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Grid-based risk mapping for gas explosion accidents by using Bayesian network method

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ABSTRACT

Gas explosions at process facilities close to residential areas may lead to catastrophic consequences. It is difficult for traditional quantitative risk analysis (QRA) to consider all the specific local details and conduct risk assessments efficiently. A grid-based risk mapping method is developed to enable a more detailed and reliable explosion risk screening for large areas under complicated circumstance. A target area is divided into a number of grids of an appropriate size and with simplified conditions, and risk analysis is conducted at each grid. A total risk mapping can be depicted based on risk evaluations of all grids. Meanwhile, in order to consider multi-consequences and the complex inter-relationships between consequences and basic factors, a Bayesian network (BN) model is implemented for the proposed method instead of conventional Event Tree and Fault Tree methods. Furthermore, three kinds of data—practical information, computational simulations, and subjective judgments—are involved in the quantification of the proposed BN in order to reduce the uncertainties caused by data shortage and improve the reliability and accuracy of the proposed method. A case study is provided and a mesh convergence of different grid sizes is conducted. Results show that the proposed method is capable of dealing with large and complex situations effectively.

1. Introduction

In the gas processing industry, explosion risk analysis is very important as explosions may lead to catastrophic consequences. If the gas facility is located close to residential areas, not only would process facilities be damaged during an explosion event, but severe human loss may also be incurred due to the large population and complicated environment of residential areas. For example, on 31 July 2014, a series of gas explosion occurred in Kaohsiung, Taiwan, which caused 32 fatalities and 321 injuries. More than four main roads with a total length of approximate 6 km were damaged and traffic was blocked for several months (Liaw, 2016). In 2013, another severe explosion occurred in storm drains in Qingdao, China, and caused 62 fatalities and 136 injuries (Zhu et al., 2015).

In regards to explosion risk analysis of oil and gas facilities, traditional quantitative risk analysis (QRA) is the most widely applied approach. It normally focuses on macroscale evaluation, which provides an overall statistical result of risk for a target area, such as a fatality accident rate (FAR) and potential loss of life (PLL) for human loss (Vinnem, 2014). However, for risk analysis of a large area under complex circumstances, it is difficult for such macro-scale analysis to consider all specific local details and deal with complicated conditions.

In this study, a grid-based risk mapping method is developed to enable a more detailed and reliable explosion risk screening for large areas with complicated conditions. The proposed method divides the target site into a number of girds of appropriate size and with simplified conditions. Then, risk analyses can be conducted easily at each end of the grid, and finally, a risk mapping can be depicted for the whole target area. Based on the mapping, further detailed risk assessment and protective measure can be conducted at the most endangered areas.

A limit amount of research has applied grid-based risk analysis methods to process safety. Pula et al. (2006) employed grid-based impact modelling to model and analyse radiation and

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overpressures at different locations in the process area. Seo and Bae (2016) applied a grid-based method to risk assessment of fire accidents in offshore installations. Zohdirad et al. (2016) used the grid-based method to measure the risk from secondary grade releases in order to determine the results' accuracy of risk evaluations of releases.

Furthermore, to conduct risk analyses of both process and residential areas, multiple consequences, such as overpressure impacts, building damage, and human loss, need to be considered. In order to consider multi-consequences and complex inter-relationships between consequences and basic risk influence factors, a Bayesian network (BN) is implemented for the proposed grid-based method as a risk modelling tool because traditional QRA modelling tools, such as Event Tree (ET) and Fault Tree (FT), have difficultly revealing the complicated mechanisms of inter-relationships. The BN is capable of dealing with multi-state variables with different causal relationships, while the traditional ET and FT only have simple Boolean functions and sequentially dependent failures.

