RISK-BASED DESIGN TOOLS FOR PROCESS FACILITIES

by

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Abstract

Process facilities include operations with different levels of risks. Risk-based design incorporates risk analysis into the design process and thus facilitates discovering design limitations and making improvements with respect to process safety. This work presents two risk-based design tools: (i) a hazard identification methodology and (ii) a risk-based layout optimization technique.

The first tool developed and presented in this research is for dynamic hazard identification. In risk assessment, the first major step is hazard identification that helps to unveil what may go wrong during operation of a process. Traditional hazard identification tools have the limitations of being static in nature; changing circumstances are not considered in the existing tools. Therefore, the present work develops a new methodology which realizes hazard identification by tracing hazard evolutions. A generic model is proposed. The model is dynamic in making predictions for the most likely hazard in terms of different input evidences based on field observations.

A risk-based design is to design for safety. Means of conducting risk-based design can be various. The second aspect of this thesis presents a risk-based design method that uses inherent safety metrics for layout optimization of floating liquefied natural gas (FLNG) facilities. Layout plays a paramount role in hazard evolution and thus affects the risk of an operation. Three topside layouts are proposed and evaluated using inherent safety indices. Finally, a layout is chosen as the most optimal one in terms of layout evaluation results. In this way, the layout becomes inherently safer and thus brings tremendous benefits to reducing risks as well as potential loss.

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List of Symbols, Nomenclature and Abbreviations

FLNG	Floating Liquefied Natural Gas Facility
QRA	Quantitative Risk Analysis
PRA	Probabilistic Risk Analysis
HAZOP	Hazard and Operability Study
FMEACA	Failure Mode, Effects, and Criticality Analysis
BN	Bayesian Network
VCE	Vapor Cloud Explosion
BLEVE	Boiling Liquid Expanding Vapor Explosion
CPT	Conditional Probability Table
GT Module	Gas Treating Module
PMR Module1	Pre-Mixed Refrigerant Module 1
PMR Module 2	Pre-Mixed Refrigerant Module 2
MR Module	Mixed Refrigerant Module
I2SI	Integrated Inherent Safety Index
HI	Hazard Index
DI	Damage Index
PHCI	Process and Hazard Control Index
HCI	Hazard Control Index
ISI	Inherent Safety Index
ISIa	Inherent Safety Index (Attenuation)
ISIs	Inherent Safety Index (Simplification)

ISIl	Inherent Safety Index (Limitation)
CSCI	Conventional Safety Cost Index
CSC	Conventional Safety Cost
Closs	Expected Loss Caused by Accidental Events
ISCI	Inherent Safety Cost Index
ISC	Inherent Safety Cost
LSI	Loss Saving Index
DHI	Domino Hazard Index
DHIi,k	DHI Score for Secondary Units

Co-authorship Statement

In all the papers presented in the following chapters, I am the principal author. I carried out the practical aspects of the research and completed data analysis. My supervisors, Dr. Faisal Khan and Dr. Salim Ahmed contributed by providing theoretical guidance and technical suggestions in the progress of the research. I prepared the first drafts of manuscripts. Co-authors Dr. Faisal Khan and Dr. Salim Ahmed assisted in reviewing and revising the paper drafts. I continuously revised the manuscript in terms of co-authors' revisions and suggestions as well as the feedback of peer review from the journals where the papers were submitted.

Chapter 1. Introduction

1.1 Risk-Based Design

Risk of an event can be expressed as the frequency of the event multiplied by the severity of its associated consequence. An event may bring unexpected and sometimes catastrophic outcomes for which huge a cost must be paid to compensate for losses including human loss, asset loss, or environmental loss. Process industries are considered risky due to the frequent occurrence of process incidents. To lower risk to a practical and acceptable level, risk-based design has become a complementary approach along with traditional design. Risk-based design incorporates risk analysis into the design process and provides support for decision-making to meet safety purposes in a cost-effective way (Papanikolaou, 2009). The advantages of risk-based design over traditional approaches are listed in Thodi's (2011) work. Simply put, a risk-based design is to design for safety. The ultimate goal is to make the total risk meet the following criterion:

where is the estimated risk, and is risk threshold regulated by engineering safety authorities (Hamann and Peschmann, 2015).

The framework of conducting a risk-based design is shown in Figure 1.1. In general, it consists of three major steps: define safety goals, implement risk analysis, and assess risk acceptance. The first step is to define a preliminary safety objective. In this step, design parameters are varied in compliance with process requirements. Then, the tuned design goes through a risk analysis process. Risk assessment includes hazard identification, frequency analysis, and consequence analysis. In this step, the risks are both qualitatively and quantitatively defined. Finally, the assessed risk is compared with the threshold as previously defined to decide whether the risk associated with the current design is acceptable. The relative level and absolute level are the two options to determine the risk threshold. The relative level is used to select a reference design, while the absolute level refers to engineering safety standards or other conventions specified by authorities (Boulougouris and Papanikolaou, 2013).

