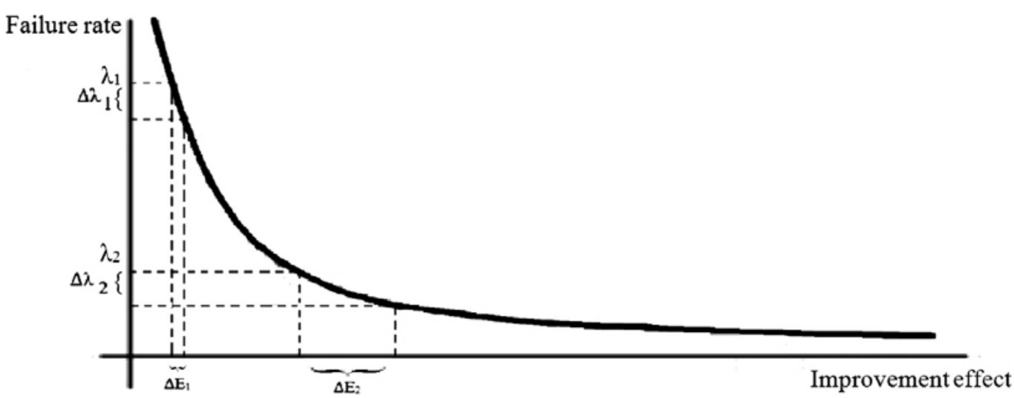


Figure 1 – Nonlinear relation between failure rate and improvement effort.

Source: Yadav & Zhuang (2014).

The authors then proposed, based on Kim et al. (2013), a relation between the occurrence indices established via FMEA and the failure rate. This functional relation was characterized through an exponential adjustment in the MilStd 1629A reference table, as given in Equation 1, with goodness of fit greater than 0.99.

$$\lambda_{ij} = \exp(-9.993 + 0.77020.O_{ij}) \tag{1}$$

where λ_{ij} is the estimated failure rate, O_{ij} is the occurrence index, which varies from 1 to 10 (the greater the index, the higher the chance of occurrence), for the j-th failure mode of the i-th subsystem.

The same reasoning for was proposed by the authors for the severity index. According to Yadav & Zhuang (2014), the impact of an improvement in the severity index is not linear as indicated in Equation 2, just as the effort to reduce low failure rates is greater than that is to reduce larger failure rates. With this, the authors proposed a modified severity index by using an exponential transformation according to Figure 2.

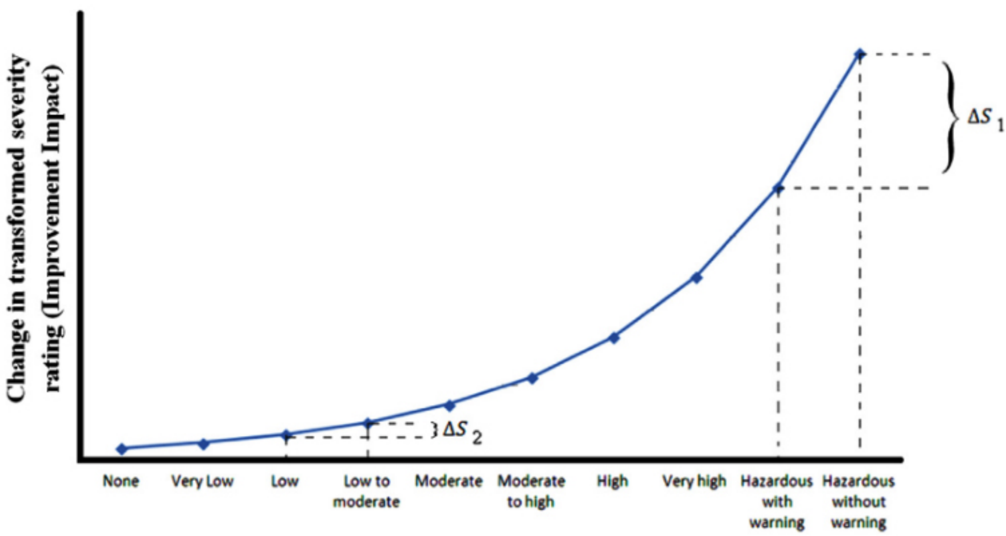


Figure 2 – Transformed severity index and failure effects.

