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Development of a weighted probabilistic risk assessment method for offshore engineering systems using fuzzy rule-based Bayesian reasoning approach

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ABSTRACT

This study presents a new safety methodology that is capable of transforming qualitative expert judgement into probabilistic risk outcomes for offshore engineering systems. In the framework, fuzzy set theory is applied to describe variables. Fuzzy data of each input is expressed in terms of the belief degree format representing the extent to which the fuzzy data belongs to the associated fuzzy set. Such data is subsequently combined to derive appropriate consequents using a fuzzy rule approach considering the weights of each input. The information generated in the antecedent and consequent of each rule are then synthesized to reach the fuzzy conclusions using the Bayesian reasoning approach. Such fuzzy conclusions are defuzzified and consequently transformed into the probabilistic nature. The framework is validated using two axioms and demonstrated by a risk study of the propulsion malfunction of an offshore Floating Production, Storage and Offloading (FPSO) during tandem offloading operations. The results are consistent with the axioms since the outcomes are sensitive to the minor alterations of input data and weights. It is concluded that the new approach produces reasonable results considering input weights and the logicality between inputs and outputs without losing too much useful information in the inference process.

1. Introduction

The growing technical complexity of large offshore engineering products and the public concern regarding the safety of such systems have facilitated the development of scientific risk assessment approaches. The safety of a system is often affected by a variety of factors regarding design, manufacturing, construction, commissioning, operation and maintenance (Wang et al., 1995). It is difficult to construct a sole mathematical model to completely evaluate the safety behavior because of the inadequate knowledge about such parameters. Accordingly, this inevitably leads to problems of uncertainty which would drive risk outcomes upwards or downwards thus distorting results. Fuzzy set theory is one of the most widely applied methods dealing with such a situation and a number of recent studies conduct risk analysis based on such an approach He et al., 2017; Xiang et al., 2017; Sahin and Yip, 2017; Senol and Sahin, 2016; Liu et al., 2016; Lower et al., 2016; Salah and Moselhi, 2016; Wang et al., 2016; Zhang et al., 2016a; Gou, 2016; Karimpour et al., 2016; Kabir et al., 2016; Lavasani et al., 2015; Wang et al., 2015; Helvacioglu and Ozen, 2014). This is because its advantages of tackling the uncertainties caused by vagueness of human judgement due to the lack or insufficiency of safety related evidence. Such an approach is capable of manipulating linguistic terms expressed by experts to assess the safety behavior of systems. Safety modeling based on Bayesian reasoning, on the other hand, is often developed for the purpose of a thorough consideration of the interdependences and conditionality among risk parameters in the inference process (Afenyo et al., 2017; John et al., 2016; Zhang et al., 2016a). However, the drawbacks of the lack in considering the relative importance of inputs and the ignorance of rule logicality between the antecedent and the consequent are often criticized and have not been addressed.

Given the beauty of fuzzy set theory for expert judgement elicitations and the strength of Bayesian reasoning in the inference procedure, a revised Fuzzy-Bayesian hybrid methodology is developed in this study to tackle such problems. Provided that the fuzzy sets describing inputs are defined, expert judgement can be transferred into subjective belief degrees by the mapping and transformation steps. Such opinions are combined based on the fuzzy rules developed. Fuzzy conclusions in a format of fuzzy sets associated with confidence degrees are obtained using the Bayesian reasoning mechanism. The risk outcomes are consequently obtained in a probabilistic nature after the defuzzification and

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transformation processes. The applicability of the proposed methodology is investigated by a risk study of the propulsion malfunction of an offshore Floating Production, Storage and Offloading (FPSO) during tandem offloading operations.

2. Literature review

Uncertainty problems are often encountered in safety and reliability assessment. Thus, uncertainty treatment is a crucial issue in risk analysis. It is particularly true in the domain where the lack or incompleteness of data and information often exist. Probability and possibility methods are the principal types of approaches dealing with such dilemmas (Hooda and Raich, 2015; Klir and Yuan, 1995; Wang et al., 1995). Probability theory is one of the most important traditional methods describing and systematizing the phenomenon of uncertainty. It deals with the uncertainties which are random in nature. By virtue of probability distribution, risk assessment can be carried out on a probabilistic basis to depict system states. Possibility theory, on the other hand, tackles the uncertainties caused by vagueness of human judgements due to the lack or insufficiency of safety related evidence. Such judgements are often fuzzy and non-probabilistic and therefore need to be analyzed using fuzzy modeling or belief functions.