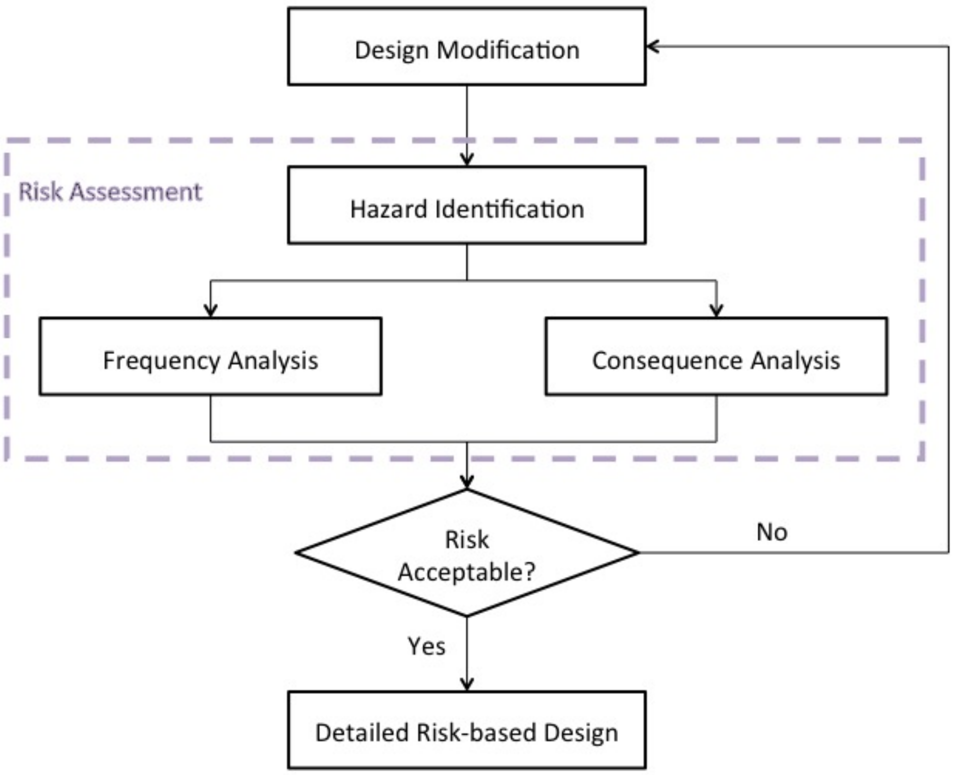

Figure 1.1 Risk-based design framework

1.2 Risk Assessment

Risk assessment is the core of a risk-based design which is a systematic approach to evaluate a design from safety perspectives. There are three main components of risk assessment; hazard identification that addresses what may go wrong for a process, frequency analysis that defines how frequently it might happen and consequence analysis that identifies what outcomes it may bring.

The essence of risk is uncertainty and casualty. An uncertainty always has two directions to evolve. Useful risk assessment helps to predict what will occur next among casualties and to improve risk management decision-making, which increases the probability of having preferred outcomes and avoiding hazards (Cox Jr, 2013).

1.2.1 Hazard Identification

Hazard identification is the first step in risk assessment. A hazard and its adverse impact cannot be fully understood until it is identified. Methods of hazard identification have been developed for decades and can be roughly described as either qualitative or quantitative. Qualitative methods are generally achieved by listing all possible hazards, finding the causes, and studying how to improve systems to avoid these hazards.

Typical and well-known qualitative hazard identification approaches are What-if analysis, and Hazard and Operability (HAZOP). Details of these approaches and associated applications can be found in Kletz (1997); Dunjo, Fthenakis, Vilchez, & Arnaldos (2010); Nolan (1994); and Chen, Zhu, & Chen (2011). Nolan (2011) discussed the limitations and advantages of these along with Preliminary Hazard Analysis (PHA). In fact, many other qualitative approaches have also attracted enough attention and become quite comprehensive, such as Failure Mode and Effect Analysis (FMEA), checklist, and fault & event tree (Mannan, 2012). Some of these approaches are continuously evolving, e.g. Computer HAZOP, social HAZOP, and Failure mode, Effects, and Criticality Analysis (FMEACA). The illustration can be found in Mannan (2012), Ericson (2005), and Avila, Pessoa, & Andrade (2013)'s work.

Quantitative hazard identification varies using index-based approaches and ranking systems. The ranking system hierarchizes hazards, and accordingly the most hazardous potential will be clearly recognized and fully analyzed so that measures can be taken to prevent such a risk from turning into reality.

