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A grid-based risk screening method for fire and explosion events of hydrogen refuelling stations

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ABSTRACT

As hydrogen is a comparatively less safe fuel compared to conventional fuels such as gasoline and diesel, major accidents such as explosions and fires at hydrogen refuelling stations close to residential areas may lead to catastrophic consequences. It is difficult for a traditional quantitative risk analysis (QRA) method to efficiently assess human safety in a large region that includes not only the hydrogen refuelling station but also nearby commercial and residential areas. Therefore, a grid-based risk mapping method has been developed to enable efficient and detailed risk screening of such large areas. The target area is divided into a number of grids of an appropriate size, and a risk analysis is conducted for each grid. A total risk map can be depicted based on the risk evaluations of all grids, and a detailed risk assessment can then be applied to the most hazardous grids. Meanwhile, in order to consider multiple consequences and the complex interrelationships between risk factors, a Bayesian network (BN) model is implemented for the proposed method. At the same time, to reduce uncertainties caused by a shortage of data, three kinds of data—practical information, computational simulations and subjective judgements—are involved in the quantification of the proposed BN. The results from the case study show that the proposed method is capable of effectively conducting risk screenings for large and complex situations.

Introduction

Hydrogen has one of greatest potentials as a clean energy source that can be used as an alternative to fossil fuels. With the rapid development of hydrogen vehicle technology, an increasing number of hydrogen refuelling stations have been built worldwide. Compared with conventional fuels such as gasoline and diesel, hydrogen is a comparatively less safe fuel due to its high energy content, low ignition energy, fast burning speed, extensive flammability and detonability ranges. Meanwhile, since hydrogen refuelling stations are normally located close to residential areas, not only would process facilities be damaged during major events such as fires and explosions, but severe loss of human life may also occur because of the large population of nearby commercial

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and residential areas. Therefore, it is necessary to develop a risk-based method to evaluate human safety in regard to hydrogen-related fire and explosion accidents at refuelling stations.

A large amount of research has been conducted on the risk assessments of hydrogen facilities. Skjold et al. [23] introduced a 3D risk management (3DRM) concept for hydrogen applications by using a computational fluid dynamics (CFD) tool to simulate flow-related accident scenarios. Nakayama et al. [19] conducted a preliminary hazard identification study on a hybrid gasoline-hydrogen refuelling station and identified 314 accident scenarios for further risk analysis. Groth and Hecht [7] developed a HyRAM toolkit for conducting quantitative risk analysis (QRA) and consequence assessment for hydrogen fuelling and storage infrastructure. Sun et al. [24] performed a risk analysis of mobile hydrogen refuelling stations in Shanghai to assess human safety inside and outside of the stations. Kasai et al. [11] carried out a risk analysis of an electrolytic hydrogen generation system by using hazard and operability (HAZOP) and failure mode effect analysis (FMEA) methods. Al-shanini et al. [1] proposed a systematic accident modelling method for safety assessment of a hydrogen station and the method incorporates prevention barriers associated to human factors, management and organizational failures in the risk assessment framework. Mohammadfam and Zarei [18] developed a comprehensive risk analysis framework which included both qualitative and quantitative methods to assess fuel safety in a hydrogen production plant. Li et al. [15] conducted a QRA study on a hydrogen refuelling station of 2010 World Expo in Shanghai and evaluated human risks to station personnel, refuelling customers and third parties.

This study focuses on the risk analysis of major accidents such as fires and explosions that may occur at hydrogen refuelling stations. Due to the different building types and population distributions, different degrees of consequences may occur in different areas. The efficiency may be a problem for traditional QRA to conduct detailed evaluations of all local areas if the total area is large. Therefore, a grid-based risk mapping method is developed in this study to enable efficient and detailed risk screening for large areas with complicated conditions. The proposed method divides the target site into a number of grids of appropriate size and with simplified conditions. Then, risk analyses can be conducted easily at each grid, and finally, a risk map can be depicted for the whole target area. Based on the map, further detailed risk assessments and protective measures can be applied to the most hazardous areas.

Meanwhile, evaluation of hydrogen release-related fire or explosion risks is complicated when multiple factors (e.g. leak severity, vent condition, structural complexity), multiple consequences (e.g. building damage, human loss, environmental effects) and complex interrelationships are considered. Therefore, Bayesian network (BN) modelling is implemented in this study to model complicated mechanisms of hydrogen release-induced fire or explosion events and consequent human loss as the BN is able to deal with complex interrelationships between risk factors. The BN is a probabilistic graphical model that represents a group of random variables and conditional dependencies between them. It can deal with multistate variables with different causal relationships, while the traditional event-tree and fault-tree approaches only have simple Boolean functions and sequentially dependent failures.

In the process industry, BNs have been increasingly applied for risk and safety assessments. Friis-Hansen [8] built a BN model of gas risks at a hydrogen refuelling station that considered gas leaks, jet fires and loss of life. Pasman and Rogers [22] applied BN modelling to the risk analysis of two types of hydrogen refuelling stations and three supply transportation types. Zarei et al. [28] developed a BN-based dynamic and comprehensive QRA (DCQRA) method for risk modelling and safety assessment of natural gas stations. Xin et al. [27] used the BN method to enable real-time dynamic hazard identification and scenario mapping for further risk analysis in process industry. Norazahar et al. [21] developed a method to identify critical human and organizational factors in the escape, evacuation and rescue systems and used BN to assess the criticality of those factors. Wu et al. [26] employed the BN and the Dempster-Shafer evidence theory to probabilistically analyse natural gas pipeline network accidents. LaChance et al. [13] compared two H_2 standards and introduced a Bayesian statistical approach used to generate the component hydrogen leakage frequencies.

However, the accuracy of BN modelling can be affected significantly by a shortage of data for the quantification process. To improve the reliability and accuracy of the proposed method, three kinds of data are included in the proposed study: practical information, logical judgements and computational simulations. Practical information includes historical data of basic risk factors, such as observed frequencies of leak scenarios and ignition sources, and specific information of target sites. Logical judgements are applied when no data can be found. Such judgements are useful for determining conditional dependencies when logic between nodes is simple and straightforward. Meanwhile, numerical simulation is used to conduct a detailed fire and explosion assessment to provide data for BN quantification. PHAST [3] is selected to simulate explosions in this study, as PHAST has been proven to be an efficient and reliable tool for fire and explosion assessments.

Methodology

The proposed method is a semi-quantitative risk analysis approach that can be used as a risk screening tool. From the grid process, each grid will be given a risk indication including fire or explosion severity, budding damage and human loss. Then, the areas with higher risks can be defined and be further assessed by detailed risk assessment methods. Meanwhile, protective measures can also be conducted at the most endangered areas.

To be more specific, the grid based method is applied to evaluating physical effects caused by explosion or fire accidents on local buildings and humans based on local conditions such as building type, number of people, etc. The extent of physical effects are calculated by a source model according to source conditions. The grids are generally considered independently and each grid has its own probability of receiving hazards from the source area. Then, combined with building and human information inside the grid, the probability of

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