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General model for the risk priority number in failure mode and effects analysis

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ABSTRACT

Failure mode and effects analysis (FMEA) is a structured method used during a given stage of the system life cycle to understand all probable failure modes and the effects of their occurrences. The risk priority number (RPN) is calculated in FMEA to select more critical failure modes by multiplying three factors: occurrence, detection, and severity. In the literature, these three factors are defined qualitatively without any underlying model, and multiple definitions and conflicting interpretations exist for each factor. As the interrelationships between the three RPN factors are not known, previous research has treated each factor as a criterion in multiple criteria decision making, under the assumption that the three factors are independent of each other. In this paper, we present a general model to explain the functional relationship among the three factors. Using the model, we discuss the unique role of each factor for comparing the risk of different failure modes.

1. Introduction

For assuring the safety and reliability of a system, engineers identify all independent failures that may occur during a given stage of the system life cycle, and prepare actions to reduce the occurrences of failures or mitigate the severity of their consequences. Failure mode and effects analysis (FMEA) is a structured method used for fully understanding failure modes and their consequences in a given stage of the system life cycle. A failure mode is defined by the manner in which a system or process may fail, whereas the consequence of the failure mode occurrence is called the failure effect [8,35]. Once all probable failure modes and their consequences are identified, the risk of each failure mode is evaluated so as to select more critical failure modes as well as to identify appropriate actions to reduce their risk. Toward this end, FMEA standards adopt the risk priority number (RPN), in which the three factors - the occurrence, detection, and severity - are multiplied [3,8,14,41]. Each factor is evaluated by an expert using a ten-point numerical value.

Since FMEA was first developed in the 1960s by the aerospace industry [10,14], it has been widely used in various industries such as automotive [16], semiconductor processing [41], and biomedical industries [1,15]. Although the method is simple, a basic problem may be encountered when conducting a detailed analysis because the three RPN factors are defined verbally without any underlying model and multiple definitions exist for each factor. For example, one [8] defines occurrence by the likelihood that the failure mode and its associated cause will be present in the item, detection by the chance that the relevant control method will detect the failure cause or failure mode, and severity by the seriousness of the most serious effect for a given failure mode. Another [3] explains the occurrence by the chance that a failure cause will actually occur, detection by the inability to detect a failure cause or the subsequent failure mode, and severity by the severity of a failure mode on the customer. The other [19] defines occurrence by the chance of a failure mode occurring, detection by the chance of the customer detecting the failure mode before it results in the failure effect, and severity by the seriousness of the failure effect. Mcdermott et al. [35] explain that the severity factor should be assigned only to the failure effect but not to the failure mode, although Besterfield et al. [3] recommend that only one severity value should be assigned to each failure mode regardless of the number of its failure effects.

Even though all these definitions and interpretations may be valid in practice, multiple definitions and conflicting interpretations have led to confusion among the users and researchers of FMEA. Rhee and Ishii [40] and Kmenta and Ishii [27] criticize the confusing definition of the detection factor by asking whether the detection factor involves the capability of the design and process controls to detect the failure mode, or whether it is related to the chance that the final user will catch the problem before the most serious effect occurs. Such confusion has led some researchers to eliminate the detection factor from FMEA [2,19,27,40]. On the other hand, Kara-Zaitri et al. [25] has doubts

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about which of the three factors is related to which of failure cause, failure mode, and failure effect. For example, occurrence is considered to be related to a failure mode and its cause [8,40,41], a failure cause [13,42], a failure mode [4,19,39], and a failure mode and its effect [14,35].

Without any answer forthcoming for these questions, previous researchers treat each factor as a criterion in multiple criteria decision making, failing to consider the functional relationship among the three factors for a given failure mode [21,31–33]. Claiming that the three factors are not comprehensive enough to evaluate the risk of each failure, some researchers include more factors in addition to the three factors, such as cost [4], mean time to repair [5], and production loss and domino effect [18]. One considers an addition of the three factors rather than using their product [25], whereas the other employs a weighted product of the three factors to consider the importance of each factor relative to the others, assuming that not all factors are equally important [6,17,30,45]. A considerable number of researchers have developed more complex and diverse methods for risk evaluation in FMEA, including the technique for order of preference by similarity to ideal solution (TOPSIS) [7,43], analytic hierarchy process (AHP) [9,20,49], VIKOR (an acronym in Serbian of multicriteria optimization and compromise solution) [29,34], evidence theory [10,12,48], and fuzzy methods [11,23,28,29,37].

Unlike these approaches, this paper is intended to develop a general model to show a functional relationship among the three factors. On the basis of the functional relationship, we clarify the confusing definition of the detection factor and explain which of the three factors is related to which of failure cause, failure mode, and failure effect. Even though in the traditional FMEA, each RPN factor is rated by an expert using a ten-point numerical value, we assume that quantitative data are available to evaluate each factor so as to focus on explaining the definition of each factor after excluding the problem resulting from the measurement scale of each factor.