Most of the index based approaches are used for evaluating fire, explosion, and toxic dispersion, which are the three main hazards in process industries. Representative indices are Dow Fire and Explosion Index, Mond Fire, Explosion, and Toxicity Index, and Dow Chemical Exposure Index (Crowl &Louvar, 2002; Mannan, 2012). Estimation of these indices begins with estimating an initial factor, which is decided by the properties of materials, and then gradually adds other considerations by multiplying the initial factor with other factors. Finally, the hazardous level is quantified by assessing economic loss.

The severity of risk can also be judged by fatalities and injuries. For example, Ordouei, Elkamel, &Al-Sharrah (2014) dedicated a new risk index to estimate the maximum affected people per year by dividing multi process streams and investigating each stream's effects. While some think though fatality is a paramount factor when assessing damage potentials, other factors which might be chronically affected, such as environment contamination and property damage, should also be considered (Khan &Abbasi, 1997). Khan &Abbasi (1998) developed the Accident Hazard Index (AHI), which addressed the hazardous impact on population, assets, and the ecosystem. They also proposed the Hazard Identification and Ranking System (HIRA) (Khan &Abbasi,

1998) which first separates the entire plant into small units, such as storage units and transportation units, and then assesses risks by using functions of penalties. Considering that damage effects from different installed safety devices may vary, Khan &Abbasi (2001) proposed the Safety Weighted Hazard Index (SWeHI) based on HIRA, which considered the quantitative measure of damage as well as the credit value of the safety measures. Khan (2001) provided a worst-scenario identification method by indexing the credibility factor. In addition, Davaselle, Fieves, Pipart, and Debray (2006) presented another comprehensive approach, named ARMIS, to identify major accidents and scenarios based on Bow-tie analysis.

Similar to the use of Bow-tie analysis used in ARMIS, Dynamic Procedure for Atypical Scenarios Identification (DyPASI), developed by Paltrinieri, Tugnoli, Buston, Wardman, &Cozzani (2013) is a dynamic approach for identifying atypical scenarios. It can dynamically retrieve previous risk records because the database can be updated in real time, thus prioritizing of hazards. Dynamic hazard identification is an emerging area which makes breakthroughs to static barriers. Other than DyPASI, other literature presented in this area includes Patrinieri, Tugnoli, & Cozzani (2015) and Knegtering &Pasman's (2013) works. More discussion about dynamic hazard identification is presented in Chapter 2.

1.2.2 Probability Analysis

Probability analysis, or frequency analysis, is an integral part of risk assessment. Probability means the likelihood of a certain event occurring. It is a quotient of the number of events that are expected to occur over the total number of all possible events; therefore, it falls into a range between 0 and 1. The events are random and equal which means each event has the same chance to occur. The randomness of events can be represented by a probability density function, while the probability density function can be represented by mathematical models, i.e. probability distribution, to capture uncertainties in the use of random variables (Kalantamia, 2010). The random variables can be discrete or continuous.

The probability that is most widely applied to process industries is the failure rate. The failure rate is the probability of getting one failure over a period of time. The cause of a failure is based on interactions among process components (Crowl &Louvar, 2001). Event tree and fault tree are the two most commonly used approaches to calculate the failure rate of a system. The mechanism behind them is to investigate logistics for the interactions. The event tree and fault tree have been fully developed and the associated applications can be found in the literature (Huang, Fan, Qiu, Cheng, & Qian, 2016; Liu &Yokoyama, 2015; You &Tonon, 2012). In recent years, dynamic risk assessment has emerged as a new area to deal with information updates. The Bayesian network has become a popular dynamic tool because of its dynamic feature. It enables updating posterior probabilities given prior probabilities, which provides more accurate results by appropriately accommodating new evidences to the existing model. Applications of the combination of a fault tree or event tree and the Bayesian network are documented in Leu &Chang (2015), Khakzad, Khan, &Amyotte (2011), and Sorbradelo &Martí’s (2010) works.

1.2.3 Consequence Analysis

Consequence analysis is also of paramount importance in risk assessment. It identifies the consequences of a potential event and estimates the associated losses it may cause, such as human, environmental, and asset loss.

Accidents start from incidents. An incident could be a fluid leakage or a material failure. To estimate the impact, selecting a proper accident model is necessary so that hazards can be simulated and associated consequences can be estimated. Crowl and Louvar (2002) illustrated a source model which provides a profile of the state of discharge, discharge rate, and total quantity discharged (Center for process safety, 2010). The accident model is decided in terms of the defined accident scenarios; for example, a dispersion model is necessary for a toxic gas release. In addition to the source model, Dadashzadeh (2013) expanded an overview of the approaches to consequence analysis, using empirical modeling, fire and explosion modeling, and computational fluid dynamics modeling.

