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Confidence-based quantitative risk analysis for offshore accidental hydrocarbon release events

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ABSTRACT

Quantitative risk analysis (QRA) has been widely used to conduct the assessment of offshore accidental risks. However, the accuracy and validity of QRA is significantly affected by uncertainties when subjective judgments are involved. Therefore, it is unrealistic to determine the probability of a hazardous event by using one single explicit value when safety experts have a relatively low confidence level in their judgments. This paper proposes a new methodology for incorporating uncertainties into conventional QRA using the concept of confidence level. Offshore hydrocarbon release hazards are focused on and a barrier and operational risk analysis (BORA-Release) method is selected as the basic model to illustrate the proposed methodology. A left–right (L–R) bell-shaped fuzzy number is employed and its membership curve is able to control its shape to represent different confidence levels. As to the complex geometry of the bell-shaped fuzzy number, an α-cut operation is introduced to conduct the arithmetic operations of the fuzzy number, and a defuzzification method with total integral value is chosen to match the α-cut operations and acquire complete information for the fuzzy numbers. In the meantime, an optimism index is used to describe the attitude of the decision-maker. One case study is provided in this paper to demonstrate the implementation of this method.

1. Introduction

In order to assess the risks of offshore facilities, several methods have been widely used during the last few decades such as hazard and operability study (HAZOP) (Kletz, 1999), preliminary hazard analysis (PHA) (Vincoli, 2006), and failure mode and effect analysis (FEMA) (Stamatis, 2003). The concept of quantitative risk analysis (QRA) has also been increasingly widely used to evaluate the risks in the offshore oil and gas industry.

QRA is a quantitative assessment methodology to evaluate the risks of hazardous activities systematically in order to assist the decision-making process (Spouge, 1999). The world's first requirement for offshore QRA was issued by the Norwegian Petroleum Directorate (NPD) according to its “Guidelines for Safety Evaluation of Platform Conceptual Design” in 1981 (Brandsæter, 2002). After 30 years of development, QRA has become one of the most important techniques for identifying major offshore accident risks in accordance with worldwide regulations. For instance, under the UK safety case regulations, QRA is one of the main methods for showing that the risks are as low as reasonably practicable (HSE, 2006).

However, during the quantitative analysis process, uncertainties form some of the main limitations of QRA. The uncertainties mainly come from two aspects for offshore QRA (Spouge, 1999). First, as QRA is a relatively new technique, a large variation in study quality will occur due to the lack of agreed approaches and poor availability of data. Second, although QRA is assumed to be objective, subjective judgments are often involved in offshore risk assessments due to the complex circumstances of oil and gas platforms. These subjective judgments based on experts' experience may lead to inaccurate risk estimates. In addition, the extent of simplification made in the modeling of risks may also cause uncertainties (Vinnem, 2007).

Since QRA was proposed, research has been conducted in order to quantify the uncertainties. Three of the most common approaches for representing and reasoning with uncertainties are Monte-Carlo simulation (Vose, 1996), Bayesian probability theory (Bernardo and Smith, 2009), and fuzzy set theory (Zadeh, 1965). In

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this study, the uncertainties from subjective judgments will be the main focus. Thus, the fuzzy set theory is assumed to be a proper choice due to its suitability for decision-making with estimated values or experience-based judgments according to imprecise information (Liu et al., 2003).

Several existing methods take fuzzy set theory into consideration for conventional decision-making and reasoning methods. Huang et al. (2001) provided a formal procedure for the application of fuzzy theories to evaluate human errors and integrate them into event tree analysis. Cho et al. (2002) introduced new forms of fuzzy membership curves in order to represent the degree of uncertainties involved in both probabilistic parameter estimates and subjective judgments. Dong and Yu (2005) used fuzzy fault tree analysis to assess the failure of oil and gas transmission pipelines and a weighting factor was introduced to represent experts' elicitations based on their different backgrounds of experience and knowledge. With regard to the application of fuzzy concepts to the risk analysis of the oil and gas industry, Markowski et al. (2009) developed a fuzzy set theory-based "bow-tie" model for process safety analysis (PSA) to deal with the uncertainties of information shortages and obtain more realistically determined results. Wang et al. (2011) proposed a hybrid causal logic model to assess the fire risks on an offshore oil production facility by mapping a fuzzy fault tree into a Bayesian network. Recently, Sa'idi et al. (2014) proposed a fuzzy risk-based maintenance (RBM) method for risk modeling of process operations in oil and gas refineries. This study showed that the results of the fuzzy model were more precisely determined in comparison to the traditional RBM model. Rajakarunakaran et al. (2015) presented a fuzzy logic-based method for the reliability analysis of a liquid petroleum gas (LPG) refueling station in order to model inaccuracy and uncertainty when quantitative historical failure data is scarce or unavailable.

