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Fuzzy arithmetic based reliability allocation approach during early design and development

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ABSTRACT

During early design and development stages, every engineering system has to meet its specific reliability goals. The target reliability of the system is achieved through application of an effective reliability apportionment technique to its subsystems. There are various traditional methods exist to perform the reliability allocation based on engineering factors that are assessed in a subjective manner. The conventional reliability allocation approach requires the assessment of factors like complexity, cost, and maintenance. This may not be realistic in real applications if they are assessed in a crisp manner by the domain experts of their varied expertise and background.

In this paper, we treat allocation factors as fuzzy numbers, which are evaluated in fuzzy linguistic terms. As a result, fuzzy proportionality factor scales are proposed for the subsystems. In order to accomplish fuzzy division to evaluate the fuzzy proportionality factor, an approximation method based on linear programming for trapezoidal fuzzy numbers is also proposed in this paper. For the evaluation of weighting factors from fuzzy proportionality factors, centroid method of defuzzification is being employed. The allocated reliability of each subsystem is computed with the help of weighting factor thereafter. An example is provided to illustrate the potential application of the proposed fuzzy based reliability allocation approach.

1. Introduction

Reliability allocation is an important and iterative task during the design and development activities of any engineering system. It is also difficult task because of the obscured and incomplete design details and a number of factors have to consider in design process (Aggarwal, 2007; Wang, Yam, Zuo, & Tse, 2001). During the design phase of a system with a specified target reliability level, the reliability levels of the subsystems affect the overall system reliability. Therefore, a proper reliability allocation method needs to be adopted to allocate the target system reliability to its constituent subsystems proportionately. There are a number of conventional methods available for reliability allocation. The simplest method being is to allocate the target reliability equally to all the subsystems (Ebeling, 2008). Other methods include, AGREE method, cost minimization approach, Karmiol method, and integrated factors method (Elegbede, 2003; Kyungmee, Yoonjung, & Ming, 2013). However, the reliability allocation methods, which implicitly consider design and reliability factors, appear to be more appropriate and practical approach at early stages of design and development than these traditional methods. For instance, there are the reliability allocation methods based on engineering factors and product knowledge, such as, cost, criticality, complexity, time of operation, state-of-art, work condition, frequency of failure etc., which utilize the scale based assessment and conventional mathematics to derive the subsystem proportionality factors (Aggarwal, 2007; Jafarsalehi, 2009; Wang et al., 2001).

In past, few researchers (GU & Huang, 2009; Hong-bin & Zhi-xin, 2009; Mahapatra & Mahapatra, 2011; Yingkui & Shuyun, 2010) have discussed on the implementation of fuzzy logic in reliability allocation. Hong-bin and Zhi-xin (2009) implemented fuzzy decision method for the reliability allocation of complex system. A fuzzy reliability allocation method for engine was proposed based on multi-field experts' knowledge by GU and Huang (2009). In this method, fuzzy set theory has been used to decrease subjective preferences of decision makers as well as fuzzy and uncertain factors in reliability allocation process. Yingkui and Shuyun (2010) proposed a fuzzy reliability allocation method for the product based on expert's knowledge, which translates the system reliability goal into reliability levels for all subsystems. Further in this method, the risk evaluation of the product development process and the multi-domain experts' comprehensive opinions are taken into account. When the available data is not sufficient (or lacks

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of the experts information) about the product to assess reliability accurately, in such a case, to catch the vagueness and subjectivity of expert's information, entropy redundancy based allocation approach has been proposed (Mahapatra & Mahapatra, 2011). This approach maximizes the reliability and entropy of the system using intuitionist fuzzy optimization technique subjected to the specified system cost to find out optimal level of redundancies at each subsystem. Since these approaches lack the incorporation of engineering factors and product knowledge, therefore at early stages of design and development reliability allocations using these approaches are practically inappropriate.

Aggarwal (2007) discusses the reliability allocation method based on various engineering factors, which utilize the scale based assessment. In this method, experts will assign scale from 1 to 10 on each factor. The major challenge in this conventional reliability allocation solution is the subjectivity involved in selecting the factors and then rating them as per the method proposed. This subjectiveness varies with the experience of the reliability and design experts. For example, it may be possible for different experts to select different factors and they can scale them differently based on the individual/team knowledge and sometimes it becomes difficult for the experts to come to a conclusion for a crisp value. During consensus making between the experts also, it is a difficulty to reach a crisp consensus value.

