Quantitative Risk Analysis for Explosion Safety of Oil and Gas Facilities

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ABSTRACT

In the oil and gas industry, a vapor cloud explosion (VCE) induced by oil and gas leaks is one of the major threats to process safety because it may lead to catastrophic consequences. Risk evaluation of such gas explosions is complicated when multiple factors (e.g., leak severity, vent condition, structural complexity), multiple consequences (e.g., building damage, human loss, environmental effect), and complex interrelationships need to be considered. Meanwhile, for various process facility types such as small petrol stations, large onshore process factories, highly congested offshore platforms, and others, specific site characteristics also need to be involved in explosion risk analyses. However, most traditional risk analysis methods are too simple to reveal the complex mechanism of gas explosions while some advanced computational methods are too time-consuming. Therefore, this research carries out a comprehensive study on the gas explosion risk analysis approaches of different oil and gas facilities and aims at developing more accurate, detailed, efficient, or reliable risk analysis methods for VCEs under different conditions.

First, to enable a more accurate explosion risk analysis when multiple factors and multiple consequences are involved, an advanced Bayesian network–based quantitative explosion risk analysis method is proposed to model risks from an initial release to vapor cloud explosions and further consequences because of the ability of the Bayesian network to reveal complicated mechanisms with complex interrelationships between parameters. Meanwhile, since fire accidents frequently occur at process facilities and may also result in significant consequences, a risk analysis of fire accidents using the Bayesian network is conducted as well.

Second, for a risk analysis of gas explosion in process facilities close to residential areas, a grid-based risk-mapping method is developed to provide a more detailed explosion risk analysis for large areas under complicated circumstances. A target area is divided into a number of grids of appropriate size and with simplified conditions, and risk analysis is conducted at each grid. Compared with traditional explosion risk analysis, the proposed grid-based method simplifies complicated conditions throughout the gridding process, and therefore, a more precise risk analysis is enabled.

Third, a multi-level explosion risk analysis method is established to offer a more efficient explosion risk assessment of super-large oil and gas facilities with highly congested environments such as floating liquefied natural gas (FLNG) platforms. When computational fluid dynamic (CFD) software is used to calculate overpressures, a large amount of computational time is required for such structures because of its enormous size and highly complicated topside structures. The
proposed method divides the whole structure into subsections and applies detailed CFD calculations only to the areas with the highest level of potential risks so that the computational time can be reduced to a realistic and acceptable level.

Both qualitative and quantitative explosion risk analyses involve a lot of uncertainty induced by subjective judgments that may significantly affect the validity of risk evaluations. Therefore, a confidence level–based approach is proposed for incorporating uncertainties into conventional risk analysis using the concept of fuzzy theory. The proposed method enables a more reliable risk evaluation by reducing the impact of subjective judgment–related uncertainties.
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Yimiao Huang
March 2017
STATEMENT OF CANDIDATE CONTRIBUTION

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text.

I have obtained the permission of all other author to include the published works in this thesis. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis, including experimental assistance, professional editorial advice, and any other original research work used or reported in my thesis.

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Journal papers


9. Jingde Li, Hong Hao, **Yimiao Huang**, Internal and external pressure prediction of vented gas explosion in large rooms by using analytical and CFD methods. Submitted to *Journal of Loss Prevention in the Process Industries*.
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CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

The search for natural sources of energy and investments into the exploration of energy sources, such as oil and gas, show a boom worldwide. In the oil and gas industry, one of the largest dangers to human life, assets, and environment comes from the risks associated with the explosive potential of handling petroleum-related products. These products vary in nature from reservoir fluids to methane.

However, on the other side of the oil and gas boom, many onshore and offshore gas explosion accidents have been occurring over the years globally. For example, Figure 1.1 shows gas explosion accidents on the Piper Alpha oil production platform, the Ghana petrol station, the Guadalajara sewer system, and the Kaohsiung underground pipelines, which are on the top of the list of the most disastrous explosion accidents in the industry.

(a) Piper Alpha platform explosion  (b) Ghana petrol station explosion
(c) Guadalajara sewer explosion  (d) Kaohsiung pipeline explosion

Figure 1.1 Explosion threats
The Piper Alpha explosion caused the deaths of 167 men with only 61 survivors (Hendershot, 2013). As one of the worst offshore oil disasters in history, this accident ceased approximately 10% of North Sea oil and gas production during the 1980s, and the economic loss was more than $3 billion (Patecornell, 1993). Another catastrophic fire and explosion event occurred at a petrol station as a result of a flood incident in Accra, Ghana, on June 4, 2015, and caused over 152 fatalities (Asumadu-Sarkodie et al., 2015). For the Guadalajara explosion, 206 people were killed, nearly 500 to 600 were missing, and 1,800 were injured (ARIA, 2007). The estimated monetary damage ranges between $300 million and $1 billion. On July 31, 2014, a series of gas explosions occurred in Kaohsiung, Taiwan, which caused 32 fatalities and 321 injuries. More than four main roads with a total length of approximately 6 kilometers were damaged, and traffic was blocked for several months (Liaw, 2016).

Vapor cloud explosions (VCE) are one of the most serious hazards to occur on oil and gas facilities. VCE is defined as “an explosion resulting from an ignition of a premixed cloud of flammable vapor, gas or spray with air, in which flames accelerate to sufficiently high velocities to produce significant overpressure” (Mercx & van den Berg, 2005). To evaluate the risks of vapor cloud explosions, it is essential to consider a large array of random variables, such as gas property, wind conditions, congestion scenarios, and others. Meanwhile, the risk analysis of VCEs can be more complicated when multiple consequences such as structural damage, human loss, environmental effects, and so on, need to be considered. Furthermore, for various types of process facilities, different environments and structures will be presented, and therefore, appropriate methods should be applied and specific site characteristics should be taken into account to ensure the reliability and efficiency of explosion risk assessments.

There are empirical and numerical methods used to quantify the overpressures of explosions. For example, the empirical TNT-equivalency method (Baker et al. 2012) has proved to be a popular overpressure calculation tool in the past. A multienergy method (Vandenberg, 1985), which is based on experimental database for approximating explosion overpressures, has become a fast and more reliable prediction solution. Later, advanced computational fluid dynamic (CFD) programs are able to use the three-dimensional Cartesian Navier-Stokes flow solver to predict cloud propagation, ignition probabilities, leak probabilities, and overpressures. By considering more fundamental physics, such as the complicated congestion and confinement in the geometry, the CFD-based approach provides more accurate overpressure results than empirical methods. However, when CFD analysis is conducted in a large process
facility with complicated environments and high congestions, an unacceptable computational force and calculation time may be required.

So far in the oil and gas industry, a wide range of risk analysis methods, from qualitative to quantitative, are available. For qualitative methods, the analysis is normally done by team studies based on the generic experience of knowledgeable personnel and does not involve any mathematical estimation. Overall qualitative evaluations are essentially checklist reviews in which questions or process parameters are used to prompt discussions of the process design and operations that would develop into an incident scenario due to an identified risk. The qualitative risk analysis of process safety involves HAZOP (CIA, 1992; CCPS, 2011; Kletz, 1999), what-if analysis (CCPS, 2011), preliminary hazard analysis (PHA) (Vincoli, 2006), layers of protection analysis (LOPA) (Summers, 2003), and the like. Qualitative risk analysis is an effective tool for risk screening or routine inspections. However, if detailed risk assessment is required, such methods may not be appropriate.

Quantitative risk analyses (QRA) are mathematical estimations based on historical data to estimate the probability of failure or to predict the consequence of an event or incident. The event tree is the most used logical model to mathematically and graphically describe the combination of failures of event and circumstances in an incident sequence, expressed in an annual estimation. Fault tree analysis (FTA) is another important quantitative risk analysis method. It is a deductive method that focuses on one particular incident, often called a top event, and then constructs a logic diagram of all conceivable event sequences that could lead to that incident. It is normally a logic model that mathematically and graphically depicts various combinations of equipment faults, failures, and human errors that could lead to an incident of interest, presented in an annual express. Quantitative risk analysis methods are widely applied to explosion risk analysis of oil and gas facilities. They normally focus 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 macroscale analysis to consider all specific local details and deal with complicated conditions.

To conclude, qualitative risk analysis is widely used to assess the explosion risks of process facilities, and it is the most efficient method when a rough assessment of explosion risks is accepted. Traditional quantitative analysis methods such as the event tree and the fault tree has
also been increasingly used to evaluate the risks in the oil and gas industry. However, conventional QRAs have difficulty revealing the complicated mechanisms of interrelationships between risk factors because they only have simple Boolean functions and sequentially dependent failures. Therefore, an advanced quantitative analysis method such as Bayesian network (BN) modelling is implemented for a more accurate risk assessment of explosion accidents when multiple consequences and complex interrelationships are required to be considered.

Meanwhile, in this research, a multi-level explosion risk analysis (ERA) method is developed to improve the efficiency of traditional CFD-based explosion risk analysis of super-large offshore structures such as floating liquefied natural gas (FLNG) facilities, as one critical issue in applying such CFD-based ERA to FLNGs is that an unacceptable computational time is normally required because of the large size and complex structures of FLNGs. Moreover, a grid-based method is proposed to conduct a detailed explosion risk analysis when the process factory is located close to residential areas, and detailed risk influences on both industrial and residential areas need to be considered. Last but not least, during the quantitative risk analysis process of explosion accidents at process facilities, subjective judgment–related uncertainties are unavoidable. Therefore, in the present study, a fuzzy set theory–based confidence level method is proposed to deal with the uncertainties in accordance with experts’ subjective judgments by incorporating confidence levels into the traditional QRA framework.

### 1.2 OBJECTIVE OF THE STUDY

The aims of the present study include:

- Developing a more accurate Bayesian network–based quantitative risk analysis method to model complicated mechanisms of explosion accidents and further consequences such as building damages and human losses occurring at oil and gas facilities because of the ability of BN to deal with complex interrelationships between risk factors.
- Developing a more detailed grid-based risk mapping method to enable a detailed explosion risk analysis for large areas with complicated environments involving not only process factories but also residential areas; a target area is divided into a number of grids of appropriate size and with simplified conditions, and risk analysis is conducted at each grid, from which total risk mapping can be depicted.
• Establishing a more efficient multi-level explosion risk analysis (MLERA) method for super-large oil and gas facilities with complicated structures, which divides the whole structure into subsections and applies detailed CFD calculations only to the areas with the highest risk levels so that the computational time can be reduced to a realistic and acceptable level.

• Developing a more reliable confidence level–based risk analysis method to reduce the uncertainties of QRAs caused by subjective judgments and consequently to provide a more robust evaluation of explosion risks of oil and gas facilities; the proposed method applies fuzzy set theory in dealing with the uncertainties.

1.3 THESIS ORGANISATION

This thesis is composed of seven chapters. Six chapters following the introductory chapter are arranged as follows. Chapter 3 to Chapter 5 are discussed by different level of structural complexity of the target sites from petrol station to super complicated offshore FNLG platforms. For different kind of oil and gas facilities, we suggested different kind of risk evaluation methods based on their characteristics.

Chapter 2 presents a broad literature review on the state-of-the-art explosion risk analysis methods including both qualitative and quantitative approaches. Meanwhile, factors influencing explosion loads and overpressure calculation methods regarding gas explosions are also reviewed.

In Chapter 3, a BN-based QRA is developed to model explosion risks of petrol stations from initial release to consequent explosions and human losses because service stations are normally located close to largely populated residential areas and explosion accidents may lead to significant human losses. Meanwhile, fire accidents, which occur more frequently than explosions at petrol stations, may also cause severe consequences. Therefore, a risk analysis of fire accidents based on BN is also conducted.

Chapter 4 presents a grid-based mapping method used to assess explosion risks of a refinery factory close to residential areas. A BN model is implemented to consider multiple consequences and the complex interrelationships between consequences and basic factors. A mesh convergence of different grid sizes is conducted to determine an optimal balance between accuracy and computational time.
In Chapter 5, a multi-level explosion risk analysis method (MLERA) is developed for accidental gas explosion events in super-large floating liquefied natural gas (FLNG) facilities. The MLERA includes three levels, which are qualitative risk screening, semi-quantitative risk classification, and quantitative risk assessment. A CFD tool called FLACS is used as a calculation tool for detailed risk quantification, and an ALARP (as low as reasonably practical) method is selected as a calibration tool and used to determine the acceptance of the explosion risk.

Chapter 6 describes a new methodology for incorporating uncertainties into conventional QRA using the concept of confidence level. A left-right (L-R) bell-shaped fuzzy number is employed, and its membership curve can control its shape to represent different confidence levels. This study focuses on offshore hydrocarbon release hazards and the barrier and operational risk analysis (BORA-Release) method is selected as the basic model to illustrate the proposed methodology.

Chapter 7 summarizes the key conclusions from this research and provides recommendations for future studies.
CHAPTER 2. LITERATURE REVIEW

2.1 OVERVIEW

This chapter presents a literature review on the existing explosion risk analysis methods including both qualitative and quantitative approaches. In the meantime, some factors affecting the severity of the gas explosion loads are introduced to enable a better understanding of the risk analysis. Moreover, empirical and numerical methods used to estimate explosion loads are also reviewed. The literature review covers: 1) introduction of factors affecting gas explosion loads; 2) existing and new approaches in gas explosion loads estimation and prediction; 3) discussion of current risk analysis methods of gas explosion accidents.

2.2 MAIN FACTORS AFFECTING GAS EXPLOSION LOADS

A gas explosion is defined as a process where combustion of a premixed flammable fuel-air cloud which is causing rapid increase of pressure. Figure 2.1 illustrates the process from gas releases to gas explosions. Both release and ignition must be present to result in fire or explosion accidents. (Bjerketvedt et al., 1997).

![Figure 2.1 Typical process of gas explosion (Bjerketvedt et al., 1997)](image)
The severities of overpressures caused by gas explosions depend on various factors and several important ones are briefly reviewed here:

- The confinement and venting surrounding the gas cloud;
- The congestion or obstacles within the cloud;
- The fuel properties and concentrations;
- The ignition type and location;

Gas explosions can occur in confined areas, such as tanks, pipes or channels, partly confined offshore modules or buildings and unconfined process plants or other open areas. In a confined situation, a high flame velocity is not required to generate pressure and the turbulent combustion process causes a more dramatic increase in overpressure. For example, the overpressures and impulses of explosions in a confined chamber can be enlarged by 2-3 times if the confinement volume increases (Kuhl & Reichenbach, 2009). Therefore, it is of great importance to investigate the flame propagation for reliable design of structures in such confined explosions (Sauvan et al., 2012; Shi et al., 2009; Tang et al., 2014). Partly confined explosions occur in structures that are partly open such as offshore modules or the production or process areas within buildings. In this situation, the size and location of the vent area play significant roles in building overpressures. Attentions have been increasingly paid to the partially confined overpressures. (Pedersen et al., 2013; Woolley et al., 2013). If the cloud is truly unconfined and unobstructed, the flame is not likely to accelerate to velocities of more than 20 – 25 m/s, and the over pressure can be neglected. In this case, the explosion normally turns to be a flash fire (Bjerketvedt et al., 1997).

Obstacles is another critical factor that may cause significant influence on gas explosion loads. The expansion-generated flow created by combustion will generate turbulence when the fluid flows past the obstacles (Dorofeev, 2007; Kim et al., 2014; Na'inna et al., 2013). The newly generated turbulence will increase the burning velocity by expanding the flame area and increasing the molecular diffusion and conduction processes, and consequently increase the expansion flow and boost the turbulence. The generation of increasingly higher burning velocities and overpressures in this cycle due to the obstacles is called Schelkchkin mechanism (Lea, 2002). Figure 2.2 shows the Schelkchkin mechanism of flame acceleration caused by obstructions constitutes a strong positive feedback loop (Bjerketvedt et al., 1997).
A blockage ratio of obstacles is an important factor that influences the flame propagation and the explosion overpressures (Oh et al., 2001). The blockage ratio of obstacle is used to describe the degree of obstruction. Generally, the maximum overpressure increases when blockage ratio increases. However, the rate of increase depends on the geometry of obstruction (Ibrahim & Masri, 2001). Normally, higher overpressures will be produced with smaller diameter objects if the blockage ratio is given. Moreover, more tortuous route (flame in baffle-type obstacles) results in greater explosion overpressures compared to round obstacles. This occurs due to the fact that the turbulence enhancement of the burning velocity is higher in the shear layer of the sharp obstacle (Bjorkhaug, 1986).

The fuel properties strongly affect the flame speeds for stoichiometric fuel–air mixtures (Dorofeev, 2011). Acetylene, ethylene-oxide and ethylene are most likely to cause significant overpressures (Dorofeev et al., 1994; Matsui & Lee, 1979). For other fuels, such as butane and propane, a strong deflagration is required to initiate the detonation (Bjerketvedt et al., 1997). Moreover, the detonation triggered by methane could be more complicated (Boni et al., 1978; Wolański et al., 1981). Meanwhile, the fuel concentration also has significant effects on the
flame region distribution and the explosion behaviours (Halter et al., 2005; Q. J. Ma et al., 2015). A premixed gas cloud below the lower flammability limit (LFL) and above the upper flammability limit (UFL) will not be burnt, and very low burning rate will be produced if the fuel mixtures near the flammability limits. The maximum explosion overpressure is normally generated within stoichiometric composition or slightly rich premixed gas cloud (Bjerketvedt et al., 1997).

Additionally, the consequences of gas explosions can be significantly influenced by types of ignition sources. If the ignition sources are jet-type, or bang-box-type other than a planar or point source, high explosion overpressures can be observed. In addition, the location of ignition is another critical factor affecting VCEs. The maximum overpressure can be considerably increased by an order of magnitude if the location of ignition is placed at less vented or more confined areas (Babrauskas, 2003; Bartknecht, 2012). Meanwhile, edge ignition may produce greater overpressures than central ignition as the edge ignition has longer flame propagation distance for flame acceleration (Zeldovich & Barenblatt, 1959).

Gas explosions are very sensitive to these parameters mentioned above, and therefore, it is important to carefully consider those factors when risk analysis of a gas explosion is conducted for any oil and gas facility.

2.3 LOAD PREDICTION METHODOLOGIES

Prediction of gas explosion overpressures is the most important part of explosion risk analysis as the severities of the other consequences such as building damage, human losses, business losses etc. are mainly dependent on blast loads. Therefore, some of the most widely used deterministic explosion load prediction methods from the traditional ones to the most state-of-the-art ones are reviewed. The explosion risk analysis can be conducted by combining risk analysis methods and detailed load prediction approaches.

2.3.1 Empirical models in DNV PHAST

DNV PHAST (DNV GL, 2016) is a leading consequence analysis tool using empirical models to simulate hazardous gas releases, gas dispersions, fires, and explosions. It is fairly simple and is typically used as a screening tool for rapid indication of physical effects and consequences. The empirical models used by PHAST include simplified TNT equivalency model (Mannan, 2012), TNO Multi-energy model (Vandenberg, 1985) and Baker-Strehlow-Tang model (Baker
et al., 1998). These models significantly simplified the physics based on correlations derived from assessments of experimental data.

The TNT equivalency method is based on the assumption of equivalency between the flammable material and TNT. It has been extensively studied by Baker et al. (2012), Mannan (2012) and Stull (1977). A yield factor plays a critical role in converting the energy of gas explosion into the same explosive charge of TNT. The relationship between the gas explosion and TNT explosion is seen below:

\[ W_{TNT} = 10\eta W_{HC} \]  

(2.1)

where \( W_{TNT} \) is the equivalent mass of TNT, \( \eta \) is an empirical explosion efficiency, \( W_{HC} \) is the mass of hydrocarbon.

The TNT equivalency has been widely used in the simplified models. For example, the Health and Safety Executive (HSE) evaluated the TNT Equivalence method for both near and far field range of explosives and energetic materials in a simplistic way (Formby & Wharton, 1996). Rui et al. (2002) used the TNT equivalency method to evaluate the distributed blast of fuel-air detonation. Skacel et al. (2013) also discussed the applicability of the TNT equivalency method for calculations of blast wave characteristics after vessel rupture in 1-D geometry detonation.

Another empirical approach is the TNO Multi-energy method (Vandenberg, 1985). It is based on the assumption that only confined or congested gas clouds contribute to the overpressure built-up, and the flame velocity is assumed to be constant for the explosion when the gas cloud is ignited from centre. Two parameters are vital in the overpressure calculation. Firstly, the combustion-energy scaled distance \( R_{ce} \), should be determined, it is defined as:

\[ R_{ce} = \frac{R_0}{3 \sqrt[3]{\frac{E}{P_0}}} \]  

(2.2)

where \( E \) is the combustion energy, \( R_0 \) is the distance from the explosion centre to the target, and \( P_0 \) is the atmospheric pressure.

The second important parameter is the strength of the explosion, which is classified from a number between 1 and 10 to represent the level of explosion, as seen on the left hand side in Figure 2.3. The choice of the explosion strength level from 1 to 10 depends on a conservative
assumption or other simulations. Therefore, the accuracy of Multi-energy method is highly dependent on subjective judgments.

![Figure 2.3 Hemispherical fuel-air charge blast for the multi-energy method (Bjerketvedt et al., 1997)](image)

The simplicity and fast estimation speed of the TNO multi-energy method was proved by Alonso, et al. (Alonso et al., 2006; Alonso et al., 2008). This fast method is used to evaluate the characteristic overpressure-impulse-distance curves and to analyse the consequence of damage to humans from VCEs. Pitblado et al (2014) also applied the TNO multi-energy model in predicting overpressures of the facility siting hazard distance of VCEs. In addition, an explicit implementation guidance was proposed in their research to improve the consistency in TNO MEM blast load predictions.

Moreover, Baker, et al. (1994) developed the Baker-Strehlow-Tang model for estimating the overpressure of VCEs. The calculation of this method relies on finding appropriate Mach number ($M_f$) by assessing fuel reactivity, flame speed and confinement. Then, the overpressures can be determined by reading a range of curves as shown in Figure 2.4 based on the value of $M_f$. This model was further revised and extended by a new set of blast curves from VCE calculations (Baker et al., 1998; Tang & Baker, 1999).
Overall, the Baker-Strehlow-Tang method provides conservative prediction of flame speed, and it considers some geometrical factors such as the confinement. However, the flame speed estimation may not be conservative for the unconfined 3D flame expansion scenarios. Therefore, Pierorazio, et al. (2005) updated the flame speed table in the Baker–Strehlow-Tang methodology for these exceptional cases and Worthington, et al. (2009) provided a correction method to the Baker-Strehlow-Tang model for the ground effect of vapour cloud explosions.

2.3.2 Computational Fluid Dynamic (CFD) Analysis

The numerical approaches use the Computational Fluid Dynamic (CFD) codes. The fundamental partial differential equations, which govern the fluid flow and other explosion processes, are employed in most of the numerical models during the calculation of VCEs. When comparing the numerical models with empirical models, the numerical models offer greater accuracy and flexibility, and by discretising the solution domain in both space and time, a wide range of geometrical arrangements and conditions in the VCEs can be considered in the numerical simulations.

One of the most popular numerical model is the FLame ACceleration Simulator (FLACS) code. The FLACS code has been developed for over two decades at Christian Michelsen Research Institute in Norway (Bjerketvedt et al., 1997). It has been widely used in the onshore/offshore
explosion analysis, and now extensive validations have been accumulated (Bakke & Hjertager, 1986; Hansen, et al., 2010; Hjertager et al., 1988; Middha & Hansen, 2009). Ma et al. (2014) applied the FLACS to predicting the consequences of explosion events at large-scale oil and gas facilities with complicated and highly congested environments. Li et al. (2016a; 2016b) used FLACS to evaluate safety gap effect on both gas dispersion and explosion risk for super-large and highly congested offshore floating liquefied natural gas (FLNG) platforms. Gavelli, et al. (2011) applied FLACS to evaluate the consequences of the ignition of a flammable vapour cloud from an LNG spill during the LNG carrier offloading process. Middha, et al. (2011) analysed the safety benefits of hythane by using FLACS regarding the flame speeds and flammability limits. Moreover, Bakke et al. (2010) carried out a study on the effect of trees on gas explosion and Yet-Pole, et al. (2009) employed FLACS to evaluate the possible hazards of different worst-case scenarios within a naphtha-cracking plant.