Source: Yadav & Zhuang (2014).

$$\overline{S}_{ij} = \exp(\alpha S_{ij}) \tag{2}$$

Based on this transformation, the authors proposed a modified criticality index to be used to weight the subsystems for the respective reliability allocations. The main idea behind the use of the severity index is related to the fact that the failure mode with higher severity must be prioritized for reliability improvement. The intent, *a priori*, is not to reduce the severity but to reduce the expected value of the consequence associated with the failure mode occurrence (Yadav & Zhuang, 2014).

Li et al. (2015) proposed a modified approach of the AGREE (Advisory Group on the Reliability of Electronic Equipment) method to contemplate analyses based on missions. In other words, they presented an approach to reliability allocation based on the number of missions proposed for the system. Cao et al. (2019) proposed an approach to contemplate the effects of failures with a common cause in the reliability allocation process. In that procedure, the authors employed the transformation defined in Equation 2 and the probability of occurrence of a group of components with a common cause. Hu et al. (2019) proposed a hybrid approach that combines fuzzy numbers with AHP and analysis of importance to establish the best weighting of the reliability allocation distribution among the components. Saadi et al. (2019) put forward an extension of the three-dimensional method proposed by Yadav (2007) and Yadav et al. (2006) to contemplate systems with multiple phases, to include the dependencies between the operational phases with impact on the reliability of the components. Wang et al. (2020) presented an approach to reliability allocation that considers the availability of production systems. The authors urged the consideration of buffers (inventories of finished and semi-finished products) for the analysis of productive processes. They established a relationship with the Markovian analysis and the buffers for allocation of availability.

All of these studies have sought to consider the subjective aspects in some way. Besides this, the transformations proposed for the FMEA indices have overcome the fact that they have an ordinal scale, whose mathematical operationalization is limited. In this paper, we propose a probabilistic transformation by using the probabilistic composition of preferences (PCP) for the FMEA indices. Unlike the approaches proposed in these previous publications, which maintain the dependence of the indices on an ordinal scale or based on fuzzification, we consider that specialists' opinions are modeled by a probability distribution, as happens in Bayesian analyses, and thus no longer consider the indices themselves, but rather their respective probabilities of being passed over or not in detriment to the others. This approach attenuates the limitations described regarding problems of scale and uncertainties, providing a probabilistic weighting for the allocation of reliability.

2 RELIABILITY ALLOCATION BASED ON CRITICALITY

For any productive system, in the absence of definitive information beyond the fact that k subsystems will be allocated in series, a fair partition of reliability among them is reasonable. This means that an equal distribution of reliability increment among the subsystems will be formulated, according to Equation 3.

$$R^* = \prod_{i=1}^{k} R_i^* \Rightarrow R_i^* = (R^*)^{1/k} \quad (3)$$

where: R^* is the reliability requirement established for the system; and R_i^* is the reliability level to be attained by the i-th subsystem (Yadav & Zhuang 2014). In this approach, the difficulty/complexity of achieving the established levels is not considered. To deal with this, the AGREE method proposes the use of the complexity level for weighting (Clement 1956). This complexity is established based on the number of components or parts in the i-th subsystem. This leads to the weighting established by Equation 4.

$$w_i = \frac{n_i}{\sum_{i=1}^{k} n_i} \tag{4}$$

where: n_i is the number of components or parts of the i-th subsystem, and k is the total number of subsystem (SS) under analysis. With this, the reliability distribution among the subsystems is given by Equation 5.

$$R_i^* = (R^*)^{w_i} \tag{5}$$

Another way to establish the reliability distribution among the subsystems is the proposal in Mil-Std 338 (USDoD, 1988), in which criteria for the feasibility of reaching the objectives are considered. This means considering viability indices on an ordinal scale from 1 to 10. The product of the values established for the indices represents the level to be considered for each subsystem. This leads to Equation 6, which establishes the weighting to be considered.

$$w_i = \frac{V_i}{\sum_{i=1}^{k} V_i} \tag{6}$$

where: V_i is the level of viability for the i-th subsystem. Kuo et al. (2001) proposed a similar approach, which they called the weighted average allocation method. This approach is based on the opinion of specialists in which for each subsystem, indices are assigned related to the complexity, state of the art, criticality, environmental impact, safety and maintenance. For each of these factors, the experts establish an index that varies on an ordinal scale from 1 to 10, to consider the average opinion for each index. Note that this consideration of the average of data on an ordinal scale is controversial.