1.3 Other Forms of Risk Analysis in Risk-Based Design

Risk-based design involves implementation of safety barriers in design and thus creates a safer environment for plant operations. To date, risk-based design has been widely applied to industries, such as marine, nuclear, process, etc. Instead of conducting the risk assessment, other forms of risk analysis are also applied in conjunction with risk-based design. Demichela &Camuncoli (2014) applied a new methodology for risk-based design, namely recursive operability analysis, to the Allyl Chloride production plant. Lee et al. (2015) began with risk-based process safety management and then modified the design for a gas treatment unit at the preliminary stage, to reduce hazards identified from quantitative risk analysis. Bossuyt et al. (2012) presented a new method by means of transferring risk data into risk appetite corrected domain, which helps to make risk-based decisions.

In Chapter 3 of this thesis, safety implementation in design is achieved through layout optimization based on the inherent safety method. Several offshore facility layouts are developed. Then inherent safety indices are used to evaluate whether risks are acceptable. The inherent safety indices are derived from inherent safety design which addresses the safety integrity of facilities and improves the safety intrinsically by eliminating contribution from the potential failure of passive safety devices.

The inherent safety indices evaluate how much the plant is inherently safer. The results yielded from using the indices can be regarded as having the same effect as conducting the risk assessment because the associated mechanisms, such as threshold values or other intermediate values, include the consideration of frequency analysis and consequence analysis.

1.4 Research Objective

The goal of this thesis is to develop design tools to improve the safety of process facilities by means of risk-based design. The thesis includes two research objectives which are reflected in two major works. To help better understand the objectives, the scope is shown in Figure 1.2. The first part aims to develop a new methodology for hazard identification, which is the first step in the risk assessment in a risk-based design. The methodology helps to construct a hazard identification model that is considered as dynamic because of the ability to dealing with changing parameters. The model enables making credible predictions for which hazard will be the most likely to occur in terms of the given evidence. This dynamic identification model overcomes the static barrier that traditional approaches used to have and enables to accommodate information update each time when changing inputs.

The second part employs safety implementation in designing an FLNG facility. The FLNG facility appears to be one favorable solution effectively dealing with remote and small gas fields and has drawn large attention. It combines floating, production, storage, and offloading to one self-driven unit and is a cost effective option due to avoiding the construction of numerous subsea pipelines. An FLNG requires the most advanced technology and a compact design; however, risks have been elevated to a new level. This part outlines the aspects of inherent safety for the topside layout design of an FLNG facility. The FLNG plant requires a compact design and needs the safest layout to tackle multi-dimensional safety issues. Thus, the layout of the facility is a paramount factor for ensuring its safety in a cost effective way. Three layouts are proposed and evaluated from the inherent safety perspective. The layout of the process area is a main focus due to its higher risks. An integrated inherent safety index, a cost index and a domino hazard index are used to evaluate three alternative layouts in quantitative terms. An optimal layout is finally chosen based on both inherent safety and cost performance.

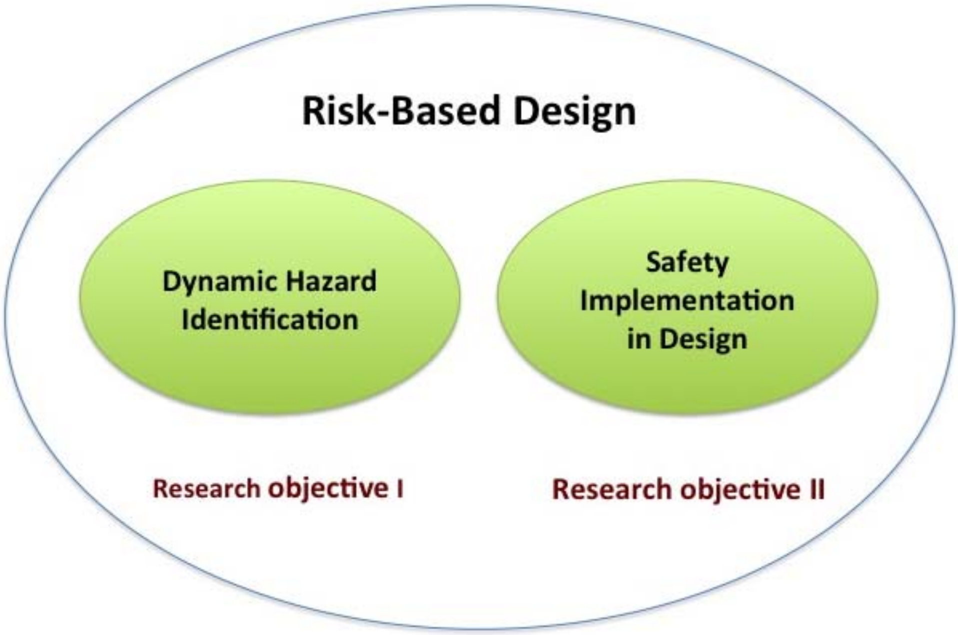

Figure 1.2 Illustration of research objectives

1.5 Thesis Outline

The thesis is structured as follows.