This paper is organized as follows. In Section 2, we differentiate two approaches taken in the FMEA literature, which we call the black box approach and the hierarchical approach. A black box approach treats an item as a black box, assuming that all failure modes of the entire item that may occur during a given stage of its life cycle are identified. In a hierarchical approach, however, a system is broken into smaller elements to start analysis at one level and span all the levels of a system hierarchy. Section 3 focuses on the black box approach, and presents a model for evaluating the risk of a given failure mode using the three RPN factors. We discuss why and how the detection factor is used in the RPN calculation. In Section 4, the bottom-up hierarchical analysis approach is considered to explain which of the three factors is related to which of failure cause, failure mode, and failure effect. Examples are given to illustrate the varying definitions of the three factors. Finally, Section 5 concludes the paper.

2. Background

FMEA is used to identify all possible failure modes that may occur during a given stage of the system life cycle and predict the consequences of the occurrence of each failure mode. In the early development stage, functional FMEA [14], or system FMEA [8,47], is used to analyze the possible failure modes of the required system functions. As system development proceeds, design FMEA is conducted to consider the failures that can occur during the system design, whereas process FMEA is focused on problems related to how the system is manufactured, operated, or maintained [8,14,47].

One may take two alternative approaches when performing FMEA during a given stage. In the first approach, the entire item or process is treated as a black box, and its failure modes and consequences are identified directly from previous experience or from the failure information of similar items [46]. Fig. 1(i) illustrates the black box approach for a given item, where the item can be a component or a system. In functional FMEA, for example, the system failure mode may be analyzed initially from the black box approach because the system requirements are written before a list of components is created [14]. In Fig. 1, stage 1 denotes the given stage of the item life cycle at which FMEA is performed. For example, if a component is designed and manufactured by a company before it is delivered to another company to be assembled in a system, then the black box approach may be taken during the component design. In that case, the component design and production stages are denoted in Fig. 1 by stages 1 and 2, respectively. The second approach is hierarchical, in which a system is broken into smaller elements, and a failure mode generated at one level is traced in the subsequent analysis [38]. A bottom-up hierarchical analysis is illustrated in Fig. 1(ii). A failure mode at the component level is first identified, and its effect on the subsystem is predicted assuming that the component failure mode will occur during stage 1. Because the effect of the component failure mode on the subsystem level is called a subsystem failure mode, the component failure mode is a cause of the subsystem failure mode. Fig. 1(ii) shows that a subsystem failure mode may appear as a failure effect at the component level, and as a failure mode at the subsystem level, and as a failure cause at the system level [8,25,39,41]. To avoid confusion, the description of a failure mode at a given level should be consistent with the analysis level. The failure mode is usually described using a physical or technical term rather than by a symptom [41] because a symptom is used to describe a failure effect.

In Fig. 1(ii), we describe the hierarchical result around the subsystem failure mode which links the component failure mode as the cause and the system failure mode as the effect, because in the literature, the terms failure cause, failure mode, and failure effect are used rather than component failure mode, subsystem failure mode, and system failure mode. To illustrate, consider the study by Sankar and Prabhu [42], who present all possible failure modes during the operation of the centrifugal pump in a cooling system. For each pump failure mode, its effect on the operation of the cooling system is given by the failure effect. For example, for the failure mode given by no pump operation, its failure effect is identified by the inoperable cooling system. A component failure mode, such as a broken shaft is then given as the failure cause.

In the literature, the three RPN factors are defined without specifying whether a black box or a hierarchical approach is considered. This is one reason for the confusing definitions of the three factors. To derive the three RPN factors, therefore, we consider the black box approach first in Section 3 and then the hierarchical approach in Section 4. Later, one can see that the three factors are defined in general regardless of the approach selected.

3. Three RPN factors for the black box approach

In Section 3.1, we obtain a preliminary result to calculate the risk of a fixed failure mode using the formal definition of risk. In Section 3.2, the three RPN factors are obtained from the preliminary result.

3.1. Preliminary result

Suppose that all failure modes are identified for the entire item that can occur during a given stage of the item life cycle, which we call stage 1. We consider the problem of calculating the risk of a fixed failure mode. Because the failure mode may or may not occur at stage 1, we define M as the event of the failure mode occurring at stage 1. A formal definition of risk is given by the product of two quantities [22,24]: (1) the probability of occurrence of a harm and (2) the severity of the consequence when the harm has occurred. Therefore, if R denotes the risk of the fixed failure mode, it can be expressed as

$$R = O \times S, \tag{1}$$

where $O = \Pr(M)$, and S is the severity of the consequence of M.

In the following, we explain how to evaluate S in Eq. (1). If M results in only one consequence, then one can evaluate S directly by considering that consequence. However, suppose that a countermeasure is prepared