More recently, various authors have published articles based on the information generated by the FMEA. Yadav et al. (2006), Itabashi-Campbell & Yadav (2008) and Saadi et al. (2019) have proposed an average risk prioritization number, considering C_i a measure of the criticality of failure of the i-th subsystem, the indices of severity (S_{ij}) and occurrence (O_{ij}), according to Equation 7. It should be recalled that the establishment of the indices should be based on the relevant specialized knowledge of a team and ratified by the managers of the previous risk processes (AIAG 2008).

$$C_i = \frac{1}{m} \sum_{j=1}^{m} S_{ij}.O_{ij} \tag{7}$$

where *i* and *j* are as stated before in Equation 1.

Wang et al. (2001) also considered criticality to be a criterion for reliability allocation. Yadav (2007) combined criticality with the functional dependence in a three-dimensional perspective, according to Equation 8.

$$w_i = \frac{w_D D_i + w_C C_i}{\sum_{i=1}^{k}(w_D D_i + w_C C_i)} \quad (8)$$

where: D_i represents a functional dependence index, with w_D and w_C being the relative importance levels of dependence and criticality, respectively.

Yadav & Zhuang (2014) reported that the approaches to that date had been based on the premise of linearity of the 10-point ordinal scale, and that these approaches did not consider the difficulty of associated with allocation according to the increase of criticality. According to them, the reliability community had a common understanding that the higher the failure rate, the easier the process of its improvement will be. Based on this comprehension, Kim et al. (2013) proposed weighting according to Equation 9.

$$w_i = \frac{\frac{1}{m_i \overline{S}_i F_i}}{\sum_{i=1}^{k} \frac{1}{m_i \overline{S}_i F_i}} \quad (9)$$

where: $\overline{S}_i$ is given by Equation 2; and F_i is the failure frequency, which can be characterized based on historical data or according to Equation 1, m_i is the number of failure modes in the i-th subsystem (SS_i) having the same $\overline{S}_i$. According to Yadav & Zhuang (2014), the approach put forward by Kim et al. (2013), in certain cases, involves allocation for failure modes that already have a low failure rate, not considering the aspects associated with the technical viability of carrying out the improvement in question. In light of this, the authors proposed an approach combining criticality with improvement efforts, as presented in Figure 2. In their approach, Yadav & Zhuang (2014) proposed a transformation of the severity index according to Equation 2, in which the most critical failure mode of a subsystem is considered, i.e., the result of Equation 10.

$$\overline{S}_i = max(\overline{S}_{i1}, \overline{S}_{i2}, ..., \overline{S}_{ij}) \quad (10)$$

Starting from the result of Equation (10), a normalization routine is applied among all the subsystems. To consider the improvement effort, Yadav & Zhuang (2014) proposed the expression $E_i = \ln(\lambda)/r$, where r is a decreasing improvement rate for the failure rate λ. Based on this characterization of the effort, in which λ can be obtained by Equation (1), normalization is established among all the subsystems, according to Equation 11.

$$e_i = \frac{E_i}{\sum_{i=1}^{k} E_i} \quad (11)$$

Based on these two normalized indices, a modified criticality level is obtained according to Equation 12.

$$C_i = \frac{S_i}{e_i} \quad (12)$$

With this, the weights for the reliability allocation distribution among the subsystems are obtained by the normalization of C_i.

Note, however, that as discussed in the abovementioned references, in all cases there is dependence on the opinion of experts to establish the severity and occurrence indices, mainly in cases in which satisfactory failure histories of the subsystems are not available. In this situation, here we propose an approach based on the probabilities of preference among indices derived from FMEA to establish the desired weighting for the reliability allocation. Also note that according to Kmenta & Ishii (2000), the score attributed to the probability of occurrence of failure reflects the probability of the cause and of the immediate failure mode, not the probability of the final effects. Xu et al. (2002) mentioned two limitations that should be considered when applying FMEA: (i) the probability calculations are not always sufficiently precise because the method relies on categorizations, not field variables; and (ii) the elements being judged are not always mutually exclusive – dependence can exist between the failure modes – which also needs to be considered in the group evaluations.