Another CFD coded model still under development is the EXSIM model which was initially created at Telemark Institute of Technology and Telemark Technological R&D centre in 1989 (Hjertager et al., 1992). The EXSIM code is similar to FLACS in the aspect of numerical modelling, namely, the Cartesian grid and finite volume code are used to represent small-scale objects in EXSIM (Hjertager, 1997). Therefore, some previously investigated projects for FLACS had also been validated by EXSIM. For example, the Buncefield explosion was investigated by both FLACS and EXSIM for explosion simulations (Taveau, 2012). Moreover, the detailed flame behaviour assessment can be found in the work of Johnson et al. (2010). Saeter (1998) conducted modelling and simulation of gas explosion in some other complex geometries. Høiset et al. (2000) implemented the EXSIM model in the investigation of Flixborough accident.

The third reviewed finite volume computational code for fluid dynamics is the AutoReaGas model. It is developed by TNO – Prins Maurits Laboratory and allows a detailed simulation of different aspects of gas explosion (Van Den Berg et al., 1995). The AutoReaGas model integrates features of the REAGAS and BLAST codes as solvers to deal with gas explosion and blast waves respectively. The gas explosion solver in AutoReaGas uses the Flux Corrected Transport technique to cope with the blast wave propagation by applying the 3D Euler equations (Hjertager & Solberg, 1999). A range of user experience of AutoReaGas also exists in the industry. For instance, Janovsky et al. (2006) performed the computational simulations of vented confined explosions by using AutoReaGas and compared the CFD results with the
Stramberk experimental data. Pang et al. (2014) used AutoReaGas to carry out numerical simulations of a series of methane–air explosion processes in a full-scale coal tunnel, and the flame propagation mechanism beyond the initial premixed methane–air region was analysed by comparing the numerical and experimental results. Jiang et al. (2012) provided a theoretical guidance for gas explosion disaster relief and treatment in underground coal mines by performing the AutoReaGas simulation, the propagation characteristics of VCES, and the safe distance for various initial temperatures had been investigated.

In conclusion, for overpressure prediction of gas explosions, using simple empirical methods is the most efficient way and the results have a certain level of accuracy when environments are not complicated. However, if the structure of an oil and gas facility is highly confined and congested, such simple methods may not be appropriate. The advanced CFD methods have the ability to deal with the complex conditions and to enable a much more accurate and reliable load prediction. Nevertheless, one of the critical issue of using CFD calculations is time constraint. Normally a large amount of computational time that may be unacceptable is required when CFD is applied to simulate gas explosions occurring at super-large and highly congested facilities.

2.4 EXPLOSION RISK ANALYSIS METHODS

Both qualitative and quantitative analysis methods may be used to evaluate the explosion risks of process facilities. The following is a brief description of typical risk analyses undertaken in the process industry.

2.4.1 Qualitative Risk Analysis

Qualitative risk analysis is normally done by team studies based on the generic experience of knowledgeable personnel and does not involve any mathematical estimation. Overall qualitative evaluations are essentially checklist reviews in which questions or process parameters are used to prompt discussions of the process design and operations that would develop into an incident scenario due to an identified risk. Table 2.1 indicates an example of qualitative explosion risk analysis based on API (2006) and UKOOA (2003). When levels of consequence and likelihood are decided, a risk matrix as shown in Table 2.2 can be used to determine the total risk level.
Table 2.1 Qualitative explosion risk analysis check list

<table>
<thead>
<tr>
<th>Consequence:</th>
<th></th>
</tr>
</thead>
</table>
| Low consequence:                       | • Low congestion level due to the low equipment count, being limited to wellheads and manifold with no vessels (i.e., no associated process pipework)  
• No more than two solid boundaries, including solid decks  
• Unattended facilities with low maintenance frequency, less frequent than 6-weekly |
| Medium consequence:                    | • Medium congestion level due to the greater amount of equipment installed compared to the low case  
• Higher confinement level than that for the low case  
• Unattended facilities with a moderate maintenance frequency, more frequent than 6-weekly  
• A processing platform necessitating permanent manning but with low escalation potential to quarters, utilities, and control areas located on a separate structure |
| High consequence:                      | • High congestion level due to the significant processing on board, which leads to a high equipment count  
• High confinement level of the potential gas release point  
• Permanent manning with populated areas within the consequence range of escalation scenarios |

<table>
<thead>
<tr>
<th>Likelihood:</th>
<th></th>
</tr>
</thead>
</table>
| Low likelihood:                        | • Low equipment and inventory count, which align closely with the consequence scenarios  
• Low frequency of intervention, less frequent than 6-weekly  
• No ignition sources within the potential gas cloud |
| Medium likelihood:                     | • Greater amount of equipment installed than for the low likelihood  
• Medium frequency of intervention, more frequent than 6-weekly  
• Weak ignition sources, such as a hot surface, exist within the potential gas cloud. |
| High likelihood:                       | • A high equipment and inventory count  
• Permanently manned installations with frequent processing on board  
• Strong ignition sources exist within the potential gas cloud. |

Table 2.2 Risk matrix for risk level determination

<table>
<thead>
<tr>
<th>Likelihood of Failure</th>
<th>Consequence of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Moderate</td>
</tr>
<tr>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Almost certain</td>
<td>1 Medium risk</td>
</tr>
<tr>
<td>Likely</td>
<td>2 Low risk</td>
</tr>
<tr>
<td>Possible</td>
<td>3 Low risk</td>
</tr>
</tbody>
</table>
Some of the widely used qualitative risk analysis methods are reviewed below. A checklist or a worksheet is a standard list which identifies common protection features for typical facility design and operations. Risks are expressed by the omission of safety systems or system features. API RP14J (1993) gives a suitable basic checklist for offshore installations. A hazard and operability (HAZOP) study is a formal systematic qualitative investigative safety review method. It is used to perform a systematic critical examination of the process and engineering intentions of new or existing facilities. Guidance on HAZOP is illustrated by CIA (1992), CCPS (2011), and Kletz (1999). The HAZOP method is deeply reviewed by Dunjó et al. (2010). Another qualitative method is called What-If analysis which originally introduced by CCPS (2011). It is a safety review method using “what-if” investigative questions which are asked by an experienced team of the system or component under review where there are concerns about possible undesired events. HAZID is a particular form of hazard identification commonly applied to offshore installations (Spouge, 1999). It is a systematic review of the possible causes and consequences of hazardous events. Other common qualitative risk methods in process industry includes preliminary hazard analysis (PHA) (Vincoli, 2006), failure mode and effect analysis (FEMA) (Stamatis, 2003), layers of protection analysis (LOPA) (Summers, 2003), etc. Qualitative risk analysis is an effective tool for risk screening or routine inspection. However, if detailed risk assessment is required, such methods may not be appropriate.

2.4.2 Quantitative Risk Analysis

Quantitative risk analyses are mathematical estimations based on historical data or estimates of failures to predict the occurrence of an event or incident. An event tree analysis (ETA) and a fault tree analysis (FTA) are the most widely used method to model explosion risks for process safety and therefore this two methods are briefly reviewed.

An event tree is a visual model describing probable event sequences which may be developed from a hazardous situation. (Vinnem, 2007). It uses branches to show the various possibilities that may arise at each step and is often used to relate a failure event to various consequence models (Spouge, 1999). A detailed procedure for constructing and analysing the ETA for a process system can be found in Mannan (2012). For explosion events, the event tree construction starts from a hydrocarbon release event and works through each branch in turn as shown in the Figure 2.5 below.
Figure 2.5 Event tree analysis of explosion event

It is relatively simple to quantify an event tree by hand, although spreadsheets or computer models are increasingly used to automate the multiplication task. A probability is associated with each branch and the probability of each outcome is the products of the probabilities at each branch leading to them:

\[ P(A_j) = \prod_{i=1}^{N} P(B_i) \]  

(2.3)

where \( P(A_j) \) = outcome probability; \( P(B_i) \) = branch probabilities on route to outcome; \( N \) = number of branches on route to outcome.

If the frequency of the initiating event is specified, the frequencies of the outcomes are obtained by multiplying the outcome probabilities by the initiating event frequency:

\[ F(A_j) = F \times P(A_j) \]  

(2.4)

where \( F(A_j) \) = outcome frequency; \( F \) = initiating event frequency.
FTA represents basic causes of occurrence of an unwanted event and estimates the likelihood as well as the contribution of different causes leading to the unwanted event. In FTA, the basic causes are termed basic events, and the unwanted event is called the top event. Kumamoto and Henley (2000) provide a detailed description of fault tree development and analysis for a process system. Figure 2.6 shows a fault tree analysis model of gas explosion created by Wang et al. (2013).

A gate-by-gate method can be used for quantification of the top event probability if all events are independent and there are no common-cause failures (Spouge, 1999). If the input probabilities are smaller than 0.1, the OR and AND gates are calculated as follows:

- **Figure 2.6 Fault tree analysis of explosion event (Wang et al. 2013)**
OR gate: 

\[ P(A) = \sum_{i=1}^{N} P(B_i) \]  

AND gate: 

\[ P(A) = \prod_{i=1}^{N} P(B_i) \]  

where \( P(A) \) is output event probability; \( P(B_i) \) is input event probabilities; \( N \) is the number of input events.

If the probability are larger than 0.1, gates with two independent inputs should be calculated as:

OR gate: 

\[ P(A) = P(B_1) + P(B_2) - P(B_1)P(B_2) \]  

AND gate: 

\[ P(A) = P(B_1) \times P(B_2) \]  

The two quantitative risk analysis methods reviewed are widely applied to risk analysis of oil and gas facilities. Aven et al. developed a barrier and operational risk analysis (BORA) method which used event tree and fault tree to assess leak frequency of offshore platforms. 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. Dong & 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. Ferdous et al. (2011) implemented fuzzy set theory and evidence theory into traditional event tree and fault tree analysis in order to provide a more robust method to handle the uncertainty in QRA for the process systems. Wang et al. (2013) proposed a hybrid method of fuzzy set theory and fault tree analysis to quantify the crude oil tank fire and explosion occurrence probability.

However, since ETA and FTA only have simple Boolean functions and sequentially dependent failures (Khakzad et al. 2011), it is difficult for them to reveal the complicated mechanisms of interrelationships between risk factors. Therefore, an advanced quantitative analysis method, the Bayesian network (BN), is implemented for risk assessments of explosion accidents when multi-consequences and complex interrelationships are required to be considered.
2.4.3 Bayesian Network Modelling

The BN is a probabilistic graphical model, which represents a group of random variables and conditional dependencies between them. Figure 2.7 shows an example of BN model of gas explosion events at petrol stations. Details of this method is described by Nielsen and Jensen (2009) and Pearl (2014). The calculation of BN depends on condition probability and Bayes’ Theorem.

![Bayesian network of explosion event](image)

Johnson et al. (2011) stated that, it was only meaningful to obtain a probability of an event if it had been referred to a sample space S. The notation \( P(A \mid S) \) is used to refer the probability of a specific sample space S, and it can be understood as \( P(A \mid S) \) is the conditional probability of A relative to S. If \( A \) and \( B \) are any event in \( S \) and \( P(B) > 0 \), the equation for condition probability can be written as:
\[ P(A \mid B) = \frac{P(A \cap B)}{P(B)} \]  \hspace{1cm} (2.9)

If A and B don’t have any influence on each other, A and B are defined as independent events. The multiplication rule can be written as:

\[ P(A \mid B) = P(A) \times P(B) \]  \hspace{1cm} (2.10)

If there are mutually exclusive events \( B_1, B_2, \ldots, B_n \), then one of the events must occur. According to Bayes’ theorem (Johnson, Freund & Miller 2011), the rule of total probability equation can be written as:

\[ P(A) = \sum_{i=1}^{n} P(B_i) \times P(A \mid B_i) \]  \hspace{1cm} (2.11)

The probability of a particular state can be obtained using the following equation:

\[ P(B_i \mid A) = \frac{P(A \cap B_i)}{P(A)} \]  \hspace{1cm} (2.12)

Substitute \( P(B_i) \times P(A \mid B_i) \) for \( P(A \cap B_i) \) and \( \sum_{i=1}^{n} P(B_i) \times P(A \mid B_i) \) for \( P(A) \)

\[ P(B_i \mid A) = \frac{P(B_i) \times P(A \mid B_i)}{\sum_{i=1}^{n} P(B_i) \times P(A \mid B_i) \text{ for } P(A)} \]  \hspace{1cm} (2.13)

where \( r = 1, 2, \ldots, n \).

BNs have been extensively applied to risk assessments in engineering aspects. Peng and Zhang (2012) modelled a BN to assess human risks due to dam-break floods. An application of a BN for earthquake risk management is considered by Bayraktarli et al. (2005). Zhang et al. (2014) introduced a BN-based risk analysis method in construction projects. Lee et al. (2009) presented risk management for large engineering project by using a BN and applying it to the Korean shipbuilding industry. Meanwhile, the BN is increasingly used for risk analysis of process facilities as it is flexible and well suited to taking the performance of human and organisational factors into consideration, and it offers a more precise quantitative link between risk factors (Vinnem, 2007). 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, and results proved that a BN is superior to a traditional FT model for complicated systems.
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. They concluded that a BN has greater freedom and flexibility to analyse the dependence between the different variables than a standard ET. Netherton and Stewart (2016) developed a risk-based blast-load modelling and used conditional probabilities as an analysis tool for likelihood evaluation. Pasman and Rogers (2013) implemented a BN to layer of protection analysis (LOPA) for gas risk analysis at a hydrogen tank station and found that the BN had great potential in describing scenarios, dealing with uncertainties, and supporting decision-making.

Furthermore, the Bayesian network is used in some parts of studies in this thesis when it is appropriate and it has more advantages than traditional event tree or fault tree method when evaluating vapour cloud explosion risks.

- Firstly, evaluation of gas explosion risks is complicated when multi-factors (e.g. leak severity, vent condition, structural complexity), multi-consequences (e.g. building damage, human loss, environmental effect) and complex inter-relationships are considered. Instead of traditional event tree and fault tree analysis, a Bayesian-network-based quantitative risk analysis method has better ability to deal with complicated mechanism and enables a more reliable risk analysis.

- Secondly, the BN allows a quick and simple evaluation of each risk factors which offers a clearer review of the criticality of each risk factor. Based on this kind of review, decisions of further detailed assessments and risk mitigation measures can be made more easily.

- Thirdly, it is actually easier and more intuitive for engineers to understand a BN than conventional event tree or fault tree. Meanwhile, assessments based on BN are also more efficient than that based on traditional methods.

2.5 SUMMARY

This chapter provides a detailed literature review of factors influencing explosion loads, prediction methods for explosion loads, and qualitative and quantitative analysis methods of explosion risks.

The review of risk factors which may affect the explosion severity includes the confinement and venting surrounding the gas cloud, the congestion or obstacles within the cloud, the fuel
properties and concentrations, and the ignition type and location. It is important to carefully consider those factors when gas explosion risk analysis is conducted for oil and gas facilities.

Three empirical models, the TNT equivalency model, the TNO Multi-energy model, and the Baker-Strehlow-Tang model, and three CFD codes, the FLACS model, the EXSIM model, and the AutoReaGas model, are reviewed in section 2.3. The empirical methods are able to provide an efficient overpressure prediction when the structures are not too complicated. CFD models has the capacity of dealing with complex environments. However, the time consumption is normally very large.

The risk analysis methods reviewed in this study includes both qualitative and quantitative approaches. For qualitative methods, Checklist, HAZOP, What-If analysis, HAZID, PHA, FEMA and LOPA are briefly introduced. In terms of quantitative risk analysis methods, event tree and fault tree are reviewed and a BN model is explained in detail. In this study, BN is applied more frequently than traditional qualitative and quantitative methods because BN is more suitable for dealing with the complicated inter-relationships among explosion risk factors when multi-consequences are considered.

In conclusion, there are some problems of current risk analysis to evaluate gas explosions accurately and efficiently. First, multi-factors are involved in the gas explosion risk analysis and inter-relationships among those factors are complicated. Thus, it is difficult for current risk analysis methods to analyse gas explosion risk accurately as traditional methods such as event tree or fault tree can only handle sequences with independent nodes. Meanwhile, load prediction methods are either too simplified to provide a reliable risk evaluation when complex conditions are involved, or too time consuming to enable an efficient risk analysis. Therefore, it is important for the current study to develop risk analysis methods for more accurate, efficient, detailed or reliable explosion risk evaluations.
CHAPTER 3. A BAYESIAN NETWORK-BASED QUANTITATIVE RISK ANALYSIS METHOD FOR EXPLOSION AND FIRE ACCIDENTS AT PETROL STATIONS

3.1 INTRODUCTION

This chapter introduces a more accurate explosion risk analysis method by using Bayesian network (BN) when multi-factors, multi-consequences and complex inter-relationships are considered. Traditional risk analysis methods such as event tree and fault tree can hardly be applied when complicated relationship are involved. Therefore, a Bayesian-network-based quantitative risk analysis method is developed to model explosion accidents and further consequences. Petrol station is selected as an analysis model used to illustrate the proposed Bayesian-network-based quantitative explosion risk evaluation.

For large-scale oil and gas facilities, a large amount of research has been conducted. Pula et al. (2006) suggested a grid-based approach for fire and explosion consequence analysis as well as an enhanced on-site ignition model to obtain better results in the consequence assessment process. Suardin et al. (2009) proposed a fire and explosion assessment framework (FEAF) to conduct risk screenings, options evaluations and assessment quality checks. Huang et al. (2017) developed a multilevel explosion risk analysis method for super large offshore floating liquefied natural gas facilities. However, very little research on explosion risk assessments has been conducted for small process facilities such as petrol stations probably because of the fact that consequences of accidents at service stations seem to be insignificant compared with those at large-scale oil and gas facilities.

Nevertheless, since petrol stations are located close to residential areas, not only would process facilities be damaged during an explosion event, but severe human loss may also occur because of the large population of residential areas. For example, a catastrophic fire and explosion event occurred at a petrol station as a result of a flood incident in Accra, Ghana, on June 4, 2015, and caused over 152 fatalities (Asumadu-Sarkodie et al., 2015). Another recent accident happened at Port-au-Prince, Haiti, on March 17, 2016. The fire and explosion killed 7 people and severely burned about 30 others. Therefore, developing a risk analysis method for explosion accidents at service stations is necessary. Meanwhile, fire accidents occur more frequently than explosions at petrol stations and may also cause severe consequences. For instance, an overfilling-induced spill happened in Mississippi, the USA, in August 1998, and led to a large
fire on an adjacent road and caused 5 deaths (Evarts, 2011). Therefore, a risk analysis of fire accidents based on BN is also conducted.

Explosions and fires normally happen as a consequence of a domino effect from initial accidents. Domino effect is determined to be a factor in which a sequence of events from the initial accident may occur and lead to more significant consequences. The domino effect occurs frequently in the process industry because escalations easily occur from oil and gas releases to catastrophic fire or explosion events. Abdolhamidzadeh et al. (2011) summarised 224 major domino events in the process industry, and they also found that vapour cloud fires or explosions are the most common events causing domino effects. Drabra et al. (2010) selected 225 accidents with domino effects from a wide range of data sources. Their analysis indicated that other than fire and explosion, loading/unloading operations also cause a significant number of domino accidents, and human error has been proved to be one of the main reasons of accidents. Kourniotis et al. (2000) examined a set of 207 major chemical accidents with domino effects, and they concluded that accidents involving vapour hydrocarbons are the most likely to cause domino effects, and liquid-fuel-induced domino accidents could cause the most severe fatalities.

Meanwhile, studies have been conducted to analyse the domino effects of accidents in the process industry. Abdolhamidzadeh et al. (2010) developed an algorithm named FREEDOM (FREquency Estimation of DOMino accidents) to evaluate the domino effects of highly complex and nonlinear systems. Cozzani et al. (2005) proposed a quantitative analysis for domino accidents to estimate individual and social risks from domino scenarios. Khan and Abbasi (2001) discussed the likelihood of domino events and developed a domino effect analysis method for risk assessments of domino accidents.

To model complicated mechanisms caused by domino effects, a Bayesian-network-based (BN) QRA is developed in this chapter because of the ability of the BN to deal with complex interrelationships between risk factors. The BN is a probabilistic graphical model which 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.

However, the accuracy of BN modelling is limited by the difficulty of finding sufficient data. Thus, three kinds of data, namely, practical information, computational simulations, and
subjective logical judgments, are included in the proposed study to improve the reliability and accuracy of the proposed method. Practical information includes historical data regarding basic risk factors, for instance, leak frequencies, ignition sources, and specific site information. The numerical software, PHAST (DNV GL, 2016), is used to simulate explosions and jet fires with different leak scenarios and output thermal radiations as input data for the BN analysis of fire risks. Subjective logical judgments are applied when no data can be found. Such judgments are useful for deciding conditional dependencies when the logic between nodes is easy to define.

Moreover, the current study focuses on the risk assessment of explosion and fire accidents during the refuelling process from a fuel tanker to a petrol station. This scenario is selected because a tanker stores a large quantity of flammable materials, which may cause significant consequences if a second tanker fire or explosion occurs as a domino effect of an initial accident. Both BN analyses of explosion and fire risks are conducted in this chapter.

3.2 BAYESIAN NETWORK ANALYSIS OF EXPLOSION RISKS

The proposed method consists of the following steps:

- Modelling: Model BN based on risk factors and their interrelationships.
- Quantification: Find data to quantify the established BN.
- Calculation: Calculate the probabilities of target nodes of BN.

3.2.1 Bayesian network model of explosion events

A Bayesian network is an illustrative diagram which contains nodes and links with conditional probabilities. As shown in Figure 3.1, a Bayesian network is built to evaluate risks of explosions and loss of life when a leak occurs at petrol stations. The network consists of 14 nodes and 18 links which describe risks of leaks, explosions and further consequences. Nodes and states of each node are listed in Table 3.1.
Figure 3.1 Proposed BN for explosion risks

Table 3.1 Nodes and states of the proposed BN

<table>
<thead>
<tr>
<th>Node</th>
<th>Name</th>
<th>No.</th>
<th>States</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Release scenario</td>
<td>5</td>
<td>Overfill, misconnect, hose rupture, coupling failure, vapour recovery</td>
</tr>
<tr>
<td>B</td>
<td>Leak severity</td>
<td>3</td>
<td>Major, moderate, minor</td>
</tr>
<tr>
<td>C</td>
<td>Ignition source</td>
<td>8</td>
<td>Smoking, arcing, hot ember or ash, spark or flame, unclassified heat,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>static discharge, friction, lightning</td>
</tr>
<tr>
<td>D</td>
<td>Ignition</td>
<td>2</td>
<td>Yes, no</td>
</tr>
<tr>
<td>E</td>
<td>Initial explosion</td>
<td>4</td>
<td>Major, medium, minor, no</td>
</tr>
<tr>
<td>F</td>
<td>Leak rate</td>
<td>3</td>
<td>Major, moderate, minor</td>
</tr>
<tr>
<td>G</td>
<td>Fire</td>
<td>4</td>
<td>Major, medium, minor, no</td>
</tr>
<tr>
<td>H</td>
<td>Tanker explosion</td>
<td>2</td>
<td>Yes, no</td>
</tr>
<tr>
<td>I</td>
<td>Building damage</td>
<td>4</td>
<td>Major, medium, minor, no</td>
</tr>
<tr>
<td>J</td>
<td>Evacuation time</td>
<td>3</td>
<td>Sufficient, short, little</td>
</tr>
<tr>
<td>K</td>
<td>Evacuation</td>
<td>2</td>
<td>Evacuated, shelter in store, failed</td>
</tr>
<tr>
<td>L</td>
<td>Time of day</td>
<td>5</td>
<td>8:00–9:00 a.m., 9:00 a.m.–4:00 p.m., 4:00–5:00 p.m., 5:00–10:00 p.m.,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10:00 p.m.–8:00 a.m.</td>
</tr>
<tr>
<td>M</td>
<td>No. of people in station</td>
<td>3</td>
<td>High, medium, low</td>
</tr>
<tr>
<td>N</td>
<td>Human loss</td>
<td>4</td>
<td>Major, medium, minor, no</td>
</tr>
</tbody>
</table>
3.2.2 Quantification of Bayesian network

The quantification of the BN has two parts: finding the probabilities of the basic nodes and determining the conditional probabilities of the interrelationship between nodes. Quantification based on historical statistical data is the most convenient and reliable way. A total of 27 cases of explosion accidents at service stations are selected and recorded as quantification data, as listed in Table 3.2.

