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Fuzzy based failure modes and effect analysis for yacht system design

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ABSTRACT

This research is aimed at utilising failure mode and effect analysis (FMEA) which is a reliability analysis method applicable to yacht system design. The failure modes which can be acquired from a group of experts can be linguistic terms including vagueness. FMEA aims to rank the failure modes from high to less risky in order to take the corrective actions by using risk priority numbers (RPNs). RPN method cannot emphasise the nature of the problem, which is multi-attributable and has a group of experts′ opinions. Furthermore, attributes are subjective and have different importance levels. In this paper, a framework is proposed to overcome the shortcomings of the traditional method through the Fuzzy Multi-Attribute Group Decision Making (FMAGDM), which helps to solve the selection of risky failure modes. Fuzzy sets (FSs) are utilised for expressing fuzziness of crisp/linguistic knowledge coupled with the well-known TOPSIS methodology for decision making. The current work demonstrates that there is not much application of FMEA and FMAGDM in the area of yacht system design. The comparison of ranking results for two methods shows that selection of the risky failure modes along with FMAGDM are more reliable from an engineering point of view.

1. Introduction

Safety/reliability engineering has not developed as a unified discipline, but has grown out of the integration of a number of activities, which were previously the province of the engineer. A safety technology for optimising risk attempts to balance the risk against the benefits of the activities and the cost of further risk reduction (Smith, 2005).

Reliability assessment of a system from its basic elements is one of the most important aspects of reliability analysis. A system is a collection of items whose proper coordinated function leads to the proper functioning of the system. In reliability analysis it is important to model the relationship of the individual items as well as the reliability of the system. There are several system modelling schemes for reliability analysis such as reliability block diagram, fault tree and success tree methods, event tree method, failure mode and effect analysis (FMEA) etc. FMEA method is inductive in nature and it is used in all aspects of failure analysis from concept to development (Modarres, 1993).

FMEA was formalised in 1949 by the US Armed Forces and later adopted in the Apollo space programme to mitigate risk. The use of FMEA gained momentum during the 1960s (Carlson, 2012). FMEA is a widely used engineering technique for defining, identifying and eliminating known and/or potential failures, problems, errors and so on from system, design, process, and/or service before they reach the customer (Stamatis, 1995).

A system, design, process or service may usually have multiple failure modes or causes and effects. In this situation, each failure mode or cause needs to be assessed and prioritised in terms of its risks so that high risky (or most dangerous) failure modes can be corrected with top priority. FMEA uses past experience of area experts to rank failure modes of any system according to three rating scales; severity (S), detection (D) and occurrence (O) (Wang et al., 2009). These are usually defined as fuzzy values such as high, low, catastrophic, etc. These three linguistic values can be transferred to crisp values by using the related scales. Failure mode of an issue can usually be calculated by multiplying $S \times O \times D$ and this value is referred to risk priority number (RPN). Higher RPN values point to the critical failure modes of the system. Ranking the failure modes according to RPN may not be realistic in real applications. Some of the reasons for this, different combinations of S, O and D values may result with the same RPN; S, O and D have different importance weights in relation to failure mode and RPN cannot emphasise the situation; also relative importance of experts cannot be included in classical RPN calculations.

The traditional FMEA methods have been reviewed by Dhillon (1992) between 1963 and1990, and Liu et al. (2013) between 1992 and 2012. The knowledge for explaining failure modes of a system

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is multi-attributed. Also the attributes are based on opinions acquired from a group of experts. Nevertheless, experts′ weights for each attribute may differ. To overcome the fuzzy nature of risk analysis, a fuzzy-based approach model may be more appropriate to analyse the problem. A very broad application of fuzzy methods to FMEA (FFMEA) is given by Wang et al. (2009).

The nature of the problem in this work is a multi-attributed selection with group of experts whose importance level may vary and for this reason it is very suitable for Multi-Attribute Decision Making (MADM), which is associated with problems whose number of alternatives has been predetermined. Complexity arises when there is more than one decision maker. MADM refers to selections among some courses of action in the presence of multiple, usually conflicting attributes (Chen and Hwang, 1992). MADM problems have been numerous and there are a lot of solution methods, which are explained by Chen and Hwang (1992). The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is one of the classical MADM methods, which was proposed and developed by Hwang and Yoon (1981). TOPSIS was chosen for this application because it is very commonly used, easy to apply and reliable.

This research aims to utilise FMEA for reliability analysis under fuzzy environment with regard to issues during yacht design as well as operation, in order to rank the most critical failure modes of the system, which are acquired by using experience of six domain experts. After seeing the shortcomings of FMEA especially in ranking according to RPN, a new method was considered. Fuzzy Multi-Attribute Group Decision Making (FMAGDM) was chosen after reviewing the literature to utilise and compare with the existing RPN method.