3 METHODOLOGY

The problems associated with the criticality index of FMEA are not new and have different aspects, both the order priority among the failure modes and for establishing weights for reliability allocation, which is a problem addressed in this article. The problems we intend to overcome are associated with the numerical scale, which in the indices adopted in FMEA is ordinal (Garcia et al. 2005, 2009). For this reason, limitations exist for the mathematical treatment and the epistemic uncertainties associated with the process of attributing these values. From a methodological standpoint, our approach is based on the probabilistic composition of preferences – PCP (Sant'Anna et al. 2015).

The PCP is a method that explores the key concept of randomization among alternatives, i.e., the evaluations that *a priori* would be considered as exact are treated as position measures of a continuous random variable. The model representing the randomness is selected according to the phenomenon associated with the criterion considered, which in the opinion of specialists can be a beta-PERT or lognormal distribution (Gavião et al. 2018; Martino 1970). Here, we consider the functionalities contained in the R software (R-Core-Team 2022).

After the randomization process, the probabilities are calculated of each alternative g being superior, preferable ($PMax$), or inferior, or unpreferable ($PMin$), in relation to the others. These maximum and minimum preference probabilities are established by means of the joint distributions attained in Equations 13 and 14 (Garcia et al. 2013; Gavião et al. 2016, 2018):

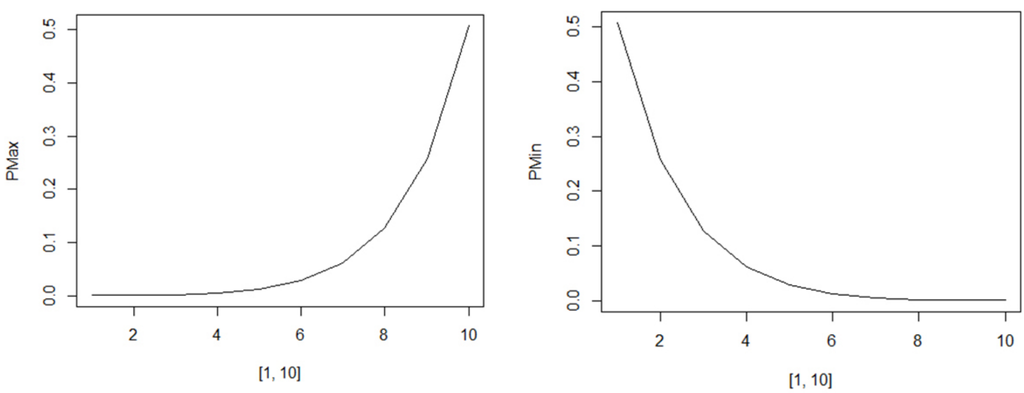
$$PMax_{gq} = \int_{L_{gq}}^{U_{gq}} \left[\prod_{h=1}^{t} \int_{L_{hq}}^{X_{gq}} f_{X_{hq}}(x')dx' \right] f_{X_{gq}}(x)dx \tag{13}$$

$$PMin_{gq} = \int_{L_{gq}}^{U_{gq}} \left[\prod_{h=1}^{t} \int_{X_{gq}}^{U_{hq}} f_{X_{hq}}(x')dx' \right] f_{X_{gq}}(x)dx \tag{14}$$

In these two equations, L_{gq} and U_{gq} are, respectively, the lower and upper bounds of the domain of the random variable X_{gq}, which represents the preference of alternative q in relation to criterion g, while t is the number of alternatives being considered. With this, Equation 13 supplies the maximum probability of a q-th alternative being preferred in relation to the others according to a g-th criterion. In turn, Equation 14 provides the minimum probability of a q-th alternative being undesired in relation to the others according to a g-th criterion.

Note that this probabilistic transformation of the criteria causes the entire development of the process to be based on a probability distribution, irrespective of their scale. Besides this, based on the transformation applied and the calculation of the probabilities, the subsequent operationalization is not limited by questions of numerical scale. Furthermore, since the probabilities are calculated based on probabilistic models representing the uncertainties associated with the opinions of experts, these uncertainties will be included in the future decisions, as observed by (Sant'Anna 2012; Sant'Anna et al. 2015).