<table>
<thead>
<tr>
<th>No.</th>
<th>Year</th>
<th>Time</th>
<th>Location</th>
<th>DESCRIPTION</th>
<th>Death</th>
<th>Injury</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2015</td>
<td>1800</td>
<td>Riverton, Australia</td>
<td>Explosion of gas cylinders caused major fire</td>
<td></td>
<td></td>
<td>ABC News, 2015</td>
</tr>
<tr>
<td>2</td>
<td>2015</td>
<td>2200</td>
<td>Accra, Ghana</td>
<td>Flood-swept fuel to nearby fire caused explosion</td>
<td>152</td>
<td></td>
<td>Asumadu-Sarkodie et al., 2015</td>
</tr>
<tr>
<td>3</td>
<td>2016</td>
<td>1751</td>
<td>Kaduna, Nigeria</td>
<td>Fire ignited and escalated over 3 hours while tanker discharged</td>
<td>3</td>
<td></td>
<td>Daily Post, 2016</td>
</tr>
<tr>
<td>4</td>
<td>2015</td>
<td>1240</td>
<td>Al-Ghubra, Oman</td>
<td>Car caught fire while fuelling</td>
<td>2</td>
<td></td>
<td>Times of Oman, 2015</td>
</tr>
<tr>
<td>5</td>
<td>2009</td>
<td>1345</td>
<td>Maddington, Australia</td>
<td>Tanker caught fire and exploded while discharged</td>
<td></td>
<td>3</td>
<td>Department of Mines and Petroleum, 2009</td>
</tr>
<tr>
<td>6</td>
<td>2015</td>
<td>1100</td>
<td>Birmingham, UK</td>
<td>Electric fan heater in retail area heated up a gas cylinder</td>
<td>4</td>
<td></td>
<td>BBC News, 2015</td>
</tr>
<tr>
<td>7</td>
<td>2016</td>
<td>1825</td>
<td>Kizlyar, Russia</td>
<td>Explosion occurred when fuel truck discharged LPG into tank</td>
<td>40</td>
<td></td>
<td>RT News, 2016</td>
</tr>
<tr>
<td>8</td>
<td>2016</td>
<td>1700</td>
<td>Port-au-Prince, Haiti</td>
<td>Fuel tanker caught fire and exploded</td>
<td>7</td>
<td>30</td>
<td>Yahoo News, 2016</td>
</tr>
<tr>
<td>9</td>
<td>2016</td>
<td>1330</td>
<td>Kuala Lumpur, Malaysia</td>
<td>Explosion caused by cell phone while filling the car</td>
<td>1</td>
<td></td>
<td>FMT News, 2016</td>
</tr>
<tr>
<td>10</td>
<td>2015</td>
<td>2100</td>
<td>Cobar, NSW</td>
<td>Truck explosion, unknown cause</td>
<td></td>
<td></td>
<td>Daily Liberal, 2015</td>
</tr>
<tr>
<td>11</td>
<td>2016</td>
<td>1540</td>
<td>Southern Khatlon, Tajikistan</td>
<td>Explosion</td>
<td>1</td>
<td>17</td>
<td>Asia-Plus, 2016</td>
</tr>
<tr>
<td>12</td>
<td>2015</td>
<td>1205</td>
<td>Vienna, Austria</td>
<td>Explosion caused by leak of acetylene</td>
<td></td>
<td></td>
<td>WJLA, 2015</td>
</tr>
<tr>
<td>No.</td>
<td>Year</td>
<td>Location</td>
<td>Event Description</td>
<td>Cause</td>
<td>References</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>------</td>
<td>---------------</td>
<td>-----------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
<td>-----------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>1989</td>
<td>Laval, France</td>
<td>UST exploded when degassing and cleaning</td>
<td></td>
<td>ARIA Technologies, 2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>1993</td>
<td>La Gueriniere, France</td>
<td>Explosion while discharging caused by an electrical switch ignition</td>
<td></td>
<td>ARIA Technologies, 2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>1997</td>
<td>Annecy, France</td>
<td>Explosion caused by welding in tank manhole</td>
<td></td>
<td>ARIA Technologies, 2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>1985</td>
<td>Compiegne, France</td>
<td>Explosion caused by worker-lit cigarette</td>
<td></td>
<td>ARIA Technologies, 2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>2003</td>
<td>Les Cheres, France</td>
<td>Car crashed into dispenser</td>
<td></td>
<td>ARIA Technologies, 2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>2004</td>
<td>Montlucon, France</td>
<td>New UST exploded while filling</td>
<td></td>
<td>ARIA Technologies, 2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>2004</td>
<td>Valleiry, France</td>
<td>Flash occurred while filling car</td>
<td></td>
<td>ARIA Technologies, 2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>2004</td>
<td>Aubigny-sur-Nere, France</td>
<td>Explosion caused by vapour leak from UST</td>
<td></td>
<td>ARIA Technologies, 2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>1958</td>
<td>Paris, France</td>
<td>UST leaked and exploded a few hours later, caused by spark from electrical switch</td>
<td></td>
<td>ARIA Technologies, 2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>2007</td>
<td>Sotteville-les-Rouen, France</td>
<td>Car fire triggered an explosion of 16 LPG cylinders, fire at the service station for 4 hours</td>
<td></td>
<td>ARIA Technologies, 2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>1999</td>
<td>Mississippi, USA</td>
<td>Tanker truck overfills and spilled 2,839 litres of fuel. The spill spread outside the catchment and reached an adjacent road and was then ignited by unknown ignition sources</td>
<td></td>
<td>Evarts, 2011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>1991</td>
<td>South Carolina, USA</td>
<td>Car crashed into pipes of two 4,000 gallons above ground fuel tanks; fire was put out after an hour</td>
<td></td>
<td>Evarts, 2011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>2014</td>
<td>New Orleans, USA</td>
<td>8,500 gallons of tanker collided with car and crashed into petrol station concrete pillar</td>
<td></td>
<td>FOX8, 2014</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>2016</td>
<td>Kuala Lumpur, Malaysia</td>
<td>Exploded during maintenance work</td>
<td></td>
<td>Channel News Asia, 2016</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>2007</td>
<td>Shanghai, China</td>
<td></td>
<td></td>
<td>ABC News, 2015</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
As can be seen from Table 3.2, for most of available cases, only fatalities, injuries or estimated economic losses are reported. Therefore, quantifying the interrelationships between nodes by using historical data only is difficult. Thus, numerical simulations and logical judgements are also applied in this study to deal with the limitation of statistic data.

DNV PHAST is used to quantify the interrelationships between leaks and consequent explosions. Conducting PHAST analysis has four steps: input data, build model, calculate and output result. These four steps are briefly introduced below, and more details about how to use PHAST can be found in the PHAST manual (DNV GL, 2016).

- Input data: including site map, weather conditions and data for explosion analysis
- Build model: select the analysis method and determine explosion scenarios
- Calculate: determine calculation scenarios and run the simulation
- Output result: which can be GIS outputs, result diagrams and reports

Besides numerical simulations, logical judgements are also applied to quantifications of interrelationships of the proposed BN. If the logical relationship between nodes is obvious and easy to determine, subjective judgements are able to provide a certain level of accuracy and reliability. However, such quantification requires regular examination, and if the site condition changes, adjustment is required to ensure that the logical relationship is updated. Meanwhile, if logical relationships are complicated and uncertain, a confidence-based method can be used to reduce the uncertainties of subjective judgements (Huang et al., 2015).

3.2.3 Calculation of Bayesian network

The subnetwork of human loss is taken as a simple illustrative example to explain the BN calculation. As shown in Figure 3.2, this subnetwork contains four nodes and three links. The severity of human loss (node N) is decided by the severity of the initial explosion (node E) and the number of people inside the petrol station (node M), which varies at different times of day (node L).
The prior probability of explosion loads can be calculated by Equation 3.1.

\[
P(N = \text{major}) = \sum_{i=1}^{4} \sum_{j=1}^{5} \sum_{k=1}^{3} P(N = \text{major}, E = E_i, L = L_j, M = M_k) \tag{3.1}
\]

where \( P \) = probability, \( N \) = human loss, \( E \) = initial explosion, \( E_i \) = states of node \( E \), \( L \) = time of day, \( L_j \) = states of node \( L \), \( M \) = number of people in station, \( M_k \) = states of node \( M \) (see Table 3.1). Based on the theorem of the Bayesian network (Nielsen & Jensen, 2009), the joint probability can be decided by Equation 3.2.

\[
P(x_1, \ldots, x_n) = \prod_{i=1}^{n} P(x_i | Pa(x_i)) \tag{3.2}
\]

where \( Pa(x_i) \) is the parent set of \( x_i \). The function remains an unconditional probability of \( P(x_i) \) if there are no parents of \( x_i \). In this subnetwork, the node of human loss has parents of evacuation and jet fire, the node of evacuation has a parent of evacuation time, and the node evacuation time has a parent of jet fire. Therefore, the following equation can be decided:

\[
P(N = \text{major}, E = E_i, L = L_j, M = M_k) = P(M = \text{major} | L = L_k, E = E_i) \times P(M = M_k | L = L_j) \times P(L = L_j) \times P(E = E_i) \tag{3.3}
\]

where the conditional probabilities are decided by the interrelationship quantification.

Figure 3.2 An example of a Bayesian network
3.2.4 Case Study – Quantifications

A case study is conducted to illustrate the proposed method and explain the quantification process in detail. Figure 3.3 shows an example GIS map of a petrol station in Australia. An explosion accident occurred in this petrol station when a tanker was refuelling the station. Therefore, this site is selected as an example to demonstrate the proposed method. The refuelling area is shaded in Figure 3.3, and the bund size is about 4 m × 6 m. In the case study, each node of the proposed BN will be described and quantification will be introduced.

![Figure 3.3 Target petrol station and shaded refuelling area](image)

Quantification of Release Scenario

Table 3.3 shows 18 cases of spill incidents during the refuelling processes from fuel tankers to petrol stations. These cases were collected from dangerous goods incident reports of Western Australia between 1996 and 2008 (Department of Minerals and Energy, 1996;1998–2000; Department of Consumer and Employment Protection, 2000; 2002; 2004; 2006; Department of Mines and Petroleum, 2008). The probability of each scenario can be decided according to the 18 cases as shown in Table 3.4. This case study is an illustrative example of the proposed method. Thus, only 18 cases are selected to quantify leak scenarios. The more data are acquired, the more accurate and reliable evaluation the BN is able to provide.
Table 3.3 Cases of spills

<table>
<thead>
<tr>
<th>No.</th>
<th>Year</th>
<th>Location</th>
<th>Volume of Spill</th>
<th>Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1996</td>
<td>Dardanup</td>
<td>40</td>
<td>Misconnection</td>
</tr>
<tr>
<td>2</td>
<td>1998</td>
<td>Coolgardie</td>
<td>200</td>
<td>Overfilling</td>
</tr>
<tr>
<td>3</td>
<td>1998</td>
<td>Bussendean</td>
<td>22</td>
<td>Misconnection</td>
</tr>
<tr>
<td>4</td>
<td>1998</td>
<td>Kalgoorlie</td>
<td>315</td>
<td>Coupling failure</td>
</tr>
<tr>
<td>5</td>
<td>1998</td>
<td>Jarrahdale</td>
<td>70</td>
<td>Coupling failure</td>
</tr>
<tr>
<td>6</td>
<td>1998</td>
<td>Moora</td>
<td>80</td>
<td>Misconnection</td>
</tr>
<tr>
<td>7</td>
<td>1999</td>
<td>Swanbourne</td>
<td>50</td>
<td>Vapour recovery</td>
</tr>
<tr>
<td>8</td>
<td>1999</td>
<td>Upper Swan</td>
<td>50</td>
<td>Misconnection</td>
</tr>
<tr>
<td>9</td>
<td>2000</td>
<td>Australind</td>
<td>50</td>
<td>Overfilling</td>
</tr>
<tr>
<td>10</td>
<td>2000</td>
<td>Geraldton</td>
<td>300</td>
<td>Hose rupture</td>
</tr>
<tr>
<td>11</td>
<td>2002</td>
<td>Mt. Pleasant</td>
<td>No record</td>
<td>Overfilling</td>
</tr>
<tr>
<td>12</td>
<td>2002</td>
<td>Dampier Port</td>
<td>No record</td>
<td>Overfilling</td>
</tr>
<tr>
<td>13</td>
<td>2002</td>
<td>North Dandalup</td>
<td>750</td>
<td>Misconnection</td>
</tr>
<tr>
<td>14</td>
<td>2004</td>
<td>Canning Vale</td>
<td>20</td>
<td>Misconnection</td>
</tr>
<tr>
<td>15</td>
<td>2004</td>
<td>Kwinana</td>
<td>5000</td>
<td>Hose rupture</td>
</tr>
<tr>
<td>16</td>
<td>2006</td>
<td>Rivervale</td>
<td>No record</td>
<td>Overfilling</td>
</tr>
<tr>
<td>17</td>
<td>2006</td>
<td>Christmas Island</td>
<td>400</td>
<td>Overfilling</td>
</tr>
<tr>
<td>18</td>
<td>2008</td>
<td>Collie</td>
<td>8400</td>
<td>Hose rupture</td>
</tr>
</tbody>
</table>

Table 3.4 Probabilities of release scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
<th>Number</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overfill</td>
<td>Gauging error, driver over fill underground storage tank</td>
<td>6</td>
<td>33.33%</td>
</tr>
<tr>
<td>Misconnection</td>
<td>Driver error</td>
<td>6</td>
<td>33.33%</td>
</tr>
<tr>
<td>Hose rupture</td>
<td>Mechanical failure of the unloading hose</td>
<td>3</td>
<td>16.67%</td>
</tr>
<tr>
<td>Coupling failure</td>
<td>Result in disconnection of unloading hose</td>
<td>2</td>
<td>11.11%</td>
</tr>
<tr>
<td>Vapour recovery</td>
<td>Stage 1 vapour recovery connection propped open</td>
<td>1</td>
<td>5.56%</td>
</tr>
</tbody>
</table>

**Quantification of Leak Severity**

The probabilities of leak severities are classified into three categories: outside catchment, inside catchment and inside cesspit. Figure 3.4 describes an example of a catchment of fill points. Major spill is determined when the spill reaches outside the catchment, while minor spill is determined when the spill can be held inside the cesspit.
The size of the catchment at the target site is approximately $6 \text{ m} \times 4 \text{ m}$ based on the measurement from the GIS map, and the height of the bund is about 50 mm. The size of a typical cesspit is about 200 L, and the specific size of the cesspit at the target site cannot be determined. Therefore, for a conservative estimate, the cesspit is assumed to be able to contain 120 litres of spill, which is about 10% of the total volume of the catchment. Consequently, the severity of the 15 cases of spills can be determined as shown in Table 3.5. In Table 3.5, if the height is lower than the height of the cesspit, the spill is defined as minor. When the height is lower or higher than the height of the catchment, the spill is then to be decided as medium or major respectively.

**Table 3.5 Classification of severity of spills**

<table>
<thead>
<tr>
<th>Volume of Spill</th>
<th>Scenario</th>
<th>Height of Spill (mm)</th>
<th>Major</th>
<th>Medium</th>
<th>Minor</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>Misconnection</td>
<td>1.67</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>200</td>
<td>Overfilling</td>
<td>8.33</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Misconnection</td>
<td>0.92</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>315</td>
<td>Coupling failure</td>
<td>13.13</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>Coupling failure</td>
<td>2.92</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>80</td>
<td>Misconnection</td>
<td>3.33</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Vapour recovery</td>
<td>2.08</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Misconnection</td>
<td>2.08</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Overfilling</td>
<td>2.08</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>Hose rupture</td>
<td>12.50</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>750</td>
<td>Misconnection</td>
<td>31.25</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Misconnection</td>
<td>0.83</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>5000</td>
<td>Hose rupture</td>
<td>208.33</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>Overfilling</td>
<td>16.67</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8400</td>
<td>Hose rupture</td>
<td>350.00</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Quantification of Ignition Sources**

As for the basic node of ignition sources, the most common heat sources ignited at the service stations in the USA from 2004 to 2008 are displayed in Table 3.6 (Evarts, 2011). The result indicates that smoking and heat generated from power equipment have the highest probability.

<table>
<thead>
<tr>
<th>Ignition Source</th>
<th>Abbreviation</th>
<th>Cases</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smoking</td>
<td>S</td>
<td>160</td>
<td>21.3%</td>
</tr>
<tr>
<td>Arcing</td>
<td>A</td>
<td>90</td>
<td>12%</td>
</tr>
<tr>
<td>Hot ember or ash</td>
<td>HE</td>
<td>140</td>
<td>18.7%</td>
</tr>
<tr>
<td>Spark or flame from operating equipment</td>
<td>SF</td>
<td>70</td>
<td>9.3%</td>
</tr>
<tr>
<td>Unclassified heat from powered equipment</td>
<td>UH</td>
<td>180</td>
<td>24%</td>
</tr>
<tr>
<td>Static discharge</td>
<td>SD</td>
<td>40</td>
<td>5.3%</td>
</tr>
<tr>
<td>Heat or spark from friction</td>
<td>F</td>
<td>60</td>
<td>8%</td>
</tr>
<tr>
<td>Lighting</td>
<td>L</td>
<td>10</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

**Table 3.6 Heat sources at a service station ignited from 2004 to 2008**

**Quantification of Ignition**

The number of ignition sources is used to determine the probability of ignitions, and it depends on the size of spills. If the spill spreads outside the catchment, the chance of reaching ignition sources is higher. Therefore, the incident of the spill spreading outside the catchment is assigned with all the possible ignition sources, while the ignition sources of the spill incident inside the catchment may be ignited by S, A, HE, SD or L. Meanwhile, only S, SD and L are considered for minor spills because only they can reach spills inside the cesspit. The probability of each source being ignited is determined to be 90% when it presents inside the spill range and 10% when it is located outside.

**Quantification of Initial Explosion**

Release-related initial explosions are simulated by DNV PHAST under 15 leak severities. In this study, wind effects such as wind directions and wind speeds are not considered. Therefore, the explosive cloud is assumed to spread from the leak point. The Baker-Strehlow-Tang model is selected in conducting the explosion analysis. A medium level of obstacle density and fuel reactivity is determined based on the specific condition of the target station. Table 3.7 lists the
results of PHAST analysis, and Figure 3.5 shows an example of a PHAST output of an explosion range of 0.689 bar when 400 litres of petrol spills.

To determine the severity of an explosion, an overpressure of 0.689 bar is used as an indicator because such overpressure can cause direct death or severe injury because of the blast loads and complete structure destructions (Lobato et al., 2009). If an area with overpressure higher than 0.689 bar reaches the nearest dispenser (about 10 m) and the store area (20 m), the severity is decided as medium and major, respectively. The severities of explosions are classified in Table 3.7.

### Table 3.7 Classification of severities of initial explosion

<table>
<thead>
<tr>
<th>Spill Severity (L)</th>
<th>Distance of 0.689 Bar (m)</th>
<th>Explosion Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Major</td>
</tr>
<tr>
<td>40</td>
<td>7.8</td>
<td>✔</td>
</tr>
<tr>
<td>200</td>
<td>13.33</td>
<td>✔</td>
</tr>
<tr>
<td>22</td>
<td>6.39</td>
<td></td>
</tr>
<tr>
<td>315</td>
<td>15.51</td>
<td>✔</td>
</tr>
<tr>
<td>70</td>
<td>9.4</td>
<td>✔</td>
</tr>
<tr>
<td>80</td>
<td>9.82</td>
<td>✔</td>
</tr>
<tr>
<td>50</td>
<td>8.4</td>
<td>✔</td>
</tr>
<tr>
<td>50</td>
<td>8.4</td>
<td>✔</td>
</tr>
<tr>
<td>300</td>
<td>15.14</td>
<td>✔</td>
</tr>
<tr>
<td>750</td>
<td>20.55</td>
<td>✔</td>
</tr>
<tr>
<td>20</td>
<td>6.19</td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td>38.82</td>
<td>✔</td>
</tr>
<tr>
<td>400</td>
<td>16.67</td>
<td>✔</td>
</tr>
<tr>
<td>8400</td>
<td>46.35</td>
<td>✔</td>
</tr>
</tbody>
</table>

Figure 3.5 Circled area of an explosion range of 0.689 bar when 400 litres of petrol spills
Quantification of Leak Rate

Leak rate is necessary for jet fire analysis, and it can be calculated based on the leak volume and time. Since no specific data of leak time for each case can be found, leak times of 60 and 300 s are used to calculate the leak rate according to the assumption that the driver has a range of react time of 60 to 300 s to stop the spill because the driver may not realise the leak immediately. For the 15 cases with recorded spill volumes, 300 s is a more reasonable assumption because, normally, only a severe spill with a longer leak time will be recorded. However, 60 s is also applied to provide another set of data of leak rates to conduct a more conservative evaluation.

Based on the assumption of 60 and 300 s of leak time, 30 leak rates can be calculated as listed in Table 3.8. According to HSE (2015), the severity of the leak rate can be considered major when the leak rate for a liquid is more than 10 kg/s and minor when the leak rate is less than 0.2 kg/s. The density of normal gasoline is approximately 0.71 kg/l. Thus, Table 3.9 indicates the severities of leak rates after calculation.

<table>
<thead>
<tr>
<th>Volume of Spill (litre)</th>
<th>Leak Rate (litre/s)</th>
<th>60 s</th>
<th>300 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.67</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>3.33</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>0.37</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>315</td>
<td>5.25</td>
<td>1.05</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>1.17</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>1.33</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.83</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.83</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.83</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>5.00</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>750</td>
<td>12.50</td>
<td>2.50</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.33</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td>83.33</td>
<td>16.67</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>6.67</td>
<td>1.33</td>
<td></td>
</tr>
<tr>
<td>8400</td>
<td>140.00</td>
<td>28.00</td>
<td></td>
</tr>
</tbody>
</table>
Table 3.9 Severities of leak rates

<table>
<thead>
<tr>
<th>Leak Rate Severity</th>
<th>Leak Rate (l/s)</th>
<th>Number of Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major</td>
<td>14.08–</td>
<td>4</td>
</tr>
<tr>
<td>Moderate</td>
<td>0.28–14.08</td>
<td>18</td>
</tr>
<tr>
<td>Minor</td>
<td>0–0.28</td>
<td>8</td>
</tr>
</tbody>
</table>

Quantification of Jet Fire

In this study, fire severity is assumed to only affect the probabilities of tanker explosion, and evacuation conditions and fire-induced fatality or injury are not considered. For the interrelationship between leak rates and jet fires, a numerical simulation using PHAST is also applied. Jet fires are calculated and quantified based on 30 leak rates as listed in Table 3.8.