2. Literature review and proposed method

2.1. FMEA

Designing a reliable product is truly a concurrent engineering process. All design disciplines must be part of the product′s development to ensure a robust design that meets customer′s needs. A reliability engineering approach with its tools such as FMEA can focus on the design process (Crowe and Feinberg, 2001). FMEA was formalised in 1949 by the US Armed Forces and later adopted in the Apollo space programme to mitigate risk. The use of FMEA gained momentum during the 1960s (Carlson, 2012). FMEA method helps to improve design decisions and product quality during operation. It is a product development (or process analysis) tool used to anticipate modes of failure and mitigate potential risk (Kmenta and Ishii, 2001).

FMEA is a complex engineering analysis methodology used to identify potential failure modes, failure causes, failure effects and problem areas affecting the system or product mission success, hardware and software reliability, maintainability, and safety. It also provides a structured process for assessing failure modes and mitigating the effects of those failure modes through corrective actions. The success of FMEA depends on collaboration between the FMEA analyst and the designers and stakeholders (Raheja and Gullo, 2012).

Furthermore, FMEA procedure starts with analysing all the systems step by step, examining system functions, subsystems etc. A table can be prepared to show system elements, a failure mode occurs and causes a failure. The following steps explain how to generate a table for an FMEA model (Modarres, 1993):

a. *System description and block diagrams*: A functional block diagram should be prepared to illustrate the operation, interrelationship, and interdependence of the functional entities of the system, which should be decomposed into more basic components. A sample system diagram for fire is given in Fig. 1.
b. *Failure modes and causes*: The manner of the failure of the function, subsystem, component or part should be defined clearly. In the current work, six different area experts have been asked to explain failure modes of yacht systems.
c. *Effect(s) of failure*: The consequence of each failure mode should be carefully examined and recorded.
d. *Failure detections and compensation*: All the detected failures should be corrected to eliminate their propagation to the whole system and to maximise reliability.
e. *Severity classification*: For the current work severity ranking is developed.
f. *Remarks*: Any pertinent information should be noted.

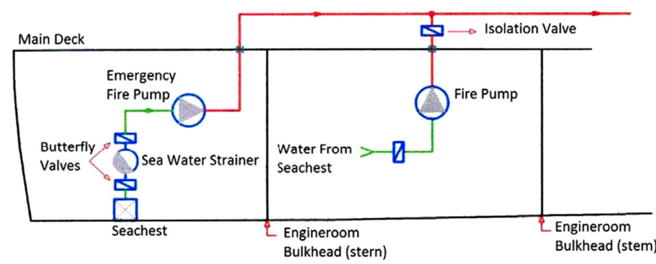

Fig. 1. A sample functional diagram for fire system.

FMEA methodology was introduced and started to be applied to many subjects in the early 1960s. Bowles and Peláez (1995) proposed a fuzzy model as an alternative to the conventional methods. On the other hand, a very broad review is given by Wang et al. (2009), Jee et al. (2011) and Liu et al. (2013).

FSs are a tool for transformation of the vagueness of human senses and their recognition into a mathematical formula. It also provides meaningful representation of measurement for uncertainties and vague concepts expressed in natural languages. In line with this, there has been a growing trend in FMEA literature to use fuzzy linguistic terms for describing the three risk factors S, O, and D (Dinmohammadi and Shafiee, 2013).

FMEA method has been applied to many engineering areas. Offshore structures are one of the most fertile areas for these applications. Wall et al. (2002) explained how to utilise FMEA to Floating Production, Storage and Offloading (FPSO) vessels and other Floating Storage Units (FSUs). Pillay and Wang (2003a) gave an application of FMEA for controlling a marine crane hoisting system. Wang and Trbojevic (2007) clarified the design for the safety of marine and offshore systems by giving some FME(C)A applications for the related systems. Vinnem (2007), after classifying FMEA as Qualitative Risk Assessment, gave a lot of examples for offshore accidents to learn from the past experience. FMEA combination with fuzzy sets and FMADM methods have been applied to marine and offshore engineering subjects such as ballast water (Pam et al., 2013), maritime risk assessment (Balmat et al., 2009, 2011), fishing vessels (Pillay and Wang, 2003b), explosion on board ships (Cicek and Celik, 2013) and so on. Unfortunately, there is very rare utilisation of FMEA and FMEA related fuzzy techniques with regards to yacht design.

2.2. Fuzzy set theory

Fuzzy set theory was initiated by Zadeh in the early 1960s. On a semantic level Zadeh′s theory is more closely related to Black′s work on vagueness, where "consistency profiles" (the ancestors of fuzzy membership functions) "characterise vague symbols". Since