Note also that the sum of the probabilities of maximizing (or minimizing) the alternatives in each criterion is unitary, so these probabilities can be considered weights for reliability allocation. Moreover, according to Gavião et al. (2020), the probabilistic transformation satisfies the principle of nonlinearity of the relations, as criticized by (Yadav & Zhuang 2014). This nonlinearity can be observed in Figure 3, for the maximum and minimum cases.



(a) **(b)**

Figure 3 – Nonlinear relation between the scale and probabilities of maximum (a) and minimum (b) preferences.

Source: Gavião et al. (2020).

Based on these nonlinear characteristics of the transformations, we propose to consider, as the severity index, the transformation by using the maximum preference probability, and for the case of the effort level, the minimum preference probability. Both of these are initially established by means of the opinion of specialists considering an ordinal scale in the interval [1, 10], in which higher values are attributed to greater severity and effort necessary for improvement. Based on the probabilistic transformation, one can consider, for example, Equation 15, to obtain the final weighting for the reliability allocation:

$$w_i = \frac{\alpha.PMin(S_i) + (1-\alpha).PMin(O_i)}{\sum_{i=1}^{k} \alpha.PMin(S_i) + (1-\alpha).PMin(O_i)} \tag{15}$$

where: $\alpha \in (0,1)$ is the relative importance between the severity and effort. In this setup, only *PMin* is considered since greater severity is associated with lower weight, and the same applying to the occurrence index. In the case of the occurrence index, the greater it is, the higher will be the failure rate and the lower the effort to reduce it. Note also that the higher the value of w_i is, the lower will be the reduction of reliability (failure rate). For this reason, we consider *PMin*, which will provide the lowest probability for those that should receive higher designation for improvement of reliability. Finally, any probabilistic composition to contextualize the criteria can be implemented. Thus, Equation 15 can be considered without losing generality.

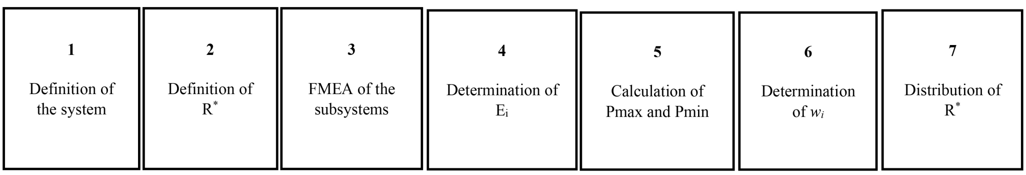


Figure 4 – Procedural flowchart.

The procedure for the distribution of the reliability requirements among the subsystems is presented in Figure 4. This consists of seven steps: (1) definition of the system and its scope; (2) definition of the minimum reliability requirement for the system; (3) analysis of the failure modes and effects on the subsystems and characterization of the risk indices – occurrence, severity and detection; (4) determination of the indices of effort for improvement, based on Equation 11; (5) calculation of PMax and PMin for the indicators to be considered for the subsystems; (6) determination of w_i according to Equation 15; and (7) distribution of the reliability requirements among the subsystems, obeying w_i.

4 APPLICATION CASE

To demonstrate the applicability of the proposed procedure, we present a compared application with the case discussed in Kim et al. (2013), involving heating, ventilation, and air conditioning (HVAC) system. The reliability block diagram proposed by the US Army (USDoD, 2006) for the HVAC can be seen in Figure 5. According to the authors, the initial failure rate of the system was $\lambda = 0.01815135$, and they considered a 20% improvement in this rate, so they defined $\lambda^* = 0.01452108$, representing a variation of 0.0036303. Table 1 presents the weights for reliability allocation and the failure rates allocated to the subsystems by using the method proposed by Kim et al. (2013). These results were attained by a combination of Equations 2 and 9.