Figure 3.6 shows the PHAST GIS output of the effect zone of a thermal radiation of 2 kW/m² when the total volume of release is 20 litres and the leak time is 60 s. Minor injury, major injury or fatality may occur based on the distance from the fire centre to the edge of the circled region as shown in Figure 3.6. According to the Federal Emergency Management Agency (1990), people may suffer severe pain or second-degree burn if they are exposed to a thermal radiation of 2 kW/m² for over 45 or 187 s, respectively. People who stay outside the circled region may have around 1 minute of evacuation time, which is assumed to be sufficient for people to seek shelter or escape. Therefore, the region outside the circled area is considered a relatively ‘safety zone. Details of distances of jet fires with a 2 kW/m² thermal radiation based on 30 release rates is listed in Table 3.10.

Figure 3.6 Circled area of a thermal radiation of 2 kW/m²

51
The severities of fire are determined based on the sizes of specific sites. In this case study, the size of this site is 40 m × 32 m, and the refuel points are located at the edge of the site. Therefore, the classification of the severity of the jet fire is shown in Table 3.11. Major fire is determined when fire covers the retail shop area, while moderate fire is considered when more than half of the dispenser area is affected. Minor fire is determined when less than half of the dispenser area is influenced. According to this classification, 4 of the 15 cases are major fire, 7 are moderate and 4 are minor.

### Table 3.10 Severities of jet fires

<table>
<thead>
<tr>
<th>Volume of Spill</th>
<th>Jet Fire Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60 s</td>
</tr>
<tr>
<td>40</td>
<td>23.49</td>
</tr>
<tr>
<td>200</td>
<td>48.88</td>
</tr>
<tr>
<td>20</td>
<td>17.89</td>
</tr>
<tr>
<td>315</td>
<td>60.1</td>
</tr>
<tr>
<td>70</td>
<td>30.31</td>
</tr>
<tr>
<td>80</td>
<td>32.22</td>
</tr>
<tr>
<td>50</td>
<td>26.01</td>
</tr>
<tr>
<td>50</td>
<td>26.01</td>
</tr>
<tr>
<td>50</td>
<td>26.01</td>
</tr>
<tr>
<td>300</td>
<td>58.78</td>
</tr>
<tr>
<td>750</td>
<td>89.11</td>
</tr>
<tr>
<td>20</td>
<td>17.13</td>
</tr>
<tr>
<td>5000</td>
<td>210.28</td>
</tr>
<tr>
<td>400</td>
<td>66.99</td>
</tr>
<tr>
<td>8400</td>
<td>265.71</td>
</tr>
</tbody>
</table>

### Table 3.11 Classifying the severity of the tanker fire distance

<table>
<thead>
<tr>
<th>Jet fire severity</th>
<th>Fire Distance (m)</th>
<th>No. of cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major</td>
<td>&gt; 34</td>
<td>10</td>
</tr>
<tr>
<td>Moderate</td>
<td>&gt; 16</td>
<td>12</td>
</tr>
<tr>
<td>Minor</td>
<td>&lt; 16</td>
<td>8</td>
</tr>
</tbody>
</table>

**Quantification of Tanker Explosion**

For a fire-induced tanker explosion, the proposed BN considers the effectiveness of a safety barrier in preventing or delaying the escalation of fire to the fuel tanker. The activation of the safety barrier relies on the tanker outlet valves as shown in Figure 3.7. In the case of major jet
fire, the effectiveness of the safety barrier is limited even if the barrier is activated successfully because of the high thermal radiation, which can cause rupture of the tanker’s vessels in a very short period of time. Meanwhile, accessing and activating the lever valve may not be safe for the driver if moderate or major jet fires occur. The barrier has a high chance of being activated in case of minor fire because the driver has more time to turn off the lever valve safely. Table 3.12 indicates the conditional probabilities of the tanker driver activating the lever valve successfully.

![Figure 3.7 Typical tanker outlet valve in an open position (Department of Mines and Petroleum, 2009b)](image)

Table 3.12 Conditional probabilities of barrier

<table>
<thead>
<tr>
<th>Jet Fire Intensity radii</th>
<th>Active Safety Barrier</th>
<th>Tanker Explosion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Failed</td>
<td>Succeeded</td>
</tr>
<tr>
<td>High</td>
<td>99</td>
<td>1</td>
</tr>
<tr>
<td>Medium</td>
<td>80</td>
<td>20</td>
</tr>
<tr>
<td>Low</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>No</td>
<td>0</td>
<td>100</td>
</tr>
</tbody>
</table>

When the active barrier fails to be activated, a tanker explosion is assumed to be triggered. The severity of a tanker explosion is determined by the number of affected compartments. In Australia, a typical fuel tanker consists of six compartments, which store different types of fuel products. The more compartments are influenced, the more severe is the explosion. However, in this study, the severity of a tanker explosion remains major because the minimum size of a single compartment contains 5700 L of petrol. Figure 3.8 shows an explosion with an overpressure of 0.689 bar when only one compartment of gasoline release is ignited, which can be seen to lead to a major explosion affecting the whole target site. Therefore, for tanker fire
quantification, only statements of ‘yes’ or ‘no’ are determined; ‘yes’ refers to major severity of explosion.

Figure 3.8 Circled area of a tanker explosion range of 0.689 bar

Quantification of Evacuation Time and Evacuation

Evacuation is assumed to be impossible when explosion is triggered because explosion normally occurs within a very short period of time in which people are not able to escape. Therefore, for release-induced explosion, evacuation is considered failed since people are assumed to be unaware of the release until it is ignited and explodes. However, for fire-induced explosion, evacuation before the fire reaches the tanker is possible. The time of evacuation is assumed to be influenced by the fire severity. Consequently, successful evacuation depends on the time of evacuation. Their relationships are illustrated in Table 3.13 and 3.14.

Table 3.13 Interrelationship between jet fire and evacuation time

<table>
<thead>
<tr>
<th>Fire</th>
<th>Evacuation Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sufficient</td>
</tr>
<tr>
<td>Major</td>
<td>0</td>
</tr>
<tr>
<td>Medium</td>
<td>10</td>
</tr>
<tr>
<td>Minor</td>
<td>70</td>
</tr>
</tbody>
</table>

Table 3.14 Interrelationship between Evacuation time and evacuation

<table>
<thead>
<tr>
<th>Evacuation Time</th>
<th>Evacuation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Succeed</td>
</tr>
<tr>
<td>Sufficient</td>
<td>80</td>
</tr>
<tr>
<td>Short</td>
<td>40</td>
</tr>
<tr>
<td>Little</td>
<td>10</td>
</tr>
</tbody>
</table>
Quantification of Time of Day and Number of People

Quantifying the number of people depends on the time of day as the number of people at petrol stations varies throughout the day. The time of day is classified into five categories. A total of 22 cases are recorded in Table 3.2 with detailed accident times. Table 3.15 shows the probabilities of times when explosion occurred during a day.

**Table 3.15 Hours of explosion at a service station**

<table>
<thead>
<tr>
<th>Hours</th>
<th>Cases</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:00–10:00 a.m.</td>
<td>1</td>
<td>4.6%</td>
</tr>
<tr>
<td>10:00 a.m.–4:00 p.m.</td>
<td>11</td>
<td>50%</td>
</tr>
<tr>
<td>4:00–7:00 p.m.</td>
<td>5</td>
<td>22.7%</td>
</tr>
<tr>
<td>7:00–10:00 p.m.</td>
<td>2</td>
<td>9.1%</td>
</tr>
<tr>
<td>10:00 p.m.–8:00 a.m.</td>
<td>3</td>
<td>13.6%</td>
</tr>
</tbody>
</table>

The peak hours during the day are 8:00–10:00 a.m. and 4:00–7:00 p.m., while the quietest hours are at night from 10:00 p.m. to 8:00 a.m. The target site has eight dispensers and customers can use both sides of each dispenser to refuel their cars, which means 16 customers can refuel in the same time. Throughout the observations of petrol stations with similar sizes, two car waiting in the queue is quite normal at the peak time. Therefore, the customer number is then decided to be 16 refueling and 16 queueing. The number of staff members is reduced to two people during a normal period and one person during night time. The fuel tanker driver is always counted as one person. The total number of people in the service station is considered high, medium or low as shown in Table 3.16.

**Table 3.16 Number of people in the service station at different times of day**

<table>
<thead>
<tr>
<th>Hours</th>
<th>Server</th>
<th>Tanker Driver</th>
<th>Customers</th>
<th>Queue</th>
<th>Total</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:00–10:00 a.m.</td>
<td>3</td>
<td>1</td>
<td>16</td>
<td>16</td>
<td>36</td>
<td>High</td>
</tr>
<tr>
<td>10:00 a.m.–4:00 p.m.</td>
<td>2</td>
<td>1</td>
<td>12</td>
<td>0</td>
<td>15</td>
<td>Medium</td>
</tr>
<tr>
<td>4:00–7:00 p.m.</td>
<td>3</td>
<td>1</td>
<td>16</td>
<td>20</td>
<td>40</td>
<td>High</td>
</tr>
<tr>
<td>7:00–10:00 p.m.</td>
<td>2</td>
<td>1</td>
<td>12</td>
<td>0</td>
<td>15</td>
<td>Medium</td>
</tr>
<tr>
<td>10:00 p.m.–8:00 a.m.</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>0</td>
<td>6</td>
<td>Low</td>
</tr>
</tbody>
</table>

Quantification of Building Damage

The store area of the target station is a single-storey structure. According to CCPS (2010), overpressure of over 35 and 17 kPa will cause severe and moderate building damages. Therefore, the severity of building damages is determined based on the explosion overpressures.
at the centre of the retail store as listed in Table 3.17. Table 3.17 also shows the classification of building damage.

<table>
<thead>
<tr>
<th>Spill Severity (L)</th>
<th>Overpressures (kPa) at Store Centre</th>
<th>Building Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Major (&gt;35 kPa)</td>
</tr>
<tr>
<td>40</td>
<td>20.48</td>
<td>✓</td>
</tr>
<tr>
<td>200</td>
<td>33.9</td>
<td>✓</td>
</tr>
<tr>
<td>22</td>
<td>16.19</td>
<td></td>
</tr>
<tr>
<td>315</td>
<td>38.4</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>24.82</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>25.9</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>22.18</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>22.18</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>37.9</td>
<td></td>
</tr>
<tr>
<td>750</td>
<td>48.29</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>15.55</td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td>72.33</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>40.95</td>
<td></td>
</tr>
<tr>
<td>8400</td>
<td>76.54</td>
<td></td>
</tr>
</tbody>
</table>

**Quantification of Human Loss**

As mentioned, fire-induced human loss is not considered in this study. Therefore, human loss is calculated based on two aspects, which are people inside a dangerous explosion range and people who shelter inside the retail store. People who are inside the affected range and are not able to escape quickly will sustain serious injury or fatality directly from the explosion, while the risk of people who evacuate to the store depends on the building damage. Therefore, the severity of human loss is determined by the number of people present in the service station, the evacuation situation and the explosion severity and is classified as either major, medium, minor or none.

**3.2.5 Case study – Calculation and Discussion**

After the quantification of basic nodes and interrelationships between nodes, human loss can be estimated for a specific site based on the equation introduced in Section 3.2.3. The final results are shown in Figure 3.9.
Figure 3.9 shows that when a release occurs, the probability of an explosion is about 3.1%, and the possibility of further human loss is about 2.7%, which means that when an explosion occurs, the probability of human loss is very high. Meanwhile, if human loss occurs, major human loss takes a large percentage (2.3%), while possibilities of medium and minor losses are only 0.3% and 0.1%, respectively. This result indicates that explosion accidents inside service stations may result in significant consequences.

Meanwhile, sensitivity studies on basic nodes and tanker explosion are also conducted in this study. The proposed BN has three basic nodes: ignition source, release scenario and time of day. To conduct a sensitivity study, each state of every basic node is assumed to occur with a probability of 100%, while the probabilities of other states are determined to be 0%.

First, Table 3.18 indicates that the ignition sources SF, UH and F may cause human loss with a probability of only about 0.6%. This happens because SF, UH and F are normally located outside the catchment where only a major spill may reach. On the contrary, S, SD and L lead to the rise of the probabilities of human loss by about 4.6% because these three ignition sources
are able to ignite a spill anywhere at the service station. In the meantime, S takes a very large percentage (21.3%) of total probability among ignition sources, while SD and L only take 5.3% and 1.4%, respectively. Therefore, smoking is determined to be the most dangerous ignition source at petrol stations and should be totally banned.

**Table 3.18 Sensitivity study on ignition sources**

<table>
<thead>
<tr>
<th>Ignition Source</th>
<th>Abbreviation</th>
<th>Human Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Major</td>
</tr>
<tr>
<td>Smoking</td>
<td>S</td>
<td>4.56</td>
</tr>
<tr>
<td>Arcing</td>
<td>A</td>
<td>2.52</td>
</tr>
<tr>
<td>Hot ember or ash</td>
<td>HE</td>
<td>2.52</td>
</tr>
<tr>
<td>Spark or flame</td>
<td>SF</td>
<td>0.58</td>
</tr>
<tr>
<td>Unclassified heat</td>
<td>UH</td>
<td>0.58</td>
</tr>
<tr>
<td>Static discharge</td>
<td>SD</td>
<td>4.56</td>
</tr>
<tr>
<td>Friction</td>
<td>F</td>
<td>0.58</td>
</tr>
<tr>
<td>Lightning</td>
<td>L</td>
<td>4.56</td>
</tr>
</tbody>
</table>

Second, the results in Table 3.19 show that the release scenario of hose rupture causes the most catastrophic consequences by causing a 4.43% major human loss. As to the other four release scenarios, the probabilities of human loss are slightly lower when overfilling or coupling failure dominates, while the probabilities decrease significantly if only misconnection or vapour recovery occurs. Table 3.19 also lists the frequency of each release scenario from AcuTech Consulting Group (2014) and indicates that overfilling is the most frequent scenario. Therefore, as the most frequently occurring and the most destructive release scenarios, overfilling and hose rupture should be paid more attention when the tanker driver conducts the refuelling job.

**Table 3.19 Sensitivity study on release scenarios**

<table>
<thead>
<tr>
<th>Release Scenario</th>
<th>Frequency per Year</th>
<th>Human Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Major</td>
</tr>
<tr>
<td>Overfill</td>
<td>$10^{-1}$</td>
<td>2.34</td>
</tr>
<tr>
<td>Misconnect</td>
<td>$10^{-3}$</td>
<td>1.44</td>
</tr>
<tr>
<td>Hose rupture</td>
<td>$10^{-5}$</td>
<td>4.43</td>
</tr>
<tr>
<td>Coupling failure</td>
<td>$10^{-3}$</td>
<td>2.04</td>
</tr>
<tr>
<td>Vapour recovery</td>
<td>$10^{-3}$</td>
<td>1.14</td>
</tr>
</tbody>
</table>

The basic nodes of time of day only affect the severities of human losses. From Table 3.20, one can conclude that there is not much difference among times during daytime. However, the probability of major human loss decreases by about 1% at night because of the relatively small number of customers. Thus, the refuelling job can be moved to night time if possible.

58
Table 3.20 Sensitivity study on time of day

<table>
<thead>
<tr>
<th>Time of Day</th>
<th>Human Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Major</td>
</tr>
<tr>
<td>8:00–10:00 a.m.</td>
<td>2.55</td>
</tr>
<tr>
<td>10:00 a.m.–4:00 p.m.</td>
<td>2.32</td>
</tr>
<tr>
<td>4:00–7:00 p.m.</td>
<td>2.55</td>
</tr>
<tr>
<td>7:00–10:00 p.m.</td>
<td>2.32</td>
</tr>
<tr>
<td>10:00 p.m.–8:00 a.m.</td>
<td>1.64</td>
</tr>
</tbody>
</table>

One more sensitivity study focuses on fire-induced tanker explosion. Figure 3.10 demonstrates that the total human loss remains the same without consideration of tanker explosion, while major human loss decreases significantly from approximately 2.3% to 1.6%. Thus, operators should pay more attention to the refilling process so that preventive actions can be done as soon as possible for risk reduction of tanker explosions.
3.3 BAYESIAN NETWORK ANALYSIS OF FIRE RISKS

As mentioned, since the fire accidents are frequent to happen and can cause severe consequences, a BN analysis of fire risks is conducted in this section.

3.3.1 Bayesian Network Modelling

Figure 3.11 shows a Bayesian network built to evaluate the risks of fires and loss of life when leaks occur on site. The network consists of 13 nodes and 15 links, which describe the risks of petrol leaks, fires, and further consequences. The nodes and their states are listed in Table 3.21.

![Figure 3.11 Proposed BN for explosion risks](image)

**Table 3.21 Nodes and states of the proposed BN**

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>No.</th>
<th>States</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Release Scenario</td>
<td>5</td>
<td>Overfilling; Misconnection; Hose rupture; Coupling failure; Vapour recovery.</td>
</tr>
<tr>
<td>B</td>
<td>Leak Severity</td>
<td>3</td>
<td>Major; Moderate; Minor.</td>
</tr>
<tr>
<td>C</td>
<td>Ignition Source</td>
<td>8</td>
<td>Smoking; Arcing; Hot ember or ash; Spark or flame; Unclassified heat; Static discharge; Friction; Lightning.</td>
</tr>
<tr>
<td></td>
<td>Description</td>
<td>Level</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>------------------------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Leak Rate</td>
<td>3</td>
<td>Major; Moderate; Minor.</td>
</tr>
<tr>
<td>E</td>
<td>Ignition</td>
<td>2</td>
<td>Yes; No.</td>
</tr>
<tr>
<td>F</td>
<td>Jet Fire</td>
<td>4</td>
<td>Major; Medium; Minor; No.</td>
</tr>
<tr>
<td>G</td>
<td>Safety Barrier</td>
<td>2</td>
<td>Yes; No.</td>
</tr>
<tr>
<td>H</td>
<td>Tank Fire</td>
<td>2</td>
<td>Yes; No.</td>
</tr>
<tr>
<td>I</td>
<td>Evacuation Time</td>
<td>3</td>
<td>Sufficient; Short; Little.</td>
</tr>
<tr>
<td>J</td>
<td>Evacuation</td>
<td>2</td>
<td>Evacuated; Failed.</td>
</tr>
<tr>
<td>K</td>
<td>Time of day</td>
<td>5</td>
<td>8 AM – 10 AM; 10 AM – 4 PM; 4 PM – 7 PM; 7 PM – 10 PM; 10 PM – 8 AM.</td>
</tr>
<tr>
<td>L</td>
<td>No. of people</td>
<td>3</td>
<td>Large; Medium; Small.</td>
</tr>
<tr>
<td>M</td>
<td>Human loss</td>
<td>4</td>
<td>Major; Medium; Minor; No.</td>
</tr>
</tbody>
</table>

### 3.3.2 Case study – Quantifications

The quantification and calculation methods of the fire BN are the same as those of the explosion BN. Therefore, they will not be introduced again. Figure 3.12 shows an example GIS map of another petrol station which is used to conduct a case study of fire risks. The selected site includes 6 petrol dispensers and a retail shop. The tanker refuelling area is circled in Figure 3.12. Some of the quantifications of fire factors are the same as those of explosion factors and only quantifications of nodes with differences will be explained.

![Figure 3.12 Target petrol station and circled refuelling area](image)

**Quantification of Leak Severity**

The size of the catchment of the target site is 5.8 m*3.4 m, and the height of the bund is 50 mm. The cesspit is designed to contain 200 litres of petrol, which account for about 20% of the...
volume of the catchment. Consequently, the severity of 15 cases of spills can be characterised as shown in Table 3.22. Meanwhile, the interrelationship between the release scenario and the severity of a spill can also be characterised.

Table 3.22 Classification of severity of spills

<table>
<thead>
<tr>
<th>Volume of Spill</th>
<th>Scenario</th>
<th>Height (mm)</th>
<th>Major</th>
<th>Medium</th>
<th>Minor</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>Misconnection</td>
<td>2.03</td>
<td></td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>Overfilling</td>
<td>10.14</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Misconnection</td>
<td>1.12</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>315</td>
<td>Coupling Failure</td>
<td>15.97</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>Coupling Failure</td>
<td>3.55</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>Misconnection</td>
<td>4.05</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Vapour Recovery</td>
<td>2.53</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Misconnection</td>
<td>2.53</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Overfilling</td>
<td>2.53</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>Hose Rupture</td>
<td>15.21</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>750</td>
<td>Misconnection</td>
<td>38.03</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Misconnection</td>
<td>1.01</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td>Hose Rupture</td>
<td>253.55</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>Overfilling</td>
<td>20.28</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8400</td>
<td>Hose Rupture</td>
<td>425.96</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Quantification of Jet Fire

Jet fire is only considered when ignition occurs. Figure 3.13 shows the PHAST GIS output of thermal radiation of 2 kW/m² when the total volume of release is 50 litres and the leak time is 300 s.

Figure 3.13 Circled area of a thermal radiation of 2 kW/m²
The severities of the fires are determined based on the sizes of specific sites. In this case study, the size of the site is 64 m \times 32 m, and the leak point is located at the centre of the target station. Therefore, Table 3.23 shows the jet fire severity classification. The jet fire is considered to be major when it covers the whole site, while it is considered to be moderate when half of the site is safe. If less than half of the site is affected by the fire, the fire is classified as minor. According to this classification, 12 of 30 cases are major fires, 10 are moderate, and 8 are minor.

<table>
<thead>
<tr>
<th>Jet fire severity</th>
<th>Fire Distance (m)</th>
<th>No. of cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major</td>
<td>32 –</td>
<td>12</td>
</tr>
<tr>
<td>Moderate</td>
<td>16 – 32</td>
<td>10</td>
</tr>
<tr>
<td>Minor</td>
<td>0 – 16</td>
<td>8</td>
</tr>
</tbody>
</table>

**Quantification of Safety Barrier and Tanker Fire**

The proposed BN considers the effectiveness of a safety barrier in preventing or delaying the escalation of the initial fire to the fuel tanker. When the barrier activation fails, a tanker fire is triggered. The severity of a tanker fire is determined by the number of affected compartments. According to the Department of Mines and Petroleum (2009b), a typical fuel tanker in Australia has a total of six compartments and normally uses a 100Ø-mm flexible discharge hose to refuel the underground storage tank. In this study, the severity of the tanker fire is major because a hose rupture is assumed to occur for a jet fire-induced tanker fire, and the hose rupture of a 100Ø-mm hose will lead to a release rate of 16.67 litres/s, which is large enough to cause a major fire. Therefore, for tanker fire quantification, only statements of “yes” or “no” are defined, and “yes” means major fire.

**Quantification of Time of Day**

Historical data regarding fire incidents at service stations is used to determine the times during which fire accidents occurred. The data is mainly obtained from yearly dangerous goods incident reports (Department of Minerals and Energy, 1996-2000; Department of Consumer and Employment Protection, 2001-2007; Department of Mines and Petroleum, 2008-2015), a report on fires at U.S. service stations (Evarts, 2011) and a report on petrol station accidents in France from 1958 to 2007 (ARIA Technologies, 2009). Table 3.24 summarises the
probabilities associated with the times when fires happen based on 50 fire accidents at the service station.

<table>
<thead>
<tr>
<th>Hours</th>
<th>Cases</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 AM – 10 AM</td>
<td>3</td>
<td>6%</td>
</tr>
<tr>
<td>10 AM – 4 PM</td>
<td>21</td>
<td>42%</td>
</tr>
<tr>
<td>4 PM – 7 PM</td>
<td>9</td>
<td>18%</td>
</tr>
<tr>
<td>7 PM – 10 PM</td>
<td>5</td>
<td>10%</td>
</tr>
<tr>
<td>10 PM – 8 AM</td>
<td>12</td>
<td>24%</td>
</tr>
</tbody>
</table>

### 3.3.3 Case study – Calculation and Discussion

After the quantification of the basic nodes and the inter-relationships between the nodes, human loss can be calculated. The final results are shown in Figure 3.14.