Fuzzy set theory has the feature of manipulating linguistic terms expressed by experts to assess the safety behavior of systems. Although traditional approaches are capable of transferring qualitative opinions into quantitative yet probabilistic results, some practical problems are exposed. These include the negligence of the effects caused by various input weights, the disregard of the rule logicality between the antecedent and the consequent as well as the loss of useful information in the inference process (Ung, 2014; Yang et al., 2013; Konstandinidou et al., 2006; Seyed-Hosseini et al., 2006; Liu et al., 2005a,b; Braglia et al., 2003). The lack of considering the relative importance of inputs causes models incapable of genuinely reflecting risk outcomes once the weights of safety parameters are not equal. The ignorance of the rule logicality impairs the rule distinguishability that results in generating the identical outcomes for the scenarios with different antecedents. On the other hand, some studies apply the methods such as the min-max approaches for rule combination allowing for the simplification of the reference process. However, useful information from both the antecedent and consequent parts of each rule may be compromised. In addition, it is not unusual that risk assessment is conducted based on approximate reasoning approaches. The outcomes generated are often in the form of a set of evaluation grade/linguistic terms associated with corresponding belief degrees or a crisp value rather than a combined yet single probabilistic result (Zhang et al., 2016a; Zhang et al., 2015, 2016b; John et al., 2016; Yang and Wang, 2015; Zarikas et al., 2015; Baraldi et al., 2015; Nwaoha et al., 2013; Mokhtari et al., 2012; Ren et al., 2009; Ung et al., 2009; Eleye-Datubo et al., 2008; Yang et al., 2008; Liu et al., 2008, 2005, 2004). This causes the difficulty of genuinely understanding the results and the interpretation between safety analysts may be various. Furthermore, it is often that risk assessment is carried out under a hybrid structure where some inputs are equipped with sufficient data while others only have qualitative information. Dilemmas will emerge with regard to the acquirement of an overall risk outcome in a probabilistic nature.

In the offshore engineering domain, the data required for safety assessment may be scarce. Fuzzy-logic based modeling is often employed due to the capability of manipulating linguistic terms as aforementioned. On the other hand, allowing for a thorough consideration of the interdependences and conditionality among risk parameters, risk studies using Bayesian reasoning are developed. Nevertheless, one of the limitations the Bayesian reasoning mechanism encounters is the requirement of too much information in the form of prior probabilities (John et al., 2016). Such a format may be difficult to obtain and this is particularly true for offshore risk assessment. A number of studies incorporating fuzzy logic and Bayesian for safety and reliability have been proven useful in compensating for such a shortcoming (John et al., 2016; Yang et al., 2008, 2013; Ren et al., 2009; Eleye-Datubo et al., 2008; Huang et al., 2006). The issues, however, with regard to the ignorance of the effects caused by various input weights and the disregard of the rule logicality have not been addressed. Thus, there is a need to establish a new risk assessment that produces probabilistic results contemplating input weights and the logicality between inputs and outputs without losing too much useful information in the inference process.

A hybrid methodology incorporating the fuzzy set theory and Bayesian reasoning is developed in this study. The new risk assessment model is proposed using fuzzy set theory for expert judgement acquirement and the Bayesian reasoning mechanism for the fuzzy-rule inference. The fuzzy-rule approach is equipped with the features of considering input weights and improving the rule logicality. Bayesian reasoning is applied to synthesize the information in the antecedent and consequent part of each rule. Such a mechanism has the feature of expressing dependence and independence relationships among variables. Yet it provides risk results in a probabilistic nature without losing too much useful information in the inference process. The methodology constructed captures the beauty of fuzzy set theory for expert judgement elicitations as well as the strength of Bayesian reasoning in inference procedures.

3. Methodology

In the methodology, fuzzy set theory is applied to describe variables. Inputs are first specified by linguistic terms that are characterized by a membership function to the defined categories. Secondly, fuzzy data of each input obtained from experts are mapped back to the defined fuzzy sets and converted to the belief degrees representing the extent to which the data belongs to the defined fuzzy set. A fuzzy rule base approach is subsequently developed to combine inputs and derive appropriate linguistic terms associated with degrees of confidence. Such an approach is equipped with a feature of considering the relative importance of variables. Bayesian reasoning is employed to synthesize the information derived from the antecedent and consequent parts of each fuzzy rule and the fuzzy conclusions are therefore obtained. Under the Bayesian reasoning scheme, the belief degrees describing inputs and the confidence degrees depicting the associated consequent are treated as the prior and conditional probabilities, respectively. The combined magnitude is therefore referred to as the posterior probabilities expressing the extent to which the fuzzy conclusion belongs to the associated linguistic terms. A conversion process is then conducted enabling the abscissa adopted by fuzzy sets depicting consequents with a logarithmical nature. This is followed by the defuzzification and transformation steps and consequently the probabilistic results are able to be acquired.

3.1. Fuzzy definition of the linguistic terms describing variables

In the beginning of the methodology, the number of the input variables is first determined. Secondly, the number of the linguistic terms adopted to evaluate the variables for a specific event by experts is judged. It is noted that the determination of the quantity of such terms depends upon the extent of the information gathered. Thirdly, the linguistic terms are defined using the discrete fuzzy set theory. In the theory, linguistic terms depicting input variables are characterized by the membership functions to a set of categories expressing the degrees of parameters (Hooda and Raich, 2015; Smithson and Verkuilen, 2006; Zimmermann, 2006; Klir and Yuan, 1995). Suppose $U = \{1, 2, 3, \ldots, n-1, n\}$ denotes a group of categories in the universe of discourse that are utilized to describe "Very Low" and "Catastrophic", which may be modeled as follows.

$$\text{"}Catastrophic\text{"} = \{0/1, 0/2, 0/3, \ldots 0.75/n-1, 1/n\}$$

$$\text{"}Very\ Low\text{"} = \{1.0/0, 0.75/2, 0/3, \ldots 0/n-1, 0/n\}$$