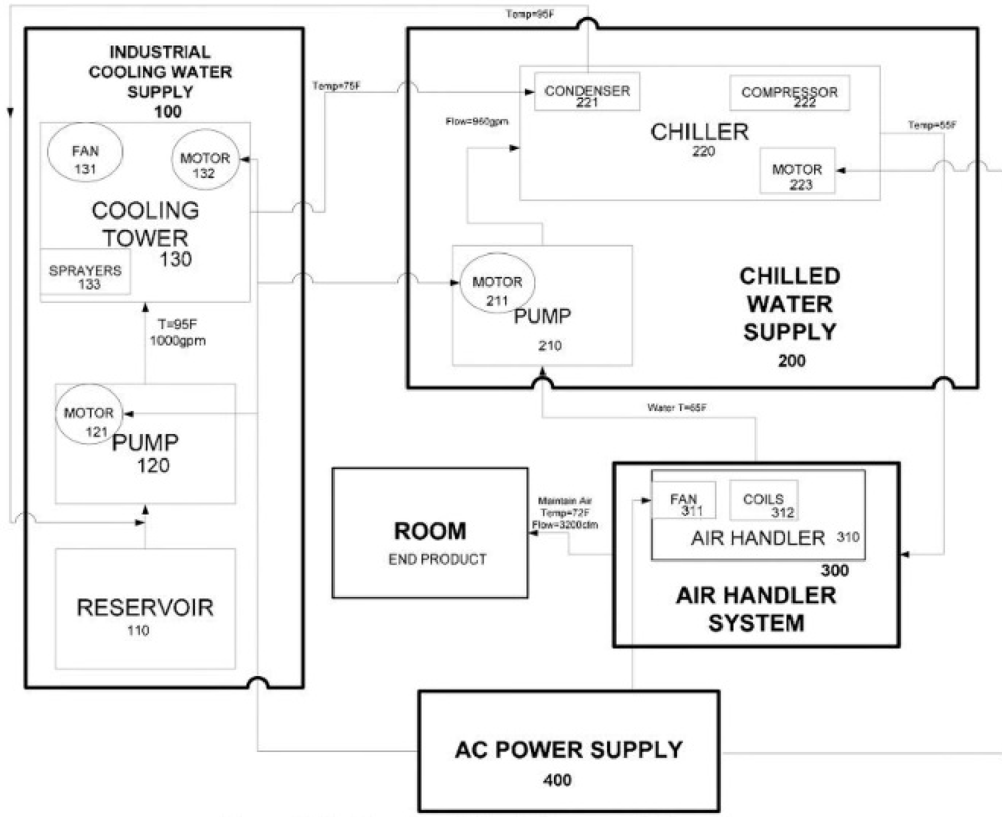


Figure 5 – Reliability block diagram of the HVAC (USDoD, 2006).

Table 1 – Results of the allocations according to Kim et al. (2013).

i	Subsystem i (SS_i)	FMs	S_{ij}	O_{ij}	λ_{ij}	λ_i	w_i	λ_i^*
1	Reservoir 110	FM11	6	2	0.000213	0.000213	0.0354	0.00051367
2	Pump 120	FM21	4	3	0.000461	0.005107	0.1297	0.00188491
		FM22	5	6	0.004646			
3	Cooling tower 130	FM31	6	3	0.000461	0.001383	0.1061	0.00154102
		FM32	5	3	0.000461			
		FM33	4	3	0.000461			
4	Pump 210	FM41	4	1	0.000099	0.000312	0.0157	0.00022758
		FM42	8	2	0.000213			
5	Chiller 200	FM51	6	7	0.010036	0.010279	0.5149	0.00747327
		FM52	8	2	0.000213			
6	Air handler 300	FM61	4	3	0.000461	0.000887	0.1983	0.00288063
		FM62	3	2	0.000213			
		FM63	7	2	0.000213			
Total					**0.0181514**	**0.0181514**		**0.00363027**

For the application of our proposed method, we used the functionalities of the PCP R-Package (Gavião et al. 2018). To calculate the probabilities, we assumed, without loss of generality, the probabilities characterized by a BetaPERT distribution with a standard shape parameter equal to 4, to serve as the indices that would in real life come from the opinion of specialists. We applied the procedure to the data reported by Kim et al. (2013), assuming that greater severity is associated with greater weight and that greater occurrence indices, i.e., higher failure rates, would be associated with greater ease in reducing it. The results are presented in Table 2. In these results, we considered the failure modes with the highest severity index.

Table 2 – Results of allocation by the proposed procedure (α=0.5 in Equation 15).