![Diagram of BN calculation](image-url)

**Figure 3.14 Final results of BN calculation**
From Figure 3.14, it is evident that, when release occurs, a jet fire has a probability of approximately 3% to occur and the probability of a major jet fire occurring is around 1.6%. Meanwhile, regarding human loss, there is only an approximately 2% chance that fires will endanger people at a petrol station. However, major human loss accounts for a very large percentage (1.65%), while the possibilities of medium loss and minor loss are 0.35% and 0.05%, respectively. This means that fire accidents at service stations may not always lead to human loss. However, if human loss occurs, the consequences will probably be significant.

Compared to the explosion accidents, it can be seen that the probabilities of fire and explosion remain same. This occurs because the same data of release scenarios and ignition probability is used for both case study. However, the consequence of explosion accident is much severe than that of fire events. As can be seen from Figure 3.09 and 3.14, the total human loss reduced by around 30% (from 3% to 2%) and major human loss decreased from 2.3% to 1.6%. Therefore, it can be concluded that fire accidents would be less catastrophic than explosion events, though fires can cause severe human losses.

3.4 SUMMARY

In this chapter, a more accurate quantitative risk analysis method for explosion and fire accidents at petrol stations is proposed. A Bayesian network (BN) is implemented as a risk analysis tool in this study to estimate the probabilities of initial leaks and consequent domino effects, such as ignitions, explosions, fires and human losses.

The proposed BN-based method is different from the conventional ones. It aims at building relationships between risk influencing factors and exploring the importance of basic risk factors rather than offering an annual fatality risks (AFR) number. The decision of risk reduction and mitigation can then be made based on the evaluation of risk factors. The more important a risk factor is, the more detailed risk assessment and mitigation measures should be focused on.

Two case studies of explosion and fire risks are conducted to illustrate the applicability of the proposed method. In the case study, the quantification of each node is described in detail, and results show that petrol leaks may lead to human loss such as death or injury with a probability of approximately 3% and 2% when explosion and fire occurs respectively.

Two BN models with explosion and fire risk influence factors was built to model and evaluate the risks of explosion and fire accident and human safety. The case study proved that the BN
is capable of dealing with complicated interrelationships caused by domino effects. Meanwhile, extra consequences or risk factors, such as environmental concerns, human factors and safety barriers, can be easily added to the proposed BN because of its flexibility.

Sensitivity studies on basic nodes and secondary tanker explosion and fire are conducted in this research. The results of the sensitivity study show the following:

- Smoking is the most dangerous ignition source at petrol stations and should be totally banned.
- Overfill is the most probable cause of release, while hose rupture may cause the most catastrophic consequences.
- The refuelling job from a tanker to a storage tank at a petrol station can be moved to night time if possible as only a small number of people may be affected.
- Tanker explosions and fires at petrol stations increase human losses. Therefore, safety barriers for stopping tanker explosion and quick evacuation are important for human safety.

Statistical data, numerical simulations and logical judgements were the three data sources used in this study. Such combination of data sources decreases the uncertainty caused by data shortage and improves the accuracy and reliability of BN quantification. However, for quantification based on subjective judgements, adjustments are required based on the specific conditions of different projects.
CHAPTER 4. GRID-BASED RISK MAPPING FOR EXPLOSION ACCIDENTS AT LARGE ONSHORE FACILITIES

4.1 INTRODUCTION

In this chapter, a grid-based risk mapping method is developed to enable a more detailed explosion risk analysis 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 end of the grid, and finally, a risk mapping can be depicted for the whole target area.

In the gas processing industry, 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 if the gas facility is located close to 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).

For risk analysis of such large areas under complex circumstances, it is difficult for traditional macroscale analysis to consider all specific local details and deal with complicated conditions. Therefore, a grid-based risk mapping method is developed to enable a more detailed explosion risk analysis. 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 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.

Meanwhile, 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, the Bayesian network is also implemented for the proposed grid-based method as a risk modelling tool.
4.2 MODELLING

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.

4.2.1 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 the Figure 4.1, 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.

Figure 4.1 Example of gridding
4.2.2 Bayesian network Modelling

A BN is an illustrative diagram that contains nodes and links with conditional probabilities. Figure 4.2 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 4.1. The states of explosion loads are defined based on damage classifications introduced by Lobato et al. (2009).

**Figure 4.2 Proposed BN for explosion risks**

<table>
<thead>
<tr>
<th>Node</th>
<th>States</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Wind Direction</td>
</tr>
<tr>
<td>B</td>
<td>Wind Speed</td>
</tr>
<tr>
<td>C</td>
<td>Release Severity</td>
</tr>
<tr>
<td>D</td>
<td>Congestion</td>
</tr>
</tbody>
</table>

**Table 4.1 Nodes and states of the proposed BN**
The reliability of the BN model is important to result accuracy of the proposed method. In order to improve the reliability of the BN analysis, a few indices such as the Ranked Probability Score (Epstein, 1969), the Weaver’s Surprise Index (Waver, 1948) and the Good’s Logarithmic Score (Good, 1952) have been proposed. Different BN errors involving node errors, edge errors, state errors, and prior probability errors in the latent structure can then be identified and corrected. Detailed definitions and explanations of the indices can be found in Williamson et al. (2000).

4.2.3 Quantification of Bayesian network

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.

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

| E | Explosion Loads | 5 | a: 0-0.024bar, “safety distance”  
b: 0.0204-0.17bar, up to 50% destruction of buildings  
c: 0.17--.689bar, up to total destruction of buildings  
d: 0.689-1.01bar, total destruction of building  
e: > 1.01bar, probable death due to lung haemorrhage |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>Building Type</td>
<td>4</td>
<td>Residential; Tank; Process facilities; No building</td>
</tr>
<tr>
<td>G</td>
<td>Population</td>
<td>4</td>
<td>Large; Medium; Small; Little</td>
</tr>
<tr>
<td>H</td>
<td>Building Damage</td>
<td>4</td>
<td>Major; Medium; Minor; No damage</td>
</tr>
<tr>
<td>I</td>
<td>Human Loss</td>
<td>4</td>
<td>Major; Medium; Minor; Little</td>
</tr>
</tbody>
</table>
weather data resources online. As for the release severity, hydrocarbon release data from the Health and Safety Executive (HSE) annual report (2016) is selected. Table 4.2 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.

Table 4.2 HSE data of hydrocarbon releases

<table>
<thead>
<tr>
<th>Year</th>
<th>06</th>
<th>07</th>
<th>08</th>
<th>09</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor</td>
<td>113</td>
<td>110</td>
<td>93</td>
<td>95</td>
<td>109</td>
<td>82</td>
<td>58</td>
<td>70</td>
<td>47</td>
<td>49</td>
<td>58.33%</td>
</tr>
<tr>
<td>Significant</td>
<td>73</td>
<td>71</td>
<td>52</td>
<td>81</td>
<td>73</td>
<td>57</td>
<td>39</td>
<td>42</td>
<td>30</td>
<td>32</td>
<td>38.84%</td>
</tr>
<tr>
<td>Major</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>8</td>
<td>6</td>
<td>3</td>
<td>3</td>
<td>2.83%</td>
</tr>
</tbody>
</table>

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 mentioned, numerical simulation and logical judgments are used to quantifying the inter-relationships between nodes.

Similar to Chapter 3, for the inter-relationship between basic explosion factors and consequent overpressures, numerical simulation using DNV PHAST is applied to provide data for quantification. Seventy-two cases have been conducted in order to provide sufficient data for such quantification. There are four steps to conducting a PHAST analysis: input data, build model, perform calculation, and output result. The four steps are briefly introduced below and more details about how to use PHAST can be found in PHAST manual (DNV GL, 2016).

- Input data: include site map, weather conditions, and data for explosion analysis.
- Build model: select analysis method and define explosion scenarios.
- Calculate: define calculation scenarios and run simulation.
- Output result: can be GIS outputs, result diagrams, and reports.

To quantify the inter-relationship of sub-network of building damage and human loss, logical judgments are mainly used due to the limitations of the data. This kind of subjective judgment is able to provide a certain level of accuracy and reliability when the logical relationship between nodes is simple and clear. However, such quantifications require regular examination,
and if the site condition changes, adjustments are required to ensure the logical relationships are up to date. Meanwhile, a confidence-based method can be used to reduce the uncertainties of subjective judgments when logical relationships are complicated and uncertain (Huang et al., 2015).

### 4.2.4 Calculation of Bayesian network

#### Calculation of sub-network of explosion loads

Figure 4.3 shows the sub-network of explosion loads. The three basic nodes are wind direction, wind speed, and release severity. The release severity and wind speed define cloud sizes, while location is decided by the wind direction. Then, the condition of congestion can be figured out based on the cloud size and location. Finally, the frequency of each explosion load level is calculated by the release severity and congestion conditions.

![Sub-network of explosion loads](image)

**Figure 4.3 The sub-network for estimating explosion loads**

This sub-network contains five nodes and five links. The prior probability of explosion loads can be calculated using Equation 4.1.

\[
P(E = a) = \sum_{i=1}^{4} \sum_{j=1}^{3} \sum_{k=1}^{3} \sum_{h=1}^{3} P(E = a, A = A_i, B = B_j, C = C_k, D = D_h),
\]

(4.1)

where \(P\) is the probability, \(E\) is the explosion loads, \(a\) is the state “\(a\)” of node \(E\), \(A\) is the wind direction, \(A_i\) is the states of node \(A\), \(B\) is the wind speed, \(B_j\) is the states of node \(B\), \(C\) is the release severity, \(C_k\) is the states of node \(C\), \(D\) is the congestion, and \(D_h\) is the states of node \(D\)
(see Table 4.1). Based on the theorem of BN (Nielsen and Jensen, 2009), the joint probability can be decided by Equation 4.2.

\[ P(x_1, ..., x_n) = \prod_{i=1}^{n} P(x_i \mid Pa(x_i)) \]  

(4.2)

where \( Pa(x_i) \) is the parent set of \( x_i \). The function remains an unconditional probability of \( P(x_i) \) if there are no parents of \( x_i \). In this sub-network, the node of congestion has parents of wind direction, wind speed, and release severity, and the node of explosion loads has parents of congestion and release severity. Therefore, the following equation can be decided:

\[
P(E = A, A = A_i, B = B_j, C = C_k, D = D_h) = P(E = A \mid D = D_h, C = C_k) \times \]

\[
P(D = D_h \mid C = C_k, B = B_j, A = A_i) \times P(C = C_k) \times P(B = B_j) \times P(A = A_i).
\]

(4.3)

**Calculation of sub-network of building damage and human loss**

As shown in Figure 4.4, two consequences, building damage and human loss, are considered at this stage. For building damage, only building type is applied as a basic factor. Different types of buildings provide different resistant levels to the explosion overpressures. Then, the total human loss is decided by explosion loads, building damage, and population within each grid.

![Sub-network for estimating building damage and human loss](image)

**Figure 4.4 Sub-network for estimating building damage and human loss**

Similar to the sub-network of explosion loads, this network also has five nodes and five links. Building damage has parents of building type and explosion loads, and the parents for human loss are explosion loads, building damage, and population. Therefore, human loss can be calculated by Equations (4.4) and (4.5).
\[
P(K = \text{Major}) = \sum_{i=1}^{5} \sum_{j=1}^{4} \sum_{k=1}^{4} \sum_{h=1}^{4} P(K = \text{Major}, E = E_i, F = F_j, G = G_k, H = H_h), \quad (4.4)
\]

\[
P(K = \text{Major}, E = E_i, F = F_j, G = G_k, H = H_h)
\quad = P(K = \text{Major}|H = H_h, G = G_k, E = E_i) \\
\quad \times P(H = H_h|F = F_j, E = E_i) \times P(G = G_k) \times P(F = F_j) \\
\quad \times P(E = E_i),
\]

where \( K \) is the human loss, \( E \) is the explosion loads, \( E_i \) is the states of node \( E \), \( F \) is the building type, \( F_j \) is the states of node \( F \), \( G \) is the population, \( G_k \) is the states of node \( G \), \( H \) is the building damage, and \( H_h \) is the states of node \( H \) (see Table 4.1).

### 4.2.5 Matrix Calculation and Result Display

In order to simplify the calculation process, the equations mentioned above are transferred into a calculation of matrices. All the data from each node and inter-relationships are shaped into forms of matrices. A MATLAB script is written to conduct the calculations between matrices and give the value to each grid automatically.

For example, Figure 4.5 shows a simple illustrative BN of building damage. From this simple BN, the probability of major building damage can be calculated by the following equation:

\[
P(H = \text{Major}) = \sum_{i=1}^{5} \sum_{j=1}^{4} P(H = H_i, E = E_i, F = F_j) = \sum_{i=1}^{5} \sum_{j=1}^{4} P(H_1|E_i, F_j) \times P(E_i) \times P(F_j) = P(H_1|E_1, F_1) \times P(E_1) \times P(F_1) + P(H_1|E_1, F_2) \times P(E_1) \times P(F_2) + \cdots + P(H_1|E_5, F_4) \times P(E_5) \times P(F_4).
\]

\[(4.6)\]

![Figure 4.5 A simple BN for estimating building damage](image)
The MATLAB script used to transfer this equation to the matrix calculation is written as:

\[
\begin{align*}
a &= P(H_1|E_1,F_1), P(H_1|E_1,F_2), \ldots, P(H_1|E_5,F_4)] \quad \%P(H_1|E_1,F_1)\% \quad (4.7) \\
b &= [P(E_1), P(E_2), \ldots, P(E_5)] \quad \%P(E_i)\% \quad (4.8) \\
c &= [P(F_1), P(F_2), P(F_3), P(F_4)] \quad \%P(F_j)\% \quad (4.9) \\
P(H = \text{Major}) &= \text{sum}(a' \cdot \text{reshape}(\text{repmat}(b, 4,1),20,1) \cdot \text{repmat}(c', 5,1)) \quad (4.10)
\end{align*}
\]

For each grid, a “for” loop is used to conduct the calculation automatically, and the result is depicted with a 3D bar plot. As shown in Figure 4.6, the height of each bar represents the probability of related states at each grid and a total risk profiling of target area is formed by the combination of risks from all the grids. Such a result display provides a clear risk indicator for each local area, and protection measures can be easily decided based on the risk mapping.

![Figure 4.6 Example of 3D result presentation](image)

### 4.3 CASE STUDY

A case study was conducted to illustrate the proposed method. Figure 4.7 shows a GIS map of a gas refinery factory with grids applied. This factory is surrounded by a residential area. From Figure 4.7, it can be seen that the closest residential building is located only about 100–200 m from a gas storage tank. Within this distance, consequences may be significant if an explosion occurs. To conduct this case study, a 50 m*50 m grid size over a domain range of 2 km *2 km is selected based on the result of mesh convergence (see Section 3.3). The BN model introduced in Section 2 is applied.
4.3.1 Quantification of Bayesian network

Quantification of basic nodes

As mentioned, there are five basic nodes of the proposed BN. Data on wind direction and wind speed are collected from a website that records local weather data daily, and all the information from 2015 are collected and analysed. Four wind directions and three wind speeds are considered in this study and their probabilities in 2015 are listed in Table 4.3. As to the release severity, the probability of each of the states from the HSE database can be found in Table 4.2.

Table 4.3 Probabilities of wind direction and wind speed

<table>
<thead>
<tr>
<th>Wind Direction</th>
<th>East</th>
<th>South</th>
<th>West</th>
<th>North</th>
<th>Wind Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3m/s 1.5m/s 0.1/s</td>
</tr>
<tr>
<td>Probability</td>
<td>0.203</td>
<td>0.284</td>
<td>0.284</td>
<td>0.229</td>
<td>0.698</td>
</tr>
</tbody>
</table>

Site information is depicted by colours in Figure 4.8. Figure 4.8(a) shows population information, with red, yellow, green, and blue representing large, medium, small, and little populations, respectively. Similarly, Figure 4.8(b) describes building type with red, yellow, green, and blue representing residential buildings, tanks, process facilities, and no buildings, respectively. Then, Excel is used to read all the colours and output numerical data for further analysis.
Quantification of inter-relationships

As mentioned, quantification of inter-relationships involves two parts. For the sub-network of the explosion loads, DNV PHAST is applied to simulate explosion loads under different conditions and provide data for BN calculation. The leak point is set at the tank that is nearest to the residential area. Huang et al. (2016) developed a multi-level explosion risk analysis method that can be used to screen the whole site, qualitatively determine the most dangerous leak source, and then, quantitative analysis can be conducted based on the results of risk screening. Table 4.4 indicates the input data for PHAST analysis.

**Table 4.4 Input data for PHAST analysis**

<table>
<thead>
<tr>
<th>Material</th>
<th>Hydrocarbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flammable mass in cloud</td>
<td>300 kg; 30 kg; 3 kg</td>
</tr>
<tr>
<td>Wind direction</td>
<td>East; North; West; South</td>
</tr>
<tr>
<td>Wind speed</td>
<td>0.1m/s; 1.5m/s; 3m/s</td>
</tr>
<tr>
<td>Congestion</td>
<td>High; Medium; Low</td>
</tr>
<tr>
<td>Explosion Load</td>
<td>A: 70kPa+; B:20-70kPa; C: 2-20kPa; D:0-2kPa</td>
</tr>
</tbody>
</table>

After performing calculations using PHAST, a GIS output of gas cloud dispersion is displayed first, and consequently, the congestion level can be decided based on the cloud size and location. Figure 4.9 shows an example of GIS output of cloud formation. Based on the cloud size and location from Figure 4.9, the congestion level for this scenario is defined as high. After a
judgment of congestion, the final GIS output of explosion loads can be depicted and different levels of load can be assigned to each grid as shown in Figure 4.10.

![Figure 4.9 GIS output of cloud formation](image)

**Figure 4.9 GIS output of cloud formation**

![Figure 4.10 GIS output of explosion loads](image)

**Figure 4.10 GIS output of explosion loads**

As to the quantification of the sub-network of building damage and human loss, a logical judgment is made based on the specific site information. For instance, the inter-relationship among building type, explosion loads, and building damage are shown in Table 4.5. For different facilities and buildings, the standards for resistance to dynamic blasting loads are different. Generally, 50% of the brickwork of houses will be destroyed, and steel frame building will be distorted under a blast load of 17 bar (Lobato et al., 2009). Therefore, for
residential buildings and process facilities, major damage is considered when explosion loads are larger than level C. Storage tanks normally have higher resistance levels than residential buildings and process facilities. Thus, medium damage is defined for storage tanks under level C blasting loads. The same method is applied to quantifying inter-relationship between basic nodes and human loss. The table of logical judgments between basic nodes and human loss is too large and complicated to be described in detail.

**Table 4.5 Inter-relationship between nodes E, F, and H**

<table>
<thead>
<tr>
<th>Residential</th>
<th>E</th>
<th>Major</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>D</td>
<td>Major</td>
</tr>
<tr>
<td>Residential</td>
<td>C</td>
<td>Major</td>
</tr>
<tr>
<td>Residential</td>
<td>B</td>
<td>Medium</td>
</tr>
<tr>
<td>Residential</td>
<td>A</td>
<td>Minor</td>
</tr>
<tr>
<td>Tank</td>
<td>E</td>
<td>Major</td>
</tr>
<tr>
<td>Tank</td>
<td>D</td>
<td>Major</td>
</tr>
<tr>
<td>Tank</td>
<td>C</td>
<td>Medium</td>
</tr>
<tr>
<td>Tank</td>
<td>B</td>
<td>Minor</td>
</tr>
<tr>
<td>Tank</td>
<td>A</td>
<td>Minor</td>
</tr>
<tr>
<td>Process facilities</td>
<td>E</td>
<td>Major</td>
</tr>
<tr>
<td>Process facilities</td>
<td>D</td>
<td>Major</td>
</tr>
<tr>
<td>Process facilities</td>
<td>C</td>
<td>Major</td>
</tr>
<tr>
<td>Process facilities</td>
<td>B</td>
<td>Medium</td>
</tr>
<tr>
<td>Process facilities</td>
<td>A</td>
<td>Minor</td>
</tr>
<tr>
<td>No structures</td>
<td>E</td>
<td>No</td>
</tr>
<tr>
<td>No structures</td>
<td>D</td>
<td>No</td>
</tr>
<tr>
<td>No structures</td>
<td>C</td>
<td>No</td>
</tr>
<tr>
<td>No structures</td>
<td>B</td>
<td>No</td>
</tr>
<tr>
<td>No structures</td>
<td>A</td>
<td>No</td>
</tr>
</tbody>
</table>

### 4.3.2 Results and discussion

Based on the equations in Section 2.4 and network quantification, the probability of each state of explosion loads, building damage, and human loss can be figured out and output as a 3D risk map that shows the risk level of each grid. Figure 4.11, 4.12, and 4.13 give the final results of the probabilities of explosion loads, building damage, and human loss, respectively.
Figure 4.11 Risk mapping of explosion loads

Figure 4.11 shows the risk mapping of explosion loads based on five states. It can be observed from the Figure 4.11(e) that overpressures that may cause direct human death and total building damage may occur only at a few grids around the explosion centre. The level “B” blast load has a high probability of occurring within a radius of 500 m from the explosion centre, while outside of 500 m, the probability of level “B” or higher overpressures is less than half. A “safety” zone with a level “A” explosion loads is defined as approximately 1800 m away from the explosion centre.
As for building damage, Figure 4.12 shows that there is a large chance for major building damage occurring at the process site and the residential areas that are close to the explosion centre. Therefore, the buildings within this area have to be reinforced to resist high blast overpressures based on the risk mapping of explosion loads. Meanwhile, Figure 4.12(b) indicates the area with probable medium building damage. For the region with probabilities over 50%, the strength of the buildings needs to be examined and structure may need to be strengthened.
Figure 4.13 describes the risks of human loss. From Figure 4.13(a), it can be observed that the most dangerous region for human safety is located in the residential area close to the explosion centre because of the large population that is assumed within that area. It can also be seen that there is a gap between the residential area and the factory with a very low chance for major human loss because no structures are present in that area. Therefore, if projectiles and fires are not present in the explosion, evacuation to the area without buildings is probably a better choice than sheltering inside the buildings within the dangerous region.

Figure 4.13(b) shows that even far from the explosion centre, there is still a chance for injury and medium human loss can still happen. The main reason for this occurring is that the storage tank is located too close to the residential area and partial building damage may happen within
1800 m under level “B” explosion loads. Therefore, careful design of protection barriers and structure strengthening of buildings are required for human safety considerations.

Other than local structure strengthening methods to protect the building and human in related areas, there are also some risk reduction methods can be applied to the petrol station directly in order to reduce the total risk of explosion events. The reduction methods include both consequence mitigation and likelihood reduction approaches. Measures for reducing explosion risks are listed and briefly explained in Table 4.6 and 4.7 based on oil and gas facility design and explosion barrier installations.

**Table 4.6 Explosion risk reduction method from design aspects**

<table>
<thead>
<tr>
<th>Measures</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment minimization</td>
<td>Leak frequency is proportional to the number of process equipment on the platform. Therefore, as simple as possible process systems are desirable.</td>
</tr>
<tr>
<td>Inventory minimization</td>
<td>The inventory in the process system may be related to the duration of any leak, and to the time required for blowdown.</td>
</tr>
<tr>
<td>Inventory Pressure</td>
<td>Flammable cloud size is determined by the leak dimension and the pressure of the inventory. Reduced inventory pressure will reduce explosive cloud dimensions and the severity of the explosion event. It will also result in a lower inventory mass within the system which will give the potential for a more rapid blowdown and reduced escalation consequence.</td>
</tr>
<tr>
<td>Operations and maintenance procedures</td>
<td>Errors in maintenance and operating procedures are important causes of leaks. The potential effect of improvements in these areas on the leak frequency is mainly judgmental at present, although human reliability modelling may give some guide.</td>
</tr>
<tr>
<td>Ventilation</td>
<td>The ignition probability depends on the gas concentration and the ignition sources in this area. Free or forced ventilation is able to reduce the gas concentration.</td>
</tr>
<tr>
<td>Ignition source minimization</td>
<td>In general, the main ignition sources are welding/hot work, compressors, electrical equipment and engines/exhausts. Remove or minimize some of those sources is possible. For instance, lights can be switched when not needed, or floodlights can illuminate hazardous areas from safer zones.</td>
</tr>
</tbody>
</table>
Highest overpressures in congested modules tend to arise when the ignition point is at the furthest point from a main vent. Although there is potential for ignition to occur at practically any point within the module, removing other ignition sources away from such extremities will, to some extent, lower the potential for high explosion overpressure to occur.