Chapter 2 presents a manuscript published on Process Safety and Environmental Protection and proposes a dynamic hazard identification methodology and a prototype for the dynamic model. This chapter discusses the relation between risk assessment and hazard identification and also the importance of hazard identification, followed by discussing the limits of existing hazard identification techniques. A dynamic hazard identification methodology on the basis of Bayesian network is then developed. Three case studies are conducted to prove whether the proposed model functions effectively. A sensitivity analysis is also performed to study the cause of dominant probabilities appearing in the simulation results.

Chapter 3 presents a manuscript published on Journal of Offshore Mechanics and Arctic Engineering. Chapter 3 performs a layout optimization for a floating liquefied natural gas (FLNG) facilities. In this chapter, the backgrounds of FLNG facilities are first reviewed. Then risks associated with FLNG facilities are discussed. Several topside layouts of an FLNG facility which meet offshore regulations are proposed and evaluated using inherent safety indices, and the best optimized layout is chosen in terms of the layout evaluation results.

Finally, Chapter 4 outlines the summary and conclusions for the current work. Future scope of work in this area is also discussed.

1.6 References

Ávila, S., Pessoa, F., & Andrade, J. (2013). Social HAZOP at an Oil Refinery. *Process Safety Progress, 32*(1), 17-21.

Boulougouris, E., & Papanikolaou, A. (2013). Risk-based design of naval combatants. *Ocean Engineering*, *65*, 49-61.

C. Davaselle, C, Fieves, A. Pipart, B. Debray. ARAMIS project : A comprehensive methodology for the identification of reference accident scenarios in process industries, Journal of hazardous materials 130 (2006), 200-219

Center for Chemical Process Safety. (2000). Guidelines for Chemical Process Quantitative Risk Analysis (2nd Edition). Center for Chemical Process Safety/AIChE.

Chen, X., Zhu, H., & Chen, J. (2011). Hazard Identification and Control in the Pre-Blasting Process. *Journal of Coal Science & Engineering, 17*(3), 331-335.

Cox Jr, L. A. (2013). *Improving risk analysis* (Vol. 185). Springer Science & Business Media.

Crowl, D., & Louvar, J. (2002). Hazard Identification. *Chemical Process Safety Fundamentals with Applications* (2nd ed., pp. 429-47). New Jersey: Prentice Hall PTR.

Demichela, M., & Camuncoli, G. (2014). Risk based decision making. Discussion on two methodological milestones. *Journal of Loss Prevention in the Process Industries*, *28*, 101-108.

Dunjó, J., Fthenakis, V., Vílchez, J., & Arnaldos, J. (2010). Hazard and operability (HAZOP) analysis. A literature review. *Journal of Hazardous Materials,*19-32.

Ericson, N. (2005). *Hazard Analysis Techniques for System Safety*. John Wiley & Sons.

Khan, F., & Abbasi, S. (1997). Accident Hazard Index: A Multi-attribute Method for Process Industry Hazard Rating. *Process Safety and Environmental Protection, 75*(4), 217-224.

Khan, F., & Abbasi, S. (1998). Accident Hazard Index: A Multi-Attribute Method for Process Industry Hazard Rating. *Risk Assessment in Chemical Process Industries* (pp. 305-317). New Delhi: Discovery Publishing House.

Khan, F., & Abbasi, S. (1998). Multivariate Hazard Identification and Ranking System. *Risk Assessment in Chemical Process Industries* (pp. 318-345). New Delhi: Discovery Publishing House

Khan, F., Husain, T., & Abbasi, S. (2001). SAFETY WEIGHTED HAZARD INDEX (SEeHI) A New, User-friendly Tool for Swift yet Comprehensive Hazard Identification and Safety Evaluation in Chemical Process Industries. *Process Safety and Environmental Protection,* 65-80.

Hamann, R., & Peschmann, J. (2015). Goal-Based Standards and Risk-Based Design. *Ship Technology Research*.

Huang, W., Fan, H., Qiu, Y., Cheng, Z., & Qian, Y. (2016). Application of fault tree approach for the causation mechanism of urban haze in Beijing—Considering the risk events related with exhausts of coal combustion. *Science of The Total*

Environment, *544*, 1128-1135.

Kalantarnia, M. (2010). *Dynamic risk assessment using accident precursor data and Bayesian theory*. Library and Archives Canada= Bibliothèque et Archives Canada.

Khakzad, N., Khan, F., & Amyotte, P. (2011). Safety analysis in process facilities: Comparison of fault tree and Bayesian network approaches. *Reliability Engineering & System Safety*, *96*(8), 925-932.

Kletz, T. (2006). Accident investigation: Keep asking "why?". *Journal of Hazardous Materials,* 69-75.

Knegtering, B., & Pasman, H. (2013). The safety barometer: How safe is my plant today? Is instantaneously measuring safety level utopia or realizable?. *Journal of Loss Prevention in the Process Industries*, *26*(4), 821-829.