SS_i	S_i	O_i	$PMin(S)$	$PMin(O)$	w*	λ_i	λ_i^*	$\Delta\lambda$
1	6	2	1.25E-1	2.98E-3	1.83E-1	2.13E-4	3.90E-5	1.74E-4
2	5	6	7.34E-1	9.70E-1	3.67E-1	5.10E-3	1.87E-3	3.23E-3
3	6	3	1.25E-1	2.20E-2	7.90E-2	1.38E-3	1.09E-4	1.27E-3
4	8	2	7.1E-4	3.00E-3	1.21E-1	3.12E-4	3.78E-5	2.74E-4
5	8	2	7.1E-4	3.00E-3	1.21E-1	1.03E-2	1.25E-3	9.1E-3
6	7	2	1.48E-2	3.00E-3	1.21E-1	8.87E-4	1.28E-1	7.7E-4
Total						1.82E-2	3.41E-3	1.48E-2

*The higher the weight, the lower will be the variation in the failure rate.

Note that the numerical results attained with the proposed approach increased the reduction of the failure rate, obeying an equilibrium between the importance of severity and the difficulty associated with the low occurrence index (which is associated with low failure rates). Here, we considered the two indices addressed, severity and occurrence, to have equal importance, meaning α=0.5. By varying the values of α in Equation 15, this distribution of the weights for the allocation of reliability will be adapted to the specific case. We also performed a sensitivity exercise regarding the values of α, reaching the weighting distributions presented in Figure 6.

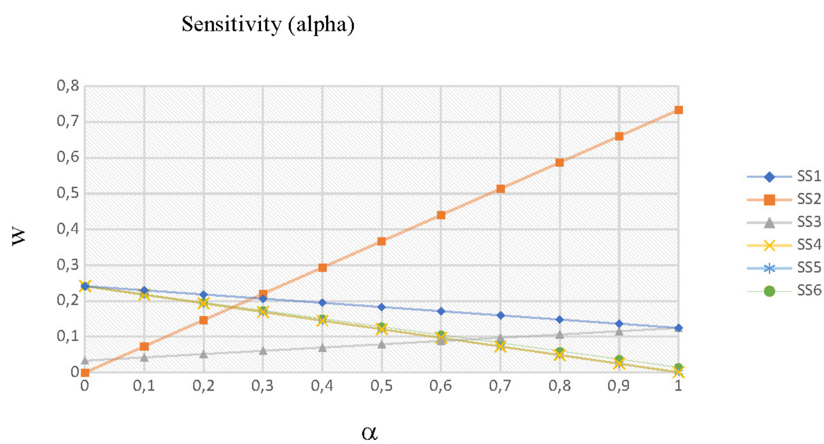


Figure 6 – Sensitivity of the weights α from Equation 15.

Figure 6 shows that the importance associated with reducing the severity index increases, the value of w becomes lower, i.e., the indication of the reduction of the failure rate increases. This can be observed by SS4 and SS5, which are superimposed, and that with α = 1 present the lowest weights, followed by SS6. The black contour rectangle highlights the weights that were adopted to obtain the results presented in Table 2.

By varying the values of α, according to the preference of the decision-maker, one can obtain different failure rate distributions along the subsystems (SS). Depending on the systema characteristics, it is possible to stress failure consequences, based on the severity index.

5 CONCLUSIONS

In this article, we have proposed a probabilistic approach to establish weights for reliability allocation in systems to improve the limitations discussed in the literature. In particular, by using the probabilistic composition of preferences, the uncertainties associated with the opinions of experts are contemplated in the weighting scheme. Besides this, the fact we work with maximum and minimum preference probabilities instead of considering transformations based on mathematical operations that are recognized as having drawbacks when applied to ordinal scale data means our proposal is more advantageous than the other approaches presented in the literature. Furthermore, the adequate combination of the probabilities also eliminates the limitations in terms of difficulties in improving the failure rate, as presented by Yadav & Zhuang (2014), since a suitable adjustment of the parameter α in Equation 15 has been overcoming this limitation. In terms of practical implications, considering that we are approaching the reliability allocation on FMEA indexes, which are experts' opinion based, it is of great importance to address the uncertainty associated with it. The proposed methodology, centered on the probabilistic composition of preferences (CPP), in addition to allowing uncertainties to be considered, its nonlinear aspect is a key element to approach a tail figure in the ordinal 0 to 10 scale for severity and occurrence indexes. In future studies, we intend to apply the proposal in other situations to corroborate its efficacy in dealing with such problem.

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