Explosion events are most likely to occur in congested areas, and therefore avoiding congestion in the modules can reduce both the probability of explosion and the overpressure if an explosion does occur.

Local fatalities may be avoided if the personnel in the area become aware of a leak, by alarms or by their own observation, and escape from the area before the ignition occurs. This can be covered under emergency procedures.

<table>
<thead>
<tr>
<th>Ignition source location</th>
<th>Minimization of congestion</th>
<th>Emergency procedures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest overpressures in congested modules tend to arise when the ignition point is at the furthest point from a main vent. Although there is potential for ignition to occur at practically any point within the module, removing other ignition sources away from such extremities will, to some extent, lower the potential for high explosion overpressure to occur.</td>
<td>Explosion events are most likely to occur in congested areas, and therefore avoiding congestion in the modules can reduce both the probability of explosion and the overpressure if an explosion does occur.</td>
<td>Local fatalities may be avoided if the personnel in the area become aware of a leak, by alarms or by their own observation, and escape from the area before the ignition occurs. This can be covered under emergency procedures.</td>
</tr>
</tbody>
</table>

**Table 4.7 Explosion risk reduction method based on barriers**

<table>
<thead>
<tr>
<th>Emergency Shut Down systems (ESD)</th>
<th>Isolation and blowdown</th>
<th>Blast wall</th>
<th>Detection device</th>
<th>Alarm</th>
<th>Safety gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>An effective ESD system will limit the inventory released in an incident and therefore the size and duration any resulting fire. The location of the ESD valves will determine the areas where each particular inventory could be released.</td>
<td>A leak may be reduced by isolating it manually or using the ESD system, and depressurising the leaking section using the blowdown system. Damage or fatality risk in escalation can be reduces by isolation and blowdown, and sometimes the necessity of evacuation may be avoided.</td>
<td>Blast walls have long been used to protect adjacent areas from the effects of overpressure. These walls are designed to absorb blast energy by displacement.</td>
<td>Detection measures can be used to identify hazardous conditions on the plant such as excess process pressure, an unignited release of flammable gas or a fire. Detection devices enable control or mitigation measures and emergency response to be initiated.</td>
<td>The alarm system may allow operators to mitigate leaks before they ignite, or at least to evacuate the area.</td>
<td>In the process industry, the safety gap which is an open space, with no congestion, deliberately placed in between congested process areas. The</td>
</tr>
</tbody>
</table>
absence of obstacles in a safety gap eliminates the fluid-obstacle interaction thereby preventing the generation of turbulence. It can be very effective in reducing pressures prior to the onset of detonation.

### 4.3.3 Mesh convergence

A mesh convergence study was conducted in order to determine an optimal balance between accuracy and computational time. During the study of mesh convergence, all information from each grid were put together to form a total input into the BN. Four sizes of grid, 200 m, 100 m, 50 m, 25 m, were tested and the results are listed in Table 4.8.

**Table 4.8 Results from different mesh sizes**

<table>
<thead>
<tr>
<th>Grid Size</th>
<th>200 m</th>
<th>100 m</th>
<th>50 m</th>
<th>25 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load A</td>
<td>0.408</td>
<td>0.434</td>
<td>0.45</td>
<td>0.453</td>
</tr>
<tr>
<td>Load B</td>
<td>0.464</td>
<td>0.464</td>
<td>0.457</td>
<td>0.458</td>
</tr>
<tr>
<td>Load C</td>
<td>0.0514</td>
<td>0.046</td>
<td>0.0426</td>
<td>0.0403</td>
</tr>
<tr>
<td>Load D</td>
<td>0.0315</td>
<td>0.0269</td>
<td>0.0252</td>
<td>0.0247</td>
</tr>
<tr>
<td>Load E</td>
<td>0.045</td>
<td>0.0291</td>
<td>0.0255</td>
<td>0.0245</td>
</tr>
<tr>
<td>Building Damage Major</td>
<td>0.118</td>
<td>0.0954</td>
<td>0.0608</td>
<td>0.0539</td>
</tr>
<tr>
<td>Building Damage Medium</td>
<td>0.122</td>
<td>0.084</td>
<td>0.0672</td>
<td>0.0635</td>
</tr>
<tr>
<td>Building Damage Minor</td>
<td>0.33</td>
<td>0.248</td>
<td>0.178</td>
<td>0.165</td>
</tr>
<tr>
<td>Building Damage No</td>
<td>0.43</td>
<td>0.572</td>
<td>0.694</td>
<td>0.718</td>
</tr>
<tr>
<td>Human Loss Major</td>
<td>0.134</td>
<td>0.094</td>
<td>0.0611</td>
<td>0.0574</td>
</tr>
<tr>
<td>Human Loss Medium</td>
<td>0.167</td>
<td>0.119</td>
<td>0.086</td>
<td>0.0803</td>
</tr>
<tr>
<td>Human Loss Minor</td>
<td>0.251</td>
<td>0.193</td>
<td>0.147</td>
<td>0.1356</td>
</tr>
<tr>
<td>Human Loss Little</td>
<td>0.448</td>
<td>0.594</td>
<td>0.705</td>
<td>0.727</td>
</tr>
</tbody>
</table>

Figure 4.14 shows the result for explosion loads, building damage, and human loss from different grid sizes. From Figure 4.14(a), there is not much difference among the four grid sizes for the probabilities of explosion load levels. However, for scenarios of building damage and human loss, the probabilities of each state shows a large difference until the grid size reduces to 50 m. When the grid size is reduced from 50 m to 25 m, the difference of probability is approximately less than 5%. Therefore, a grid size of 50 m*50 m is applied in this study.
Figure 4.14 Results from different mesh sizes
4.4 SUMMARY

A more detailed grid-based risk mapping method for explosion events is proposed in this chapter. This method uses a Bayesian network (BN) as a risk analysis tool to estimate the consequences and related probabilities for each grid. Based on the results of all the grids, 3D bar charts are formed to describe the risks of explosion loads, building damage, and human loss.

A case study is conducted to demonstrate the applicability of the proposed method. From the case study, it can be concluded that the method provides a more detailed risk analysis of a large site with complex conditions. Meanwhile, the results of 3D risk mapping charts offer a clear view of the potential risks, which is useful for risk and safety management during planning, construction, and operation stages. A mesh convergence study was also conducted and a grid size of 50 m*50 m was found to be most appropriate over a domain range of 2 km *2 km.

A simple BN with basic risk influence factors was constructed to evaluate the risks of explosion loads, building damage, and human loss. The case study proved that BN is capable of dealing with complicated inter-relationships between basic factors and consequences. Meanwhile, since BN is flexible, extra consequences or risk factors, such as environmental concerns, human factors, and safety barriers, can be easily added to the proposed BN.
CHAPTER 5. MULTI-LEVEL EXPLOSION RISK ANALYSIS (MLERA) FOR ACCIDENTAL GAS EXPLOSION EVENTS IN SUPER-LARGE FLNG FACILITIES

5.1 INTRODUCTION

This chapter proposed a more efficient explosion risk analysis for super-large offshore facilities. As the demand for natural gas increases, it becomes necessary to develop the offshore gas reserves, which normally are located in small and remote areas. However, in those areas, transporting the gas via a pipeline may not be feasible or may not be economically beneficial to install. Therefore, a new kind of production facility called floating liquefied natural gas (FLNG) has been proposed to make the development of small and remote fields in deeper water possible. This kind of floating structure does not require much external support and allows for the transformation of gas into a readily transportable form.

The FLNG facility is a multi-functional offshore structure that contains both gas processing and liquefaction equipment as well as storage for the produced LNG (Aronsson, 2012). In order to install all those processing, liquefaction, and storage units on a single ship, the FLNG ship is designed to be super large, and the topside structure is highly congested. Figure 5.1 shows the world’s first FLNG facility designed by Shell Global, the Prelude FLNG, which is 488 m long and 74 m wide, weighing more than 600,000 tons fully ballasted, which is roughly six times the weight of the largest aircraft carrier (Shell Global, 2016).

Figure 5.1 Shell Prelude FLNG (Shell Global, 2016).
Explosion risks are related to three critical conditions, which are confinement, congestion, and ventilation. Since an FLNG facility processes and stores a large amount of flammable gas in a relatively small and congested area compared to onshore LNG plants, higher explosion risks exist on FLNG platforms. Meanwhile, compared to other congested offshore structures, explosion events with much more severe consequences may occur due to the super-large space on board, which allows a larger volume of gas cloud to be accumulated. Therefore, for this kind of large and highly congested structure, explosion risks must be considered during the design process and reduced to an acceptable level.

Among all the explosion safety assessment methods, an explosion risk analysis (ERA) is one of the most widely used approaches to derive the accidental loads for design purposes. The ERA has been extensively described by Vinnem (2011), and detailed guidelines on how to perform ERA are provided by NORSOK Z013 (2001) and ISO 19901-3 (2014). Due to the complex geometry and obstacles of the offshore structures, computational fluid dynamics (CFD) tools such as FLACS (GEXCON, 2011) are normally involved in ERA. However, Hocquet from Technip (2013) pointed out that one critical issue in applying ERA to FLNGs is time constraints. Sufficient information to derive realistic design overpressures and accidental loads depends on numerous CFD dispersion and explosion calculations, which normally require an unacceptable computational time due to the large size and complex structures of FLNGs and various uncertainties that must be considered.

This study aims at developing a multi-level explosion risk analysis method (MLERA) for FLNGs, which classifies the FLNG into different subsections with different risk levels before the detailed CFD simulations are conducted. The advantage of this method is to find out and apply detailed calculations to the areas with the highest risks in order to shorten the CFD computational time to a realistic and acceptable level. The MLERA includes three levels: qualitative risk screening, semi-quantitative risk classification, and quantitative risk assessment. Throughout the three levels of analysis, an exceedance curve of frequency versus overpressure will be formed, and an ALARP (as low as is reasonably practical) method is used to decide if the explosion risk is acceptable (NOPSEMA, 2015). The risk mitigations are required until the explosion risk of the target area is as low as reasonably practical.

Another challenge in assessing explosion risks for an FLNG facility is that there are neither design rules nor industry standards available, as FLNG is a new technology (Paris & Cahay,
Current standards such as UKOOA (2003), HSE (2003), and API (2006) provide detailed guidelines on how to perform offshore explosion analysis and describe the analysis process. However, as most of those guidelines were proposed based on fixed platforms, it may not be appropriate to completely follow those standards to conduct an explosion risk analysis for FLNG platforms. For example, if the risk screening process used for fixed platforms is extended straightforwardly to FLNG facilities, all FLNG platforms remain at the highest risk level, which makes the risk screening process useless.

Therefore, other than the traditional contributors from current standards such as confinement, congestion, and ventilation, safety barriers are also involved in the risk screening and classification processes of the proposed method as extra risk indicators since the current design standards for normal offshore platforms are not sufficient for assessing the explosion risks of super-large offshore structures. Safety barriers are normally used for both likelihood reduction and consequence mitigation. Some of the important safety barriers used in the MLERA are listed and briefly introduced in the following section.

5.2 MULTI-LEVEL EXPLOSION RISK ANALYSIS (MLERA)

A multi-level explosion risk analysis (MLERA) method is proposed by implementing a multi-level risk assessment method into the traditional ERA method for offshore platforms.

The multi-level risk assessment method is extended from the framework used by the Department of Planning & Infrastructure of New South Wales Government (2011), which was used to formulate and implement risk assessment and land-use safety planning processes. It aimed at ensuring that the risk analysis is conducted within an appropriate cost and timeframe and is still able to provide high-quality results for the assessments. To achieve that, both qualitative and quantitative approaches are required. Some key aspects of the three levels of analysis from NOPSEMA (2012) are shown in Table 5.1.

<table>
<thead>
<tr>
<th>Level 1: Preliminary qualitative risk screening</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Likelihood and consequence are expressed on a scale and described in words.</td>
</tr>
<tr>
<td>• There is no numerical value for risk output.</td>
</tr>
<tr>
<td>• Often used as a preliminary risk assessment or screening tool.</td>
</tr>
</tbody>
</table>
• Rapid assessment process and relatively easy to use.

Level 2: Semi-quantitative risk classification and prioritization

• Generate a numerical value, but not an absolute value of risk.
• Provides greater capacity to classify between hazards on the basis of risk.
• Better for evaluating cumulative risk.

Level 3: Detailed quantitative risk assessment

• Provides a calculated value of risk based on estimates of consequence (usually software modelling) and likelihood (estimates based on failure rate data—site or industry).
• Good for more complex decision making or where risks are relatively high.
• More time intensive and expensive than other methods.

The traditional ERA for offshore platforms is one of the most widely used approaches to derive the design accidental loads for design purposes. The ERA has been extensively described by Vinnem (2011), and detailed guidelines on how to perform ERA are provided by NORSOK Z013 (2001) and ISO 19901-3 (2014). As mentioned before, one of the critical issues of applying ERA to FLNG platforms is the unavailability of the long computational time. Due to the huge size of the FLNG facilities, numerous CFD dispersion and explosion simulations are required in order to acquire sufficient data to derive realistic design explosion loads.

Therefore, the multi-level method is used to improve the ERA process to decrease the computational cost to a reasonable and acceptable level. The proposed MLERA method is a systematic risk analysis approach that includes three assessment stages, which are qualitative explosion risk screening as the first level, semi-quantitative explosion risk classification as the second level, and quantitative explosion risk analysis as the third level. It aims at providing an appropriate risk analysis method for explosion accidents on offshore super-large structures such as FLNG facilities.

In regards to the key aspects in multi-level risk analysis as given in Table 5.1, brief descriptions of the proposed MLERA for FLNG platforms and related analysis features of each level are listed below, and detailed explanations of each step will discussed in the following section.

Level 1: Qualitative risk screening

• Qualitative description of critical risk contributors
Taking each FLNG facility as a whole as the analysis object

Using a risk matrix diagram to rank the risk level of an FLNG platform

Level 2: Semi-quantitative risk classification

- Using a score and weight system to quantify each risk contributor
- Estimating the risk of each FLNG subsection
- Classifying the subsections by using a cumulative density function diagram

Level 3: Quantitative risk assessment

- Combining ERA and FLACS to figure out the quantitative result of explosion frequency and consequences
- Assessing the subsection with the highest risk levels. The number of the subsections requiring detailed assessment depends on the results from the analyses at the first two levels.
- The final result is indicated by an overpressure versus frequency exceedance curve.
- The ALARP concept is used to check if the explosion risk of the corresponding subsection is as low as reasonably practical.

Meanwhile, the proposed MLERA considers not only normal risk contributors such as congestion, confinement, and ventilation but also safety barriers. Some of the safety barriers that are involved in the proposed method are briefly introduced in Table 5.2.

**Table 5.2 List of Explosion Safety Barriers**

<table>
<thead>
<tr>
<th>Safety Barrier</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blast relief panels</td>
<td>The overpressure can be diverted away from potential escalation sources such as blast relief panels. Blast relief panels will open quickly during an explosion in order to reduce peak overpressures.</td>
</tr>
<tr>
<td>Emergency shut down systems (ESD)</td>
<td>An effective ESD system will limit the inventory released in an incident and therefore the size and duration of any resulting fire. The location of the ESD valves will determine the areas where each particular inventory could be released.</td>
</tr>
<tr>
<td>Isolation and blowdown</td>
<td>A leak may be reduced by isolating it manually or using the ESD system and depressurizing the leaking section using the blowdown system. Damage or fatality risk in escalation can be reduced by isolation and blowdown, and sometimes the necessity of evacuation may be avoided.</td>
</tr>
<tr>
<td>Blast wall</td>
<td>Blast walls have long been used to protect adjacent areas from the effects of overpressure. These walls are designed to absorb blast energy through displacement.</td>
</tr>
<tr>
<td>Water deluge</td>
<td>Deluge has been found to be suitable for reducing overpressure in congestion-generated explosions. If explosion mitigation is considered critical, a deluge flow-rate of at least 13-15 L/min/m² is recommended for general area coverage.</td>
</tr>
<tr>
<td>Artificial vent</td>
<td>Artificial ventilation is defined as that ventilation that is not supplied from the action of the environmental wind alone. Upon detection of flammable gas, the standby fan(s) should be started to give maximum possible ventilation in order to aid dilution of the leak to prevent or limit the generation of an explosive cloud.</td>
</tr>
<tr>
<td>Inert gas</td>
<td>Inert gas can be used to dilute the flammable mixture by flooding the volume within which the gas has been detected with, for example, CO₂ or N₂. The explosive gas can then be taken below its lower explosive limit.</td>
</tr>
<tr>
<td>Detection device</td>
<td>Detection measures can be used to identify hazardous conditions on the plant such as excess process pressure, an unignited release of flammable gas, or a fire. Detection devices enable control or mitigation measures and emergency response to be initiated.</td>
</tr>
<tr>
<td>Alarm</td>
<td>The alarm system may allow operators to mitigate leaks before they ignite or to at least evacuate the area.</td>
</tr>
<tr>
<td>Soft barriers</td>
<td>Progress is being made in the manufacture of soft barriers such as the micro-mist device, which consists of a cylinder of superheated water that is released quickly as a fine mist in response to pressure or flame sensors during an explosion. This device suppresses the explosion and significantly reduces overpressures.</td>
</tr>
<tr>
<td>Safety gap</td>
<td>In the process industry, the safety gap is an open space with no congestion, deliberately placed in between congested process areas. The absence of obstacles in a safety gap eliminates the fluid-obstacle interaction, thereby preventing the generation of turbulence. It can be very effective in reducing pressures prior to the onset of detonation.</td>
</tr>
</tbody>
</table>
5.2.1 First Level: Qualitative Risk Screening

The first level risk screening aims at defining the total qualitative risk level of an FLNG platform and also offers a guideline for the next two levels of explosion risk analysis. In the first level assessment of risk screening, not only are traditional risk screening indicators considered, but safety barriers and design, operation, and maintenance philosophies are also used to define a relative risk level for FLNG because the explosion risk will always be high if only traditional risk screening methods are used for this kind of super-large and highly congested structure. Based on API (2006) and UKOOA (2003), most of the qualitative risk indicators of the traditional risk screening process are listed in Table 5.3.

Table 5.3 Traditional Risk Screening Indicators from Explosion Risk Standards

<table>
<thead>
<tr>
<th>Consequence:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Low consequence:</td>
<td>• Low congestion level due to the low equipment count, being limited to wellheads and manifold with no vessels (i.e., no associated process pipework)</td>
</tr>
<tr>
<td></td>
<td>• No more than two solid boundaries, including solid decks</td>
</tr>
<tr>
<td></td>
<td>• Unattended facilities with low maintenance frequency, less frequent than 6-weekly</td>
</tr>
<tr>
<td>Medium consequence:</td>
<td>• Medium congestion level due to the greater amount of equipment installed compared to the low case</td>
</tr>
<tr>
<td></td>
<td>• Higher confinement level than that for the low case</td>
</tr>
<tr>
<td></td>
<td>• Unattended facilities with a moderate maintenance frequency, more frequent than 6-weekly</td>
</tr>
<tr>
<td></td>
<td>• A processing platform necessitating permanent manning but with low escalation potential to quarters, utilities, and control areas located on a separate structure</td>
</tr>
<tr>
<td>High consequence:</td>
<td>• High congestion level due to the significant processing on board, which leads to a high equipment count</td>
</tr>
<tr>
<td></td>
<td>• High confinement level of the potential gas release point</td>
</tr>
<tr>
<td></td>
<td>• Permanent manning with populated areas within the consequence range of escalation scenarios</td>
</tr>
<tr>
<td>Likelihood:</td>
<td></td>
</tr>
<tr>
<td>Low likelihood:</td>
<td>• Low equipment and inventory count, which align closely with the consequence scenarios</td>
</tr>
<tr>
<td></td>
<td>• Low frequency of intervention, less frequent than 6-weekly</td>
</tr>
<tr>
<td></td>
<td>• No ignition sources within the potential gas cloud</td>
</tr>
</tbody>
</table>
Medium likelihood:
- Greater amount of equipment installed than for the low likelihood
- Medium frequency of intervention, more frequent than 6-weekly
- Weak ignition sources, such as a hot surface, exist within the potential gas cloud.

High likelihood:
- A high equipment and inventory count
- Permanently manned installations with frequent processing on board
- Strong ignition sources exist within the potential gas cloud.

Table 5.4 describes the more in-depth risk screening process that uses safety barriers and design, operation, and maintenance philosophies as screening contributors. A modified risk matrix diagram is illustrated in Table 5.5. From the modified diagram, it can be seen that only a relative risk category is defined, and the results from this category will be used as a guideline for the further assessment levels of the proposed MLERA.

**Table 5.4 Risk Indicators Based on Safety Barriers**

<table>
<thead>
<tr>
<th>Consequence</th>
<th>Risk Level</th>
<th>Description</th>
</tr>
</thead>
</table>
| A | Moderate | - Safety barriers covering most or all parts of the FLNGs
- High design capacity of the structure to deal with dynamic pressure, overpressure, missiles, and strong shock response. No or minor structural damages would occur. |
| B | Major | - Safety barriers covering the structural critical elements only
- Medium design capacity of the structure to deal with dynamic pressure, overpressure, missiles, and strong shock response. A medium level of structural damages would occur without affecting the structural integrity. |
| C | Catastrophic | - No or only safety barriers for human living quarters
- Low design capacity of the structure to deal with dynamic pressure, overpressure, missiles, and strong shock response. Significant structural damages would occur and would affect the structural integrity. |

Likelihood

<table>
<thead>
<tr>
<th>No.</th>
<th>Risk Level</th>
<th>Description</th>
</tr>
</thead>
</table>

95
### Table 5.5 Risk Matrix Diagram for Further Risk Screening of FLNGs

<table>
<thead>
<tr>
<th>Likelihood of Failure</th>
<th>Consequence of Failure</th>
<th>Consequence of Failure</th>
<th>Consequence of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Moderate</td>
<td>Major</td>
<td>Catastrophic</td>
</tr>
<tr>
<td>Almost certain</td>
<td>Relatively medium risk</td>
<td>Relatively high risk</td>
<td>Relatively high risk</td>
</tr>
<tr>
<td>Likely</td>
<td>Relatively low risk</td>
<td>Relatively medium risk</td>
<td>Relatively high risk</td>
</tr>
<tr>
<td>Possible</td>
<td>Relatively low risk</td>
<td>Relatively low risk</td>
<td>Relatively medium risk</td>
</tr>
</tbody>
</table>

#### 5.2.2 Second Level: Semi-Quantitative Risk Classification

In this section, the second level of semi-quantitative risk classification is introduced. The analysis at this level estimates the risk level of each subsection of an FLNG facility in order to provide an assessment prioritization for the third level ERA. A score and weight system is applied to each selected risk contributor so that the subsections are able to be classified by numerical values.