In the process industry, BNs have been increasingly applied for risk and safety assessments. Barua et al. (2016) presented a dynamic BN and Fault tree-based operational risk assessment method for a chemical process system. Norazahar et al. (2017) developed a method to identify critical human and organisational factors in the escape, evacuation and rescue systems and used BN to assess the criticality of those factors. Yeo et al. (2016) proposed a BN-based dynamic safety analysis method for the offloading process of an LNG carrier and investigated the behaviour of the most risk influential factors. Wu et al. (2017) employed the BN and Dempster-Shafer evidence theory to probabilistically analyse natural gas pipeline network accidents. Pasman and Rogers (2013) implemented a BN to a layer of protection analysis (LOPA) for gas risk analysis at a hydrogen tank station. Khakzad et al. (2011) used BN to conduct safety analysis of a feeding control system that transfers propane from a propane evaporator to a scrubbing column. Haugom and Friis-Hansen (2011) built a BN of gas risks at a hydrogen refuelling station that considered gas leak, jet fire and loss of life.

However, the accuracy of BN modelling is limited by the scarcity of data. In order to improve the reliability and accuracy of the proposed method, three kinds of data are included in the proposed study: practical information, computational simulations, and subjective logical judgments. Practical information includes historical data of basic risk factors, such as leak frequencies and local wind information, and general information about each grid. The numerical software PHAST (DNV GL, 2016) is used to simulate explosions with different scenarios and output blast loads as input data for BN analysis. Subjective logical judgments are applied when no data can be found. Such judgments are useful for deciding conditional dependencies when data is lacking, but the logic between nodes is clear.

2. Methodology

The proposed grid-based risk profiling method consists of the following steps.

- Gridding: Decide the grid size and collect information for each grid.
- Modelling: Model BN based on risk scenarios and consequences concerned.
- Quantification: Find data to quantify the established BN.
- Analysis: Calculate probabilities of target nodes of BN.
- Result: Output risk for each grid to conduct total risk mapping.

2.1. Grid-based analysis

A grid-based risk analysis method is employed to enable better modelling and assessment of explosion loads, building damage, and human loss at different locations in both the process area and nearby residential areas. As shown in Fig. 1, the target area is divided into a specific number of computational grids, and the risks are then evaluated at each grid.

Information of each grid needs to be collected according to related consequences. For instance, building type has to be defined to estimate potential building damage, and similarly, the size of the population of each grid affects the risk of human loss. The more consequences need to be considered, the more information is required.

2.2. BN modelling

A BN is an illustrative diagram that contains nodes and links with conditional probabilities. Fig. 2 shows a BN of gas explosion events that is used to evaluate the risks of both building damage and human loss. It is a simplified network with 9 nodes and 10 links, which represents only the critical factors of explosion and other consequences. However, BNs are flexible, which means that extra information, such as safety barriers, human errors, or environmental concerns, can easily be added to the original network. The nodes and the states of each node are listed in Table 1. The states of explosion loads are defined based on damage classifications introduced by Lobato et al. (2009).

2.3. Quantification of BN

The quantification of a BN can be divided into two parts, finding the probabilities of the basic nodes and defining the conditional probabilities of the inter-relationship between these nodes. Quantification based on historical statistical data is the most convenient way. However, it is difficult to find available data to quantify the inter-relationship between nodes for two main reasons. First, most of the available cases only provide the consequences, such as fatalities or estimated economical losses, of an explosion event, so inter-relationships between middle nodes cannot be defined. Second, due to the complex structure of the proposed BN and the large number of combinations of states involved, hundreds of detailed records are required for sufficient quantification. Therefore, two other quantification methods, numerical simulation and logical judgments, are applied in this study because of the limitations of the statistical data.

2.3.1. Quantification of basic nodes

The proposed BN has five basic nodes: wind direction, wind speed, release severity, building type, and population. Information about wind direction and wind speed can be found from local weather data resources online. As for the release severity, hydrocarbon release data from the Health and Safety Executive (HSE) annual report (2015) is selected. Table 2 shows the HSE recorded number of accidents from 2006 to 2015 and summarises the probability of each state. The basic nodes of site information, such as building damage and population, for each grid depend on the specific condition within the grid area and are decided by subjective judgments.

2.3.2. Quantification of inter-relationships

For quantification of inter-relationships, the proposed BN is divided into two sub-networks: a sub-network of explosion loads including nodes A,B,C,D, and E and a sub-network of building damage and human loss including nodes E,F,G,H, and I. As