Lee, Y., Lee, S., Shin, S., Lee, G., Jeon, J., Lee, C. J., & Han, C. (2015). Risk-Based Process Safety Management through Process Design Modification for Gas Treatment Unit of Gas Oil Separation Plant. *Industrial & Engineering Chemistry Research*, *54*(22), 6024-6034.

Leu, S. S., & Chang, C. M. (2015). Bayesian-network-based fall risk evaluation of steel construction projects by fault tree transformation. *Journal of Civil Engineering and Management*, *21*(3), 334-342.

Liu, G., & Yokoyama, S. I. (2015). Proposal for a quantitative skill risk evaluation method using fault tree analysis. *IEEE Transactions on Engineering Management*, *62*(2), 266-279.

Mannan, S. (2012). *Lees' loss prevention in the process industries : hazard identification, assessment and control, chapter 8, 204-230*.

Nolan, D. (1994). *Application of HAZOP and What-if Safety Reviews to the Petroleum, Petrochemical and Chemical Industries*. William Andrew Publishing/Noyes.

Nolan, D. (2011). Objective and Description of PHA, What if, and HAZOP Reviews. *Safety and Security Review for the Process Industries Application of HAZOP, PHA, What if and SVA Reviews*. Elsevier.

Ordouei, M., Elkamel, A., & Al-Sharrah, G. (2014). New simple indices for risk assessment and hazards reduction at the conceptual design stage of a chemical process. *Chemical Engineering Science,* 218-229.

Paltrinieri, N., Tugnoli, A., Buston, J., Wardman, M., & Cozzani, V. (2013). Dynamic Procedure for Atypical Scenarios Identification (DyPASI): A new systematic HAZID tool. *Journal of Loss Prevention in the Process Industries,* 683-695.

Paltrinieri, N., Tugnoli, A., Cozzani, V. Hazard identification for innovative LNG regasification technologies (2015) Reliability Engineering and System Safety, 137, art. no. 006, pp. 18-28 Wilday, J., Paltrinieri, N., Farret, R., Hebrard, J., Breedveld, L.

Papanikolaou, A. (Ed.). (2009). *Risk-based ship design: Methods, tools and applications*. Springer Science & Business Media.

Sobradelo, R., & Martí, J. (2010). Bayesian event tree for long‐term volcanic hazard assessment: Application to Teide‐Pico Viejo stratovolcanoes, Tenerife, Canary Islands. *Journal of Geophysical Research: Solid Earth*, *115*(B5).

Thodi, P. (2011). *Risk based integrity modeling for the optimal maintenance strategies of offshore process components* (Vol. 73, No. 05).

Van Bossuyt, D., Hoyle, C., Tumer, I. Y., & Dong, A. (2012). Risk attitudes in risk-based design: Considering risk attitude using utility theory in risk-based design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, *26*(04), 393-406.

You, X., & Tonon, F. (2012). Event‐Tree Analysis with Imprecise Probabilities. *Risk Analysis*, *32*(2), 330-344.

Chapter 2. Dynamic Hazard Identification and Scenario Mapping Using Bayesian Network

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Abstract

Hazard identification is of vital importance in risk management. It is the first step of undertaking accident likelihood and associated consequence analysis. The traditional hazard identification techniques suffer from being static. New information or evolving conditions cannot be easily incorporated in already identified hazards. To overcome this, the Bayesian network is used to bring dynamics to the hazard identification step. The present work develops a new methodology to map hazard scenarios into the Bayesian network model, which enables real time hazard identification. The model presents a probability ranking for hazards using given input observations. It helps to identify the most credible hazard scenarios for further analysis. Sensitivity analyses are also conducted to investigate the influence of the input parameters on identified hazards.

Keywords: Hazard identification; hazard scenarios; Bayesian network; risk assessment; dynamic hazards

2.1 Introduction

Risk assessment plays a paramount role in process industries in the prevention and mitigation of unfavorable hazards. The methodologies developed for risk assessment have evolved to include various kinds, such as quantitative risk analysis (QRA) and probabilistic safety analysis (PSA), in which hazard identification is the first major step. Hazard identification is a precursor for hazard frequency analysis and consequence analysis. Though it is hard to identify all hazards, a list of techniques has evolved over decades to identify most process hazards and thus to assess risk to a satisfactory level.

Hazard identification answers what can go wrong in a process. This includes determination of vulnerable areas and equipment, investigation of causes of deviations from normal operations as well as evolution of hazards. It can be applied during any stage of process development, such as along with the conceptual design or during operation of an existing process. Methods for hazard identification have been developed over decades, of which the most notable ones are the hazard and operability study (HAZOP) (Kletz, 1997; Crawley and Tyler, 2015; Nolan, 1994; and Chen et al, 2011), Failure mode, Effects, and Criticality Analysis (FMECA) (Mannan, 2012; Ericson, 2005), and the quantitative hazard index approach (Crowl and Louvar, 2001; Khan and Abbasi, 1998; Khan et al, 2001). Many of these techniques have been widely used throughout industries and have contributed greatly to loss prevention (Kletz, 1999; McCoy et al, 1999). However, these conventional methods are static in nature as information updates are hard to incorporate, which may cause inaccurate or misleading results. This drawback is even exaggerated when process and operational parameters continue to change. Moreover, knowledge about hazard evolution also changes resulting from theoretical studies and practical experience. Therefore, a dynamic approach with flexibility to accommodate continuously changing information is needed.