Only some of the main risk contributors for offshore explosion events are selected and briefly described in Table 5.6. Each contributor is evaluated by two elements, weight and score. The weight of each risk factor is subjectively defined by the author based on relative standards and researches (API, 2006; UKOOA, 2003; Bjerketvedt et al., 1997). This may be adjusted by the safety engineers according to their own experience and the practical conditions of their projects.
<table>
<thead>
<tr>
<th>Risk Contributor</th>
<th>Description</th>
<th>Weight</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment count</td>
<td>Leak frequency is proportional to the amount of process equipment on the platform</td>
<td>3</td>
<td>= number of equipment count</td>
</tr>
</tbody>
</table>
| Ignition                 | In general, the main ignition sources are welding/hot work, compressors, electrical equipment, and engines/exhausts. A weak, continuous ignition source can sit and wait for the gas cloud to reach its flammable range. | 7      | = 3 if continuous ignition source exists  
= 2 if only discrete ignition source exists  
= 1 if no or few ignition source exists |
| Flammable limit of process material | The higher the upper flammable limit of a certain fuel, the easier it normally is to get a flammable cloud in the air. Flammability limits for fuel mixtures can be calculated by Le Chatelier’s law, as shown in equation 5.1. | 4      | = 3 if upper flammable limit > 40%  
= 2 if upper flammable limit is between 10% and 40%  
= 1 if upper flammable limit < 10% |
| Congestion               | Explosion events are most likely to occur in congested areas, and, therefore, avoiding congestion in the modules can reduce both of the probability and overpressure of an explosion event. Table 5.7 defines the congestion level based on the congestion classification of Baker-Strehlow-Tang model (Baker et al., 1996). | 10     | = 3 if congestion is defined as high  
= 2 if congestion is defined as medium  
= 1 if congestion is defined as low |
| Fuel reactivity          | The higher the laminar burning velocity, the higher the explosion loads will be. | 4      | = 3 if laminar burning velocity > 75cm/s  
= 2 if laminar burning velocity is between 45cm/s and 75cm/s  
= 1 if laminar burning velocity < 45cm/s |
| Confinement              | The ignition probability depends on the gas concentration and the ignition sources in this area. Low confinement is able to reduce the gas concentration. | 8      | = 3 if the flame expansion is defined as 1D  
= 2 if the flame expansion is defined as 2D  
= 1 if the flame expansion is defined as 2.5D or 3D |
| Distance to target area  | Distance to the target area may significantly affect the consequent load applied to the target area. | 7      | = 3 if distance is smaller than 1/3 total length of the structure  
= 2 if distance is smaller than 2/3 total length of the structure  
= 1 if distance is larger than 2/3 total length of the structure |
Table 5.7 Blockage Ratio Classification

<table>
<thead>
<tr>
<th>Obstacle layers</th>
<th>Blockage ratio per layer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 10%</td>
</tr>
<tr>
<td>3 or more</td>
<td>Medium</td>
</tr>
<tr>
<td>2</td>
<td>Low</td>
</tr>
<tr>
<td>1</td>
<td>Low</td>
</tr>
</tbody>
</table>

\[
LFL_{\text{Mix}} = \frac{100}{C_1/LFL_1 + C_2/LFL_2 + \cdots + C_i/LFL_i}
\]  

(5.1)

where \( C_1, C_2, \ldots, C_i \) [vol.%] is the proportion of each gas in the fuel mixture without air (Kuchta, 1985)

Safety barriers are considered to be extra risk contributors in the semi-quantitative risk classification process. All safety barriers are divided into three categories which are barriers for likelihood reduction, consequence mitigation and for both. Based on the classifications, safety barriers are given different weights as shown in Table 5.8. Score is decided by the quantity of each barrier is applied to each module.

Table 5.8 Weight of Barriers based on Function Classifications

<table>
<thead>
<tr>
<th>Barrier</th>
<th>Classification</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergency shut down (ESD) system</td>
<td>Likelihood reduction</td>
<td>6</td>
</tr>
<tr>
<td>Detection device</td>
<td>Likelihood reduction</td>
<td>6</td>
</tr>
<tr>
<td>Water deluge</td>
<td>Likelihood reduction</td>
<td>4</td>
</tr>
<tr>
<td>Inert gas</td>
<td>Likelihood reduction</td>
<td>4</td>
</tr>
<tr>
<td>Safety gap</td>
<td>Consequence Mitigation</td>
<td>3</td>
</tr>
<tr>
<td>Blast wall</td>
<td>Consequence Mitigation</td>
<td>3</td>
</tr>
<tr>
<td>Blast relief panels</td>
<td>Consequence Mitigation</td>
<td>3</td>
</tr>
<tr>
<td>Soft barriers</td>
<td>Consequence Mitigation</td>
<td>3</td>
</tr>
<tr>
<td>Artificial Vent</td>
<td>Both</td>
<td>9</td>
</tr>
<tr>
<td>Isolation and blowdown</td>
<td>Both</td>
<td>9</td>
</tr>
<tr>
<td>Alarm</td>
<td>Both</td>
<td>9</td>
</tr>
</tbody>
</table>
It can be seen from Table 5.8 that for safety barriers to reduce likelihood, two different weight, 6 and 4, are defined. This happens because although water deluge and inert gas are able to reduce the flammable limit of the cloud and consequently prevent the explosion, they are probably enlarge the consequence if explosion occurs. Inert gas can pose a significant asphyxiation risk to personnel and water deluge without proper design may increase turbulence of the affected area and enlarge the blast loads. Therefore, these two barriers are given lower weight than normal prevention barriers unless careful design are presented.

Then, the total weighted score of each subsection can be calculated by equation 5.2:

\[ S_T = S_C - S_B \]  
\[ S_C = \sum_{i=1}^{n} w_{ei} s_{ei} \]  
\[ S_B = \sum_{j=1}^{n} w_{bj} s_{bj} \]

where \( S_T \) refers to total weighted score for each subsection, and \( S_C \) and \( S_B \) are weighted scores of risk contributors and barrier functions, respectively, of each sub-section.

After the total score of each subsection is calculated, the total weighted scores are described with a cumulative density function and are converted to a risk category with three levels, as shown in Figure 5.2. The cumulative percentage is calculated from the total weighted scores of all the subsections from the target FLNG platform.

![Figure 5.2 Cumulative density function (CDF) for total risk score.](image-url)
First Level
Qualitative risk screening

Relatively low risk

Second Level
Semi-quantitative risk classification

Relatively medium risk

Third Level
Quantitative explosion risk assessment

Relatively high risk

Category S1:
10% of sub-sections

Category S2:
50% of sub-sections

Category S3:
90% of sub-sections

Detailed CFD assessment

Figure 5.3 Application procedure of MLERA

Figure 5.3 describes the analysis process of the proposed MLERA and explains which subsections require third-level risk quantification. The first level risk screening process divides the qualitative results into three risk levels, which are relatively low, medium, and high risks. If the FLNG facility is categorized with a relatively low explosion risk level, only the subsections with the highest risks, which belong to category S1 (top 10%), need additional detailed quantitative explosion risk assessment. From Figure 5.2, it can be seen that for an FLNG facility with relatively low explosion risks, the number of category S1 subsections is two. Otherwise, if the relatively medium or high risk is assigned, subsections of categories S2 (50%) or S3 (90%), which are 10 and 18 subsections respectively, from Figure 5.2, require risk quantification. Moreover, if all the subsections in one category fail the ERA, then the next level subsections require further ERA as well.

5.2.3 Third Level: Quantitative Risk Assessment

This third level of quantitative risk assessment is a CFD software-based quantitative analysis procedure. The process includes four main steps: leak frequency analysis, flammable gas dispersion simulation, ignition probability modelling, and flammable gas explosion simulation.
Figure 5.4 shows the detailed quantitative analysis process applied to offshore structures by using CFD tools such as FLACS.

After the quantitative ERA analysis is finished and an overpressure versus frequency exceedance curve is drawn, the risk calibration method, ALARP, is used to define the risk acceptance criteria. The ALARP framework for risk criteria is divided into three regions, as shown in Figure 5.4.

- An unacceptable region: In this region, risks are intolerable except in extraordinary circumstances, and thus risk reduction measures are essential.
- A tolerable region: It is normally known as an ALARP region, which means that the risks are considered tolerable providing that they have been made as low as reasonably practicable. In this region, risk reduction measures are desirable but may not be implemented if a cost-benefit analysis shows that their cost is disproportionate to the benefit achieved.
- A broadly acceptable region: Risks in this region are tolerable, and no risk reduction measures are required.

![Image of Exceedance frequency (year) vs Overpressure (barg) with regions labeled]

**Figure 5.5 Application of the ALARP to the final results of MLERA**

Figure 5.5 also shows an example of the ALARP application to the overpressure versus frequency exceedance curve. As shown in the diagram, if the design strength of the primary components of the FLNG is equal to the predicted explosion load in the unaccepted zone, risk reduction measures are required until the design strength proves to be sufficient to resist the explosion loads. No further reductions are required if the design strength belongs in the accepted zone. For the ALARP zone, reduction measures should be conducted unless the cost proves to be disproportionate to the benefit achieved.

### 5.3 CASE STUDY

For FLNG structures, cylindrical FLNG vessels are currently under consideration in order to improve hydrodynamic stability. Figure 5.6 shows the geometry of a cylindrical FLNG platform in FLACS. It can be seen that the cylindrical platform has a smaller area than a rectangular one, and all highly congested subsections are more focused on board, which may increase the explosion risks. However, there exists little research about gas explosion risk analysis for cylindrical platforms. Therefore, in this section, a cylindrical FLNG structure proposed by Li et al. (2016) is used as the basic model to illustrate the proposed MLERA.
Figure 5.6 Geometry of the cylindrical FLNG.

Figure 5.7 Topside arrangement of the modules.

Figure 5.7 depicts the arrangement of topside modules, including 12 modules in all. A brief introduction of each module is listed below:

- Module 1: Power generation
- Module 2: Trent gas turbines and two essential diesel generators
- Module 3: Nitrogen package, hot oil, mono-ethylene-glycol (MEG) processing, and inlet facilities
- Module 4: Boil off gas compressor and fuel gas system
- Module 5: Acid gas removal unit and end flash gas compressor
- Module 6: Dehydration and mercury removal
- Module 7 – Module 12: Liquefaction modules
5.3.1 Qualitative Risk Screening of the Cylindrical FLNG

For the first level of the risk screening process, based on the concepts from API (2006) and UKOOA (2003), the selected FLNG module is defined as a high-risk platform because it is a permanently manned and highly congested offshore structure with a large amount of equipment and inventories. Then, the next level of risk screening analysis is conducted. The conditions of safety barriers and design, operation, and maintenance philosophies are defined and listed below.

- Safety barriers: As shown in Figure 5.7, safety gaps are applied to every module. However, due to the lack of information about other safety barriers such as alarms, detection devices, ESDs, and water deluges on this FLNG model, a medium level of the condition of the safety barriers on this FLNG platform is assumed.
- Design philosophy: This FLNG is a recently designed offshore structure. It is assumed to have a high level of design philosophy because it is designed under the most recent design standards.
- Operation and maintenance philosophy: The standard of operation and maintenance philosophy is assumed to be medium, which refers to the average industry standard, because no FLNG facility has yet been operated throughout the world.

Based on the conditions listed above, this cylindrical FLNG is defined as having a relatively medium risk, which means that all subsections belonging to category S2 from the second level of semi-quantitative risk classification require detailed assessment in the third step.

5.3.2 Semi-Quantitative Risk Classification

The subsections of the selected model are defined by 12 modules. Each module is assessed in this risk classification process by applying the explosion and safety barrier contributors, which are defined in Tables 5.6 and 5.8. The target area of consequence analysis is the human living quarters. As shown in Figure 5.8, a cumulative density function diagram can be calculated based on the final scores from Table 5.9.

Table 5.9 Scores and Weights of Risk Contributors

<table>
<thead>
<tr>
<th>Subsections</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total score of explosion contributors</td>
<td>93</td>
<td>64</td>
<td>66</td>
<td>66</td>
<td>81</td>
<td>69</td>
<td>101</td>
<td>101</td>
<td>108</td>
<td>108</td>
<td>115</td>
<td>115</td>
</tr>
</tbody>
</table>
During the second level of risk classification process, some of the contributors have the same score for different subsections. For instance, as can be seen in Table 5.9, the final scores of safety barriers are the same for most of the modules. This happened for two reasons. First, this second level of risk classification process is still a rough assessment of each module, which may lead one particular contributor to the same score for all modules. Second, a lack of detailed information causes this problem. For example, in this case study, module 5 and 7 have less safety gaps than the other modules based on design drawings of the proposed model. This is the only difference of safety barriers can be defined and the other scores of barriers for each module are assumed to be same due to the limitation of data. Therefore, the total scores of barriers for most of the sub-sections remain the same. Acquiring more detailed information for the target structure leads to a higher level of accuracy for this classification.

**Figure 5.8 Cumulative density function diagram of subsections.**

From the cumulative density function diagram, it can be observed that the S2 category includes six subsections, which are from modules 7 to 12. Therefore, six subsections require further detailed assessment.
5.3.3 Detailed Quantitative Risk Assessment

As a medium risk level is defined for the selected FLNG during the first level of the qualitative risk screening process, modules 7 to 12, which belong to category S2, require further detailed assessment in this section. Therefore, a case study of detailed quantitative risk assessment with FLACS is conducted in this section. However, due to the limitation of computer force, a simple analysis model that was considered to be sufficient to demonstrate the proposed method was built and analyzed.

In this model, three leak locations on subsections 7, 9, and 11 were selected for assessment, and final results of this assessment were obtained achieved by combining the analyses on these three locations. The three selected locations are shown in Figure 5.9. Other specific assumptions of this model are described below.

- Four leak rates (12 kg/s, 24 kg/s, 48 kg/s, 96 kg/s) are simulated to study the possible gas volume buildup in the comparison and design of the blast wall configurations.
- In the simulations of dispersion leaks and explosion gas clouds, the inventory of the gas composition inside the cylindrical FLNG platform is summarized in Table 5.10.
- In this study, the assessment focuses on the living quarters with a protective blast wall on the west side. The living quarters are located at the very east side of the FLNG (Figure 5.7).
- Wind speed and wind direction are fixed at +4 m/s from west to east in order to examine the worst gas dispersion scenarios with such wind conditions.
- Leak directions are modelled in both eastern and western directions.

![Figure 5.9 Selected leak locations on the cylindrical FLNG platform.](image-url)
Table 5.10 Gas Composition for Dispersion and Explosion Study

<table>
<thead>
<tr>
<th>Component</th>
<th>Export gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>27%</td>
</tr>
<tr>
<td>Ethane</td>
<td>33%</td>
</tr>
<tr>
<td>Propane</td>
<td>15%</td>
</tr>
<tr>
<td>Hexane</td>
<td>19%</td>
</tr>
<tr>
<td>CO₂</td>
<td>6%</td>
</tr>
</tbody>
</table>

**Dispersion analysis**

Based on the assumptions, the overall leak cases used in this chapter are listed in Table 5.11. The gas monitor region for dispersion analysis covers all the modules on the cylindrical FLNG platform.

Table 5.11 Various Leak Cases Determined for Dispersion Study

<table>
<thead>
<tr>
<th>Case</th>
<th>Wind direction</th>
<th>Wind speed (m/s)</th>
<th>Leak rate (kg/s)</th>
<th>Leak position</th>
<th>Leak orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>West to east</td>
<td>4</td>
<td>12, 24, 48, 96</td>
<td>West end</td>
<td>Along and opposite wind</td>
</tr>
<tr>
<td>2</td>
<td>West to east</td>
<td>4</td>
<td>12, 24, 48, 96</td>
<td>Middle</td>
<td>Along and opposite wind</td>
</tr>
<tr>
<td>3</td>
<td>West to east</td>
<td>4</td>
<td>12, 24, 48, 96</td>
<td>East end</td>
<td>Along and opposite wind</td>
</tr>
</tbody>
</table>

Figure 5.10 demonstrates several examples of dispersion simulation outputs for gas releases with a leak rate of 48 kg/s. Those releases are simulated from both release directions, and leak locations are set on the ground and in the middle of modules 7, 9, and 11.

(a) Leaks from module 11 with both wind directions

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(b) Leaks from module 9 with both wind directions

(c) Leaks from module 7 with both wind directions

Figure 5.10 Gas dispersion simulations for leaks with a leak rate of 48 kg/s.

In order to investigate all leak rate cases thoroughly, the overall cumulative curve of gas cloud sizes within the gas monitor region is summarized in Figure 5.11. The cumulative curve is obtained by sorting the gas cloud size from small to large and equal leak frequencies are assigned to all leaks.

Figure 5.11 Cumulative curve of gas cloud sizes for all leak rate scenarios.
Explosion analysis

Explosion simulations are performed by using gas cloud data resulting from dispersion simulations with leak rates of 12 kg/s to 96 kg/s. The gas clouds are situated in four different locations, covering the entire platform, so that the overall gas explosion consequences for all modules can be analysed. For all gas clouds, the plan view sizes are all fixed at $100 \times 80$ m$^2$, while the heights of the clouds vary, which is consistent with the gas dispersion results obtained previously. For each gas explosion simulation, the gas cloud is ignited in the ground center of each module.

It is seen in Figure 5.12 that each gas cloud covers four modules; about 200 monitor points are homogeneously assigned on the ground to record the overpressures in a gas explosion simulation. By taking all different gas leak rate scenarios, gas cloud sizes, and locations into account, more than 3000 VCE overpressures are monitored in this probabilistic study regarding the gas explosion simulations. Since a major interest of this study is to assess the condition of the living quarters, 10 monitor points are assigned near the living quarter to record the overpressures for each gas explosion scenario.

![Figure 5.12 Overview of gas cloud coverage and ignition locations.](image)

As shown in Figure 5.13, three explosion examples are simulated based on different leak rates: 96 kg/s, 48 kg/s, and 24 kg/s. The explosive gas clouds are set at the north and east ends of the model. The ignition is in the center of the gas cloud located in the east and north ends of the platform. The gas explosion blast is seen spreading from the ignition center to all surrounding objects, and the maximum overpressures are observed in the congested region near the edge of the gas cloud.
(a) Leak rate of 96 kg/s  
(b) Leak rate of 48 kg/s  
(c) Leak rate of 24 kg/s

Figure 5.13 Gas explosion simulation examples based on different leak rates.

Figure 5.14 Example illustrating the influence of blast wall
In order to consider the influence of blast walls, a blast wall is modelled in front of the west end of the living quarter and two monitors are set at both sides of the blast wall. A large overpressure of approximately 1.8 bar can be observed at the left side of the wall under the leak rate of 96kg/s as shown in Figure 5.14. However, after the overpressure reduction by the blast wall, the overpressure at right side of the wall is only about 0.2 bar.

In order to consider all gas dispersion output as input in the gas explosion simulations, 120 explosion cases are numerically modelled. The 120 gas explosion cases are corresponding to former dispersion simulations consisting of 4 leakage rates, 2 leakage directions, 3 gas release locations and 5 different series of blast wall layout designs (Li, 2015). The overpressure of each case is calculated by FLACs and the overall cumulative curve of gas explosion simulations is summarized in Figure 5.15. Equal frequencies are allocated to all monitored overpressures for the living quarters, which are sorted from small to large.

![Image of cumulative curve of overpressure for living quarters](image)

**Figure 5.15 Cumulative curve of overpressure for living quarters.**

**Frequency analysis.**

A simple illustrative explosion frequency calculation is performed in this section. The exceedance curve of frequency against overpressure at the living quarters is formed by using the monitored overpressures over 1000 scenarios.

To simplify the analysis process, the leak frequencies of different leak rates are assumed to be the same. Based on the data from the Purple Book (Uijt & Ale, 2005), the leak frequency is taken as $3.33 \times 10^{-1}$ per year. Moreover, based on the ignition intensities and the previously performed dispersion simulations, the ignition probability is determined to be 0.36%. The
The explosion frequency is consequently calculated by multiplying the leak frequency and ignition probability. Therefore, the total explosion frequency is approximated at $1.2 \times 10^{-3}$ per year.

Consequently, the explosion risk regarding the living quarters subjected to overpressures of VCE from the liquefaction modules is evaluated, and the probability of exceedance curves with a frequency of $10^{-4}$/year is shown in Figure 5.16.

**Figure 5.16** Exceedance curve of overpressures around the living quarters for all leak rate scenarios.

From Figure 5.16, it can be seen that the maximum overpressure is about 0.4 bar in the living quarters. With the application of the ALARP concept, the accepted zone starts from 0.2 bar, which means that no further risk reduction method is required if the maximum strength of the primary components of the FLNG is designed to be larger than 0.2 bar, which corresponds to a frequency of $10^{-5}$. Otherwise, risk reduction measures are required until the design strength proves to be at least greater than 0.05 bar (corresponding to $10^{-4}$) and also proves to be as low as reasonably practical.

### 5.4 SUMMARY

In conclusion, a more efficient multi-level explosion risk analysis method (MLERA) is proposed in this chapter. This method includes three levels of assessment, which are qualitative risk screening for an FLNG facility at the first level, semi-quantitative risk classification for
sub-sections at the second level, and quantitative risk calculation for the target area with the highest potential risks at the third level.

Since the current design standards for normal offshore platforms are not sufficient for assessing explosion risks of super-large offshore structures, during the risk screening and risk classification processes, safety barriers are used as extra risk indicators beyond the traditional ones such as congestion, confinement, ventilation, etc. As mentioned, with only traditional standards, FLNG platforms will always be defined as high risk. However, with the extra contributors of safety barriers, the target FLNG facility is able to be defined as having relatively low, medium, or high risks, which provides a possibility for further assessments.

For detailed quantitative risk assessment, a CFD software, FLACS, is used to model and analyse the target FLNG platform. The results are shown as an exceedance curve, which describes the possibilities of overpressure at the target area. Then, an ALARP method is selected as a calibration tool to decide if the explosion loads from the exceedance curve can be accepted or not. If the overpressure exceeds the acceptable limitation, it is necessary to install safety barriers, and further assessments are required until the final results show that the risk is reduced to an acceptable level and as low as is reasonably practical.

Throughout the three levels of risk assessment, the areas with the highest level of potential risks are assigned to be assessed first and to decide if further assessment is necessary or not. From the case study, it can be seen that only half of the subsections on the selected model require detailed assessment by using FLACs if the analysis focuses on the living quarters, which means that a large amount of calculation time is saved.
CHAPTER 6. CONFIDENCE-BASED QUANTITATIVE RISK ANALYSIS FOR OFFSHORE ACCIDENTAL HYDROCARBON RELEASE EVENTS

6.1 INTRODUCTION

In this chapter, in order to enable a more reliable risk evaluation, a confidence-based quantitative risk analysis method is developed by implementing fuzzy set theory into traditional event tree analysis. Hydrocarbon release-related risks will be the focus of this study because hydrocarbon release plays a critical role in explosion accident risks of process facilities. 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. Therefore, the BORA method is selected to be the basic model to demonstrate the confidence level-based method.

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 (Brandsater, 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 modelling of risks may also cause uncertainties (Vinnem, 2007).

Three of the most common approaches for representing and reasoning with uncertainties are Monte-Carlo simulation (Vose, 1996), Bayesian probability theory (Bernardo, & Smith, 2009), and fuzzy set theory (Zadeh, 1965). In 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). Therefore, a fuzzy set theory-based confidence level method is proposed 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.

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 & 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 modelling 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.

6.2 CONFIDENCE LEVEL-BASED BORA-RELEASE METHOD

6.2.1 Brief introduction of the BORA method

The BORA-Release method has been proposed to analyse 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, Skelt, & Vinnem (2006) described the process using eight steps: (1) developing a basic risk model; (2) modelling 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); (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 organisational 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, Vinnem, & Aven (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.
6.2.2 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 Figure 6.1.