This paper proposes a fuzzy set theory-based confidence level method to deal with the uncertainties in accordance with experts' subjective judgments by incorporating confidence levels into the traditional QRA framework. Since it is unrealistic to estimate the frequency of an accidental risk precisely using one definite probability when safety experts are uncertain about the accuracy of their risk evaluation due to uncertainties, it is assumed that the proposed confidence level method may be beneficial for mitigating the influence of uncertainties and improving the reliability of QRA. Compared to previous methods, this proposed method focuses on subjective judgments and divides the expert's confidence into five levels by introducing a new form of fuzzy member function. This new L–R bell-shaped fuzzy number can be pictured as a group of modified fuzzy membership curves that represent different confidence levels of the experience-based judgments.

Hydrocarbon release-related risks will be the focus of this study because hydrocarbon release plays a critical role in major accident risks on offshore oil and gas production platforms (Øien, 2001). To evaluate the offshore hydrocarbon release risk, a barrier and operational risk analysis (BORA) method (Aven et al., 2006) has been proved to be one of the most applicable and practicable form of QRA in the offshore oil and gas industry. In addition, the application of the BORA method relies heavily on experts' judgments. Thus, the BORA method is selected to be the basic model to demonstrate the confidence level-based method.

2. Confidence level-based BORA-Release method

2.1. Brief introduction of the BORA method

The BORA-Release method has been proposed to analyze the hydrocarbon release risks of offshore structures from a set of hydrocarbon release scenarios based on the combined used of event trees, barrier block diagrams, fault trees, and risk influence diagrams (Seljelid et al., 2007). To conduct the BORA method, Aven et al. (2006) described the process using eight steps: (1) developing a basic risk model; (2) modeling the performance of barrier functions; (3) assigning the industry average frequencies/probabilities to the initiating events and basic events; (4) developing risk influence diagrams; (5) scoring risk influence factors (RIFs) by using a six-point classification (Thomassen and Sorum, 2002); (6) weighting RIFs; (7) adjusting industry average frequencies/probabilities; and (8) determining the platform-specific risk by recalculating the risk.

In comparison with the normal QRA method, the BORA-Release method allows risk analysis experts to describe the specific conditions of offshore platforms from technical, human, and operational, as well as organizational RIFs. The performance of the initial events and barriers will be affected by the RIFs. Based on the evaluation of RIFs, a relatively more realistic frequency/probability can be achieved because the platform specific conditions are considered.

However, there exist some uncertainties during the analysis of the BORA method. First, uncertainties are unavoidable during the scoring and weighting process of RIFs because the process is conducted mainly based on subjective judgments of risk analysis experts according to their previous experience. Second, Sklet et al. (2006) pointed out that the validity of the RIF scoring was evaluated to be low due to the limitation of the scoring methods. Third, the imprecision and lack of data is another problem that increases the uncertainties of the experts' evaluation.

2.2. Application of the confidence level method to the BORA method

It is illustrated in this study that a confidence level-based methodology can be effectively used to incorporate the uncertainties into the QRA model. A simple illustrative schematic capturing the framework that needs to be followed in the implementation of the proposed method is depicted in Fig. 1.

As mentioned in Section 2.1, since the RIF scoring and weighting process of the BORA method highly depends on the expert's subjective judgments, the result may contain many uncertainties if the data is insufficient or the scoring method is inappropriate. Thus, the proposed method provides the experts with a measurement of their confidence levels to assist them in defining the probability of hydrocarbon release accidents more accurately. The application of the confidence level to the BORA model contains the following main steps:

1) Analysis using an L–R bell-shaped fuzzy number.

First, the adjusted results from the BORA method need to be applied to an L–R bell-shaped fuzzy number, which can be pictured as a group of modified fuzzy membership curves to represent different confidence levels of the experience-based judgments. The fuzzy number is defined by a triplet $\tilde{A} = (a_1, a_2, a_3)$ and the membership function is shown in Eq. (1).

$$\mu_{\tilde{A}}(x) = \left\{ \begin{array}{ll} 0 & \mathit{for}\ x < a_1 \\ e^{b\left(\frac{a_2 - x}{a_2 - a_1}\right)^n} & \mathit{for}\ a_1 \le x < a_2 \\ 1 & \mathit{for}\ x = a_2 \\ e^{b\left(\frac{x - a_2}{a_3 - a_2}\right)^n} & \mathit{for}\ a_2 < x \le a_3 \\ 0 & \mathit{for}\ x > a_3 \end{array} \right\} \tag{1}$$