This idea of dynamic hazard identification has already been conceptualized and incorporated into risk assessment to capture ever-changing variations and possible deviations from a normal process and also to learn from early warning systems as well as new and emerging technologies (Villa et al, 2015). The list of developments includes the Dynamic Procedure for Atypical scenarios Identification (DyPASI) (Paltrinieri et al, 2013), dynamic risk assessment (Kalantarnia et al, 2009), and risk barometer (Knegtering and Pasman, 2013). Applications of these approaches have been documented in the literature, e.g. Wilday et al (2011), Paltrinieri et al (2014), Paltrinieri et al (2015), and Kalantarnia et al (2010).

The dynamism lies in the adequate recognition of time's influence on hazard evolution. As time goes on, process parameters are changing. Accordingly, hazard evolution routes and hazards are changing. The current work develops a new dynamic hazard identification method aiming to predict likely hazards in response to real-time inputs. Unlike DyPASI, which aims at identifying atypical scenarios, the current work is limited to "Known Known" scenarios, mainly associated with the evolutions which are within the domain of process knowledge. Nevertheless, the proposed method can be used along with DyPASI to provide a more comprehensive risk picture.

A dynamic tool is needed to combine all the variations of new and emerging risk notions, development of early warning tools, and updated knowledge and experiences so that the risk profile can be updated in real-time to capture the actual circumstances. The Bayesian network (BN) has been adopted in the literature to implement dynamic concepts for dynamic risk assessment and reliability studies (Kalantarnia et al, 2009; Khakzad et al, 2014; Khakzad et al, 2012; Yuan et al, 2015). BN is a directed acyclic graph that encodes the dependencies and independencies among variables from a probabilistic perspective. The current work utilizes the Bayesian network as the dynamic tool because it not only updates but also probes the hidden problem in the use of inference (Knegtering et al, 2013). Note that the probabilistic feature of BN is used in a limited probabilistic way in this work; the probabilities used here only provide an indication of the likelihood of occurrence of a specific event rather than denoting frequency or exact accurate probabilities, which is with the same effect as the weather forecast predicting a 10% chance of rain. The probability is only used for a predictive purpose and to assess the likelihood of the occurrence of a certain event. This probability can also be updated over time when comes into operational use.

A hazard is the final consequence in a hazard scenario. The hazard scenario can be either a single event or a combination of probable events in a certain sequence (Khan &Abbasi, 1998). It depicts the evolution of hazards which describes the process through which normal operations become hazardous following deviations. The hazard scenario is initiated by one or several abnormal primary events, such as overpressure or material degradation. The primary events gradually evolve under the influence of additional energy sources, asset conditions, environmental impacts, and so on triggering a chain of hazard evolution. Finally, the hazard appears. A basic assumption when investigating the hazard evolution is that the sequence is in a linear progression (Kim et al, 2003). Therefore, if each step in a hazard evolution is clearly recognized, the hazards will then be easily determined. Thus, the hazard scenario is a fundamental element in hazard identification, and it becomes a basis for the dynamic hazard identification in the current work.

The purpose of this work is to dynamically identify hazards by mapping hazard evolution into the Bayesian network. The dynamic feature of the proposed method makes it possible to identify hazards varying due to different inputs which reflect the altering field observations in real time. The proposed model is the most suitable for release or release relevant scenarios. Although the current model is unable to identify unknown hazards, it can provide satisfactory results in determining hazards of known types. In addition, the model facilitates the updating of information, updating both the structure and conditional probability table (CPT), whenever new evidence is available.

The article is structured as follows. In Section 2, the feature of Bayesian network and the application of using the Bayesian network on hazard identification are discussed. Section 3 presents the proposed methodology for dynamic hazard identification. The method will enable real-time hazard identification given any input parameters during a process. The input parameters dynamically change with time, and the Bayesian model can make corresponding predictions for which a probability ranking for each hazard will be displayed. In Section 4, a generic Bayesian simulation model is proposed based on the mapping algorithm. Further, three case studies involving fire, explosion, and toxic scenarios are conducted in Section 5 to verify the feasibility of this method. In Section 6, a sensitivity analysis is presented to demonstrate the influence of input parameters on hazards.