To overcome these issues, in this paper we propose fuzzy numbers and their arithmetic based reliability allocation method considering engineering attributes. It may be better way to select the scales of the allocation factors and evaluate proportionality factor. The methodology proposed is based on the design and reliability experts' individual opinions on major contributory factors such as: cost, criticality, state of art, maintenance, time of operation, and complexity. Fuzzy based guideline for selecting the relative scale for factors is also provided to the experts' team to assigns fuzzy rating for each factor. Therefore, the main contribution of this paper is in the proposition of factor based reliability allocation using fuzzy logic. Besides, we also provided formulation for the division of trapezoidal fuzzy numbers using linear programming approach.

In next section, factor based conventional reliability allocation method is explained. In Section 3, basic concepts of fuzzy numbers and arithmetic are discussed and also fuzzy division using linear programming for triangular fuzzy number is modified to trapezoidal fuzzy numbers. New fuzzy based reliability allocation methodology is proposed in Section 4. In Section 5, an example is provided to illustrate the proposed methodology. Section 6 presents summary and conclusion of this study.

2. Factors based conventional reliability allocation method

In this allocation method, the target reliability based on the reliability factors is apportioned to subsystems for which no predicted reliability values are known. The relationship between apportioned reliability of ith subsystem (R_i) and target system reliability (R^*) is defined with a weightage factor (ω_i).

$$R_i = (R^*)^{\omega_i}, \tag{1}$$

where weightage factor (ω_i) can be expressed with proportionality factor (Z_i) as

$$\omega_i = Z_i / \Sigma Z_i. \tag{2}$$

Proportionality factor (Z_i) in turn bears the relationship with various reliability factors considered for apportionment. The factors can be increased or decreased based upon the product and its application. For doing this in a logical manner, the reliability factors like complexity, cost, maintenance, criticality, redundancy, state-of-the-art, and time of operation have generally been considered (Aggarwal, 2007).

2.1. Complexity

The complexity factor varies from subsystem to subsystem within a system and is measured in terms of number of active components that a subsystem is composed of. The number of components in a subsystem has a direct bearing on the reliability of the subsystem. Thus, complexity has a strong impact on the reliability allocation. The failure rate of the subsystem with high complexity is generally going to be high. So, the failure rate is allocated proportional to the complexity of the subsystem.

Hence, $Z_i \propto K_i$, where K_i is the complexity factor for the ith subsystem.

It is more difficult to attain the target reliability for a subsystem with higher complexity. Thus, lower reliability targets should be allocated to the subsystem with higher complexities. The guidelines for giving the complexity grade to a subsystem are as follows.

- Multiple functional relationships with the other groups.
- Number of components comprising subsystem.

2.2. Cost

In the reliability allocation program, cost is also an important factor. For a large system, the cost increment for reliability improvement is relatively high. The demonstration of a high reliability value for a costly system may be extremely uneconomical. Based on this point, for a costlier subsystem a relatively lower value of reliability (a higher failure rate) is desired to be allocated.

Hence, $Z_i \propto Co_i$, where Co_i is the cost factor for the ith subsystem.

2.3. State-of-the-art

When the component has been available for a long time, it is quite difficult to further improve the reliability of a component even if the reliability is considerably lower than desired. For such components, it is assumed that it has undergone an extensive development program including failure analysis and corrective action of deficiencies. Whereas the reliability of the components with high initial reliabilities can be relatively improved further rather economically. Thus, for achieving this improvement *state-of-the-art* is one of the possibilities. When no improvement can be achieved a factor of 1 is chosen and for the subsystem where lot of improvement is possible, a larger value S_i is chosen. Obviously a larger S_i means higher reliability and hence a lower failure rate.

Hence, $Z_i \propto 1/S_i$, where S_i is the state-of-the-art factor for the ith subsystem.

2.4. Criticality

Criticality is another very important factor in reliability allocation. It is logical, higher reliability target should be allocated to the functionally critical sub-systems and thus Z_i is proportional to criticality.

Hence, $Z_i \propto 1/Cr_i$, where Cr_i is the criticality factor for the ith subsystem.

To arrive at the relative grade for criticality, the following guidelines can be followed.

- The failure effect of the functional group on system.
- Frequency of failure.