![Figure 6.1 Schematic of the proposed confidence level method framework.](image)

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:
**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 Equation (6.1).

\[
\mu_{\tilde{A}}(x) = \begin{cases} 
0 & \text{for } x < a_1 \\
\frac{a_2}{b(a_2-a_1)} e^{b(a_2-x)^n} & \text{for } a_1 \leq x < a_2 \\
1 & \text{for } x = a_2 \\
\frac{x-a_2}{b(a_3-a_2)} e^{b(x-a_2)^n} & \text{for } a_2 < x \leq a_3 \\
0 & \text{for } x > a_3 
\end{cases}
\] (6.1)

where \( a_2 \) is the center of a fuzzy membership curve, which represents the expert judgment value; \( a_1 \) and \( a_3 \) represent the values of the upper and lower bounds; \( n \) is the confidence factor, and \( b \) is a boundary index used to control the boundary of the membership function in order to ensure the membership is smaller than or equal to \( \Delta \alpha \) when \( x = a_1 \) or \( a_3 \). To achieve this, the boundary factor \( b \) needs to equal or be smaller than \( \ln \Delta \alpha \). An example of the bell-shaped curve is depicted in Figure 6.2.

![Figure 6.2 Example curve of a bell-shaped fuzzy number.](image-url)
To form the triplets for the BORA models, the RIF-revised probability can take the value of $a_2$ to represent the center of the bell-shaped curve and the experts need to define the lower limit and higher limit of the probabilities to find the values of $a_1$ and $a_3$.

**Fuzzy calculations**

Initiating event and safety barriers in the BORA event tree are analysed separately using the L-R bell-shaped fuzzy number in the second step. Then, a total fuzzy number is derived using $\alpha$-cut arithmetic operations.

When multiple events require modification according to the confidence-based bell-shaped fuzzy number, the $\alpha$-cut operation is selected to execute the arithmetic operations of fuzzy numbers based on the extension principle proposed by Zadeh (1965). The basic rules of the $\alpha$-cut arithmetic operations are illustrated by Eqs. (2), (3), (4), and (5). The fuzzy membership curve of each component is pictured and a final diagram is derived using an $\alpha$-cut operation as shown in Figure 6.3.

$$A_\alpha = \{x|x \in R, \mu_A(x) \geq \alpha\} \equiv \text{the } \alpha\text{-cut of } \tilde{A},$$

$$B_\alpha = \{x|x \in R, \mu_B(x) \geq \alpha\} \equiv \text{the } \alpha\text{-cut of } \tilde{B},$$

then,

$$A_\alpha(+)B_\alpha = [a_1^\alpha, a_2^\alpha](+) [b_1^\alpha, b_2^\alpha] = [a_1^\alpha + b_1^\alpha, a_2^\alpha + b_2^\alpha] \quad (6.2)$$

$$A_\alpha(-)B_\alpha = [a_1^\alpha, a_2^\alpha](-) [b_1^\alpha, b_2^\alpha] = [a_1^\alpha - b_2^\alpha, a_2^\alpha - b_1^\alpha] \quad (6.3)$$

$$A_\alpha(\times)B_\alpha = [a_1^\alpha, a_2^\alpha](\times) [b_1^\alpha, b_2^\alpha] = [a_1^\alpha \times b_1^\alpha, a_2^\alpha \times b_2^\alpha] \quad (6.4)$$

$$A_\alpha(\div)B_\alpha = [a_1^\alpha, a_2^\alpha](\div) [b_1^\alpha, b_2^\alpha] = [a_1^\alpha \div b_2^\alpha, a_2^\alpha \div b_1^\alpha] \quad (6.5)$$

where $(+),(-),(\times),\text{and}(\div)$ represent fuzzy addition, subtraction, multiplication, and division respectively.
Defining the confidence level of the RIF scoring process

The confidence levels are classified into five categories. The values of the fuzzification factors are given in Table 6.1. A diagram of each confidence level can be obtained by assigning different confidence factors to the fuzzy membership equation. The bell-shaped fuzzy number has the ability to represent different confidence levels by transforming its shapes, which can be done using different confidence factors as shown in Figure 6.4. The larger value for the confidence factor, $n$, represents the lower confidence level, which also means the existence of more uncertainties.

Figure 6.3 Illustration of $\alpha$-cut operations for multiple components.
Table 6.1 Category of confidence levels

<table>
<thead>
<tr>
<th>Confidence level</th>
<th>Description</th>
<th>Confidence factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very confident</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>Confident</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>Neutral</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>Unconfident</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>Very unconfident</td>
<td>3</td>
</tr>
</tbody>
</table>

In general, safety experts can define the confidence level of judgments based on the degree of uncertainties from four aspects (Cho et al., 2002): (1) the complexity of the judgmental condition; (2) the level of education, assurance, and experience; (3) the condition of data (sufficient/insufficient/none); (4) the standard of the analysis method, and the higher the degree of uncertainties, the lower the confidence level.

Deciding the degree of optimism and defuzzifying the final fuzzy number

In order to match the $\alpha$-cut operations and to acquire complete information, the defuzzification method with a total integral value (Liou & Wang, 1992) is chosen and a factor, $\delta$, of the optimism levels is used to represent the attitude of the decision-maker. Thus, for the L-R bell-shaped fuzzy number, the total defuzzified integral value will be:
\[ I_T^\delta(\tilde{A}) = (1 - \delta)I_L(\tilde{A}) + \delta I_R(\tilde{A}) \quad \delta \in [0,1] \]  

\[ I_L(\tilde{A}) = \sum_{\alpha=0}^{1} \alpha_i(\tilde{A})\Delta\alpha \]  

\[ I_R(\tilde{A}) = \sum_{\alpha=0}^{1} \alpha_i(\tilde{A})\Delta\alpha \]  

where \( I_L(\tilde{A}) \) and \( I_R(\tilde{A}) \) are the left and right integral values of \( \tilde{A} \) respectively; \( \delta \) is the optimism factor; and \( I_T^\delta(\tilde{A}) \) is the total integral value with the influence of \( \delta \).

When \( \delta = 0 \), the total integral value represents the optimistic viewpoint of the decision-maker. Alternatively, for a pessimistic or moderate decision-maker, \( \delta \) equals 1 or 0.5 respectively.

The degree of optimism is also classified into five categories and the values of the optimism factor, \( \delta \), are given in Table 6.2. After determining the attitude, the safety engineers/managers are able to find an appropriate probability of hydrocarbon release risks for their offshore facilities. Finally, the total integral method is used to defuzzify the final result of the fuzzy analysis and to apply the final probability to the BORA risk model.

**Table 6.2 Category of optimism factors**

<table>
<thead>
<tr>
<th>Optimism level</th>
<th>Description</th>
<th>Optimism factor ( \delta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Very optimistic</td>
<td>0.1</td>
</tr>
<tr>
<td>B</td>
<td>Optimistic</td>
<td>0.3</td>
</tr>
<tr>
<td>C</td>
<td>Neutral</td>
<td>0.5</td>
</tr>
<tr>
<td>D</td>
<td>Pessimistic</td>
<td>0.7</td>
</tr>
<tr>
<td>E</td>
<td>Very pessimistic</td>
<td>0.9</td>
</tr>
</tbody>
</table>

### 6.2.3 Assumptions for practical implementation of the proposed method

For the practical implementation of the proposed method, the following assumptions need to be noted:

- The proposed method is assumed to be useful for dealing with uncertainties that are related to subjective judgments.
- The proposed fuzzy membership function is assumed to be formed by a triplet \( \tilde{A} = (a_1, a_2, a_3) \). Therefore, for the practical implementation of the proposed method, the experts may be required to define the probabilities for the lower and higher boundaries.
The confidence and optimism levels in this study are assumed to be divided into five levels. However, the number of the levels and the specific values of confidence and optimism factors can be decided by the specific conditions of real projects.

The memberships of two bounds, $a_1$ and $a_3$, are assumed to be 0. Therefore, to achieve this assumption, it is suggested that $\Delta \alpha$ should equal or be smaller than 0.01 in the defuzzification process in order to make the membership of both bounds close to 0.

6.3 CASE STUDY

6.3.1 Application of the proposed method to the BORA model - Scenario B

For a better understanding of the application using the suggested procedure, a typical case study is described here as an illustration based on the case study of risk scenario B from the work of Sklet et al., (2006). The barrier block diagram of risk scenario B is shown in Figure 6.5 and all relevant results for scenario B (Sklet et al., 2006) are listed in Table 6.3.

![Diagram](image)

Figure 6.5 Scenario B: Release due to incorrect fitting of flanges during maintenance.
### Table 6.3 Scenario B: Industry probabilities/frequencies from the BORA method

<table>
<thead>
<tr>
<th>Description</th>
<th>Event Description</th>
<th>Average Probability: $P_{\text{ave}}$</th>
<th>Lower Bound: $P_{\text{low}}$</th>
<th>Higher Bound: $P_{\text{high}}$</th>
<th>Revised Probability: $P_{\text{rev}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of incorrect fitting of flanges or bolts after inspection per year</td>
<td>$f(B0)^a$</td>
<td>0.84</td>
<td>0.168</td>
<td>4.2</td>
<td>1.064</td>
</tr>
<tr>
<td>Probability of failure to reveal failure by self-control</td>
<td>$P_{\text{Failure}}(B1)^b$</td>
<td>0.34</td>
<td>0.069</td>
<td>0.69</td>
<td>0.37</td>
</tr>
<tr>
<td>Probability of failure to reveal failure by third party control</td>
<td>$P_{\text{Failure}}(B2)^c$</td>
<td>0.11</td>
<td>0.022</td>
<td>0.55</td>
<td>0.15</td>
</tr>
<tr>
<td>Probability of failure to detect release by leak test</td>
<td>$P_{\text{Failure}}(B3)^d$</td>
<td>0.04</td>
<td>0.008</td>
<td>0.2</td>
<td>0.066</td>
</tr>
<tr>
<td>Total release frequency from scenario B per year</td>
<td>$f_{\text{B_{total}}}$</td>
<td>0.0012</td>
<td>2.04E-6</td>
<td>0.32</td>
<td>0.0038</td>
</tr>
</tbody>
</table>

Figure 6.5 describes the basic event tree model for the incorrect fitting of flanges during maintenance. There are three safety barriers in this scenario and the relationship between the initiating event and all barriers are in series. Thus, the only arithmetic calculation required in this event tree analysis is multiplication. From Table 6.3, it can be observed that the frequency of the higher bound (0.32) is approximately 100 times larger than the revised average frequency (0.0039) after the multiplication calculations, and this huge difference represents the range of uncertainties.

Table 6.4 shows that the values of $P_{\text{low}}, P_{\text{rev}},$ and $P_{\text{high}}$ for the initiating event B0 and safety barriers B1, B2, and B3 are applied to triplets $\tilde{B} = (b_1, b_2, b_3)$. Equation (6.1) and the $\alpha$-cut operations are used to conduct the analysis of the fuzzy numbers with $\Delta \alpha = 0.01$ and $b = -7$. After defuzzification, the final modified probabilities based on confidence levels and optimism levels will be acquired using Equation (6.6).

### Table 6.4 Values for triplets of initiating event and basic events

<table>
<thead>
<tr>
<th>Events $\tilde{B}$</th>
<th>Triplets Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{B}(B0)$</td>
<td>0.168 1.064 4.2</td>
</tr>
<tr>
<td>$\tilde{B}(B1)$</td>
<td>0.069 0.37 0.69</td>
</tr>
<tr>
<td>$\tilde{B}(B2)$</td>
<td>0.022 0.15 0.55</td>
</tr>
<tr>
<td>$\tilde{B}(B3)$</td>
<td>0.008 0.066 0.2</td>
</tr>
</tbody>
</table>
Figure 6.6 illustrates the final results using different confidence factors for scenario B. As can be seen from the diagrams, the right-hand side has a more significant dispersion than the left-hand side while the confidence level decreases, which means that the right-hand side dominates the influence of the uncertainties. This is due to the probability deviation between $P_{rev}$ and $P_{high}$ (approximate 0.3) being much larger than that between $P_{rev}$ and $P_{low}$ (approximate 0.003).

![Figures 6.6](image)

(a) $n = 0.1$  
(b) $n = 0.5$  
(c) $n = 1$  
(d) $n = 2$  
(e) $n = 3$

Figure 6.6 Final fuzzy number curves with different confidence levels for scenario B.
Table 6.5 represents the final modified industry probabilities after defuzzification according to five confidence levels with a moderate attitude only. As can be observed, the modified probability with the highest confidence level equals the revised frequency of the BORA method, and as the confidence level decreases, the probability of hydrocarbon release increases. However, since there are four components that require adjustments in the event tree analysis of scenario B, the deviations among the modified frequencies by different confidence levels become very large. As shown in Table 6.5, there are about 10 times the differences from confidence level 1 (0.0039) to level 5 (0.034).

<table>
<thead>
<tr>
<th>Confidence level</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modified industry probabilities/frequencies</td>
<td>0.0039</td>
<td>0.0048</td>
<td>0.0085</td>
<td>0.021</td>
<td>0.034</td>
</tr>
</tbody>
</table>

### 6.3.2 Results discussion

From Table 6.3, it can be concluded that the BORA method considers the platform-specific operational factors and quantifies those operational factors to modify the industrial average value. However, according to the degree of data adequacy and the RIF scoring method standard, the revised industrial frequencies may have certain amounts of uncertainties. Those uncertainties will affect the result significantly when the higher bound of the industrial probabilities are observed to be much higher than the revised frequencies, for example, 100 times in scenario B (0.32 for the higher bound and 0.0038 for the revised value). Therefore, it is unrealistic to determine the likelihood of an initial event or the failure of barrier functions using one definite value.

From Table 6.5, it can be observed that the confidence level divided revised industrial average probabilities into five groups from confident level 1 to 5. With the highest confidence level, the experts can obtain the same probability acquired from the BORA method. However, for the lower level of confidence, more uncertainties are considered, which causes a higher frequency of hydrocarbon release risks. Compared to the risk difference calculated by the BORA method between the revised industrial average probability (0.0039) and the higher bound probability (0.32), the difference has been decreased dramatically by defining the probability with the lowest confidence level (0.034), as shown in the results. This difference reduction mitigates the influence of uncertainties by 10 times for the situation with insufficient experience and data.
Based on the five levels of confidence classification, the proposed method quantifies the uncertainties into five ranges, and then assists the experts to estimate the risks more realistically based on their specific confidence levels.

6.3.3 Sensitivity analysis of the optimism factor

Sensitivity analysis is performed for the optimism factor to observe the influence of different attitudes on the final results of risk evaluations. Table 6.6 shows the results with different optimism factors. It can be observed that the influence of the optimism factor has more effect on the final frequencies when the confidence level is lower. For instance, the industrial frequency remains the same when experts have the highest confidence level, while differences of 0.0021, 0.0093, 0.031, and 0.053 occur when the confidence levels equal 2, 3, 4, and 5 respectively.

<table>
<thead>
<tr>
<th>Optimism Level</th>
<th>Confidence Level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>A</td>
<td>0.0039</td>
</tr>
<tr>
<td>B</td>
<td>0.0039</td>
</tr>
<tr>
<td>C</td>
<td>0.0039</td>
</tr>
<tr>
<td>D</td>
<td>0.0039</td>
</tr>
<tr>
<td>E</td>
<td>0.0039</td>
</tr>
</tbody>
</table>

Therefore, it can be concluded that the attitude of safety experts will have more effect on the final risk estimates when the confidence level is lower. For example, in the risk analysis of scenario B, if the experts are very confident about their risk assessments, it is unnecessary for them to decide the optimism factor because the final result will remain the same, at 0.0039. However, when the experts are very unconfident, the modified probability may change to 0.047 rather than 0.034 from the lowest confidence level in Table 6.6 if a conservative design is favored, or a lower probability (0.0204) is also probable if it is evaluated that the platform condition and operational standard are underestimated.
6.4 SUMMARY

In conclusion, QRA plays an increasingly important role in offshore risk analysis. However, the accuracy and validity of QRA are significantly affected by uncertainties. This chapter proposed a new methodology for incorporating uncertainties using confidence levels into conventional QRA. It also introduced a new form of the bell-shaped fuzzy number, designed to consider the degree of uncertainties that are represented by the concept of confidence levels, since it is unrealistic to define the probability of an event by one single explicit value.

As mentioned in the results discussion, it can be seen that the influence of the uncertainties has been reduced by approximately 10 times. Therefore, based on the results from the case study, it is concluded that the proposed confidence level methodology can be very helpful for offshore safety experts to improve the validity of risk evaluations by reducing the impact of subjective judgment-related uncertainties. In addition, it also provides a useful tool for safety experts to make more realistic and accurate risk estimates based on the confidence level evaluations of their risk assessments.

When large-scale process systems are considered, the final risk may increase significantly if the experts are very unconfident about their risk assessments at every step or most steps of the large-scale process. Otherwise, if they are only unconfident about a few steps of the whole process, the final risk estimates should not show large difference from the initial results. However, whichever condition occurs, the proposed method should be able to provide a more realistic result because the differences are dominated by the uncertainties and larger quantities of uncertainties cause larger differences.
CHAPTER 7. CONCLUSION REMARKS

7.1 MAIN FINDINGS

The thesis carries out a comprehensive study on the risk analysis of explosion accidents at oil and gas facilities. An advanced Bayesian network–based quantitative explosion risk analysis method is proposed to model risks from initial release to consequent explosions and human losses because of the ability of the Bayesian network to reveal complicated mechanisms with complex interrelationships between explosion risk factors. Another major concern of the present study is gas explosion risk analysis for process facilities close to residential areas, which may lead to catastrophic consequences. A grid-based risk-mapping method is developed to enable efficient and reliable explosion risk analysis for large areas under complicated circumstances. A multi-level explosion risk analysis method (MLERA) is developed for assessing explosion risks of super-large oil and gas facilities with highly congested environments. Finally, a confidence level–based approach is proposed for incorporating uncertainties into conventional risk analysis using the concept of fuzzy theory.

A more accurate BN-based quantitative risk analysis method is developed for explosion and fire accidents at petrol stations. Two case studies show that petrol leaks may lead to human loss such as death or injury with a probability of approximately 3% and 2% when explosion and fire occurs, respectively. The case studies prove that the BN can deal with complicated interrelationships and provide a more accurate risk analysis. Sensitivity studies are conducted in this research, and the results indicate that smoking is the most dangerous ignition source, overfill is the most probable cause of release while hose rupture may cause the most catastrophic consequences, refueling jobs are better conducted at nighttime, and tanker explosions and fires at petrol stations increase human losses.

A more detailed grid-based risk-mapping method is established for explosion events. This method uses a Bayesian network (BN) as a risk analysis tool to estimate multiple consequences and related probabilities for each grid. Based on the results of all the grids, 3-D bar charts are formed to describe the risks of explosion loads, building damage, and human loss. A case study is conducted to demonstrate the applicability of the proposed method. From the case study, it can be concluded that the method provides a more detailed risk analysis of a large site with complex conditions. Meanwhile, the results of 3-D risk-mapping charts offer a clear view of potential risks, which is useful for risk and safety management during the planning,
construction, and operation stages. A mesh convergence study was also conducted, and a grid size of $50 \times 50$ m was found to be most appropriate over a domain range of $2 \times 2$ km.

A more efficient multi-level explosion risk analysis method (MLERA) is developed for massive oil and gas facilities. This method includes three levels of assessment, which are qualitative risk screening for an FLNG facility at the first level, semi-quantitative risk classification for subsections at the second level, and quantitative risk calculation for the target area with the highest potential risks at the third level. Throughout the three levels of risk assessment, the areas with the highest level of potential risks are assigned to be assessed first and to decide if further assessment is necessary or not. From the case study, only half of the subsections on the selected model require detailed assessment by using FLACs if the analysis focuses on the living quarters, which means that a large amount of calculation time is saved.

A more reliable risk analysis method for incorporating uncertainties using confidence levels into conventional QRA is proposed. It also introduced a new form of the bell-shaped fuzzy number, designed to consider the degree of uncertainties that are represented by the concept of confidence levels. From the case study, the influence of the uncertainties has been reduced by approximately 10 times. Therefore, the proposed confidence level methodology can be very helpful for safety experts to improve the reliability and validity of risk evaluations by reducing the impact of subjective judgment–related uncertainties.

### 7.2 RECOMMENDATIONS FOR FUTURE WORK

Further investigation could be made in future studies as follows.

First, the application of BN modelling can be widely extended to other scenarios of risk analysis, and if required, more consequences such as environmental concerns and business losses, or more risk factors such as human factors and safety barriers, can also be easily added to the current BN to enable a more detailed explosion risk assessment. Meanwhile, the explosion risk assessment method proposed in Chapter 3 can be validated if detailed information and environments of oil gas facilities and damage incurred in explosion accidents become available. In addition, BN modelling can be further improved by reducing the uncertainties which may significantly affect the reliability of BN. Therefore, future studies will focus on the methods that can mitigate uncertainties caused by data shortage, subjective judgments, and modeling errors and, consequently, improve accuracy and reliability of BN.
Second, for explosion risk analysis of large oil and gas facilities with complex structures and environments, it is suggested that a grid-based risk analysis method provide a more detailed and accurate risk analysis compared with traditional QRAs by simplifying the complicated conditions throughout the gridding process. A computer program is composed to conduct BN calculations automatically for all the grids to ensure the efficiency of the proposed model. However, the efficiency of the present method can be further improved by image identification technologies because the current assessment of building damages and human losses are handled manually. Meanwhile, since the GIS output of PHAST results can only be depicted as circled regions, the overpressure at each grid has to be defined manually as well. Therefore, the future work in this part aims at developing a completely automatic grid-based risk analysis method by implementing other advanced image-processing technologies.

Third, in terms of the multi-level method, it has been successfully applied to a cylindrical offshore FLNG platform. However, since the selected platform is newly designed and information for explosion risk screening and classification is not sufficient, the result of the current case study is quite conservative; only half of the calculation time can be saved. It can be further improved when more detailed information is acquired. In addition, it is probable for the proposed method to be applied to other large offshore or onshore process facilities. Nevertheless, weights and scores of explosion risk contributors and barriers should be adjusted based on the specific conditions of real projects.

Furthermore, since the confidence-based method can effectively deal with uncertainties related to experts’ judgments for the BORA method, it is expected that the proposed methodology also have the ability to be successfully applied to various types of QRAs with only minor modifications of specific characteristics for each QRA. However, it needs to be clarified that the confidence level factors presented are only an illustrative example. It barely considers any practical conditions of actual offshore hydrocarbon release risk analysis. Thus, future work will focus on the establishment of a detailed confidence level category in accordance with real situations for hydrocarbon release QRA to provide the risk analyst with a more applicable and operable methodology.

Meanwhile, other than the possible future improvements for the works done in the current thesis, some more big issues and challenges in the related research area are also discussed here.
First, in order to enable a reliable risk analysis, accurate prediction of gas explosion overpressures is very important. However, the current numerical methods used to simulate gas explosions is not able to reach a high level of accuracy. Empirical models are simple ones proposed based on experimental results and can barely consider the influence created by the nearby structures. CFD methods are more advance than empirical method. A wide range of geometrical arrangements and conditions in the gas cloud can be considered by discretizing the solution domain in both space and time. However, CFD methods are not fully developed up to now. For example, the far field transportation of fluid flow caused by the initial gas explosion cannot be calculated. Therefore, the further development of numerical method may improve the explosion risk analysis significantly.

Second, data is a big issue for the current study of risk analysis. As the gas explosion events are rare to occur compared to other extreme events such as fire or earthquake, the data which can be collected is already insufficient at the first stage. Meanwhile, records of previously occurred explosion accidents can be hardly to find. During my PhD study of gas explosion risk analysis, data shortage is always one for the most critical issues. Therefore, developing a data source of explosion events which can be fully accessed by the public can be a very meaningful work for future risk analysis.

Third, the current risk analysis of gas explosions requires high level of practical experience. As the explosion procedure of oil and gas facilities are quite complicated, the familiarity with the oil and gas structures and equipment is critical to a reliable gas explosion risk analysis. However, due to the fast development of oil and gas facilities, there may not be enough experienced engineers or technicians to conduct risk analysis for all of the facilities. Therefore, developing risk analysis methods which can be easily understood and applied will be another important work in the future study.
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