2.2 Bayesian Network

A Bayesian network (BN) is a graphical modeling technique that consists of a qualitative part (directed acyclic graph) and a quantitative part (conditional probability). The BN can be simply interpreted as finding the best suitable structure for mapping interdependence among random variables in a set (Friedman et al 1997). The variables are netted via dependence or independence and quantified by assigned conditional probabilities, and the independencies of variables are derived by d-separation (Geiger et al, 2013). Because of this feature and mechanized by Bayes' theorem, the BN enables both forward analysis used as computing posterior probabilities and backward analysis used for Bayesian reasoning.

Discrete random variables and continuous random variables can both define the BN (Bobbio et al, 2001), and the variables may have multi-states to satisfy the given logic (Darwiche, 2009). Each variable can be reached along with the directed edges, and the probability of each state in every node of the structure can be expressed by a conditional probability conditioned by other states in the nodes. The chain rule enables the probability of any number of joint distributions to be obtained by multiplying conditional probabilities (Wang et al, 2011).

BN is characterized by updating prior probabilities given a set of random variables based on observations (i.e. evidence). The evidence can be either deterministic (hard evidence) or probabilistic (soft evidence or virtual evidence). Reflecting real practice, the evidence can be the process data from a certain observation, for example operational parameters (temperature, pressure, etc.) or an estimation when the current situation is uncertain.

Based on these features, how BN suits for the current study is explained as follows: i) the types of hazards and their causes are various which can be briefly represented by propositional variables with multiple states in a BN; ii) the directed edges help to encode causal relations in the evolution of hazards; iii) it is a probabilistic tool which better deals with the concept "hazard and risk" as risk itself is associated with uncertainties; iv) deterministic and probabilistic evidence better represent situations in real practice and effectively solve problems brought by uncertainties; iv) the model will assign the most credible hazards a probability ranking . Using such a ranking one is able to estimate which hazard is the most likely to occur considering current process performance, environmental conditions, and other parameters. Another advantage of the BN is the ability to update the prior marginal probabilities for parent nodes, which refer to the set of initial conditions in this case, if the probability of a certain hazard is given.

2.3 Methodology to Develop Dynamic Hazard Identification Model

The methodology behind the dynamic hazard identification is described in this section. As mentioned above, understanding hazards evolution is the foundation for tracking the final hazards. If primary events and an accident sequence are determined, hazards are then easily identified. The following sections take the release-based category as an example and describe how to create corresponding hazard scenarios as well as the rules of mapping scenarios into BN. Though the current work defines the scope of scenarios within a certain category, it can be equally applied to other domains by using the same method to construct a similar BN model. The developing procedure will be the same. The difference will be in the creation of different hazard evolution framework that encompasses cause-effect chains according to a certain circumstance. The BN mapping algorithm and the applications of the model will be the same.

2.3.1 Creating Accident Scenarios

Each scenario describes a unique accident sequence in a specific situation given certain parameters. Therefore, creating accident scenarios become a necessary step in which the sequence of hazard evolution will be investigated and the hazard will be consequently identified if any primary event is identified. Methods of envisaging accident scenarios are various, such as using ontologies (Batres et al, 2014) or a computer-aided tool (Kim et al, 2003). Accident scenarios are generated in a sequence based on logic with respect to relevant knowledge and past experience. The logic algorithm can be found in CCPS (1999), Kim et al (2003), and Assael and Kakosimos (2010). Khan (2001) also developed a basic logic for generating fire, explosion, and toxic dispersion scenarios. The current work adopts the framework (Khan, 2001) as a basis and makes further improvement by incorporating the effects of a larger set of parameters and considering additional scenarios. The framework for creating accident scenarios is depicted in Figure 2.1.

A scenario is influenced by various parameters in different categories. As Figure 2.1 shows, the input parameters are partitioned into five categories, namely, chemical states, operational parameters, process impact factors, chemical characteristics, and site characteristics. The chemical state refers to the physical state of the contained chemicals which includes solid, liquid, vapor, as well as liquefied gas. Operational parameters include a series of monitored variables such as pressure, temperature, mass flow, and so on. Process impact factors consider whether an abnormal phenomenon occurs during process and whether safety measures work effectively. Process abnormal phenomena include out of bound variables e.g. tank overflow and process degradation such as low material strength resulting from corrosion, collision with other objects, lack of maintenance, etc. These incidents will decide the type of release which greatly influences the final type of hazard. This influence brought by the release type will be discussed later in Section 4. Chemical characteristics refer to the properties of chemicals, such as vapor pressure, combustibility, toxicity, etc. The last category site characteristics refer to the surrounding environment which includes location (rural or urban area), confinement, meteorological conditions, etc.

Ignition and dispersion are both introduced to further determine accident scenarios. At each instant of evaluation, according to whether or not there is a source of ignition and/or dispersion, combined with the consideration of the input parameters, a specific scenario will be determined. The same procedure is repeated and all accident scenarios can be generated. Each of the accident scenarios involves a final hazard to identify. The final hazards include fire (pool fire, jet fire, flash fire, fireball, vapor fire), explosion (dust explosion, VCE, BLEVE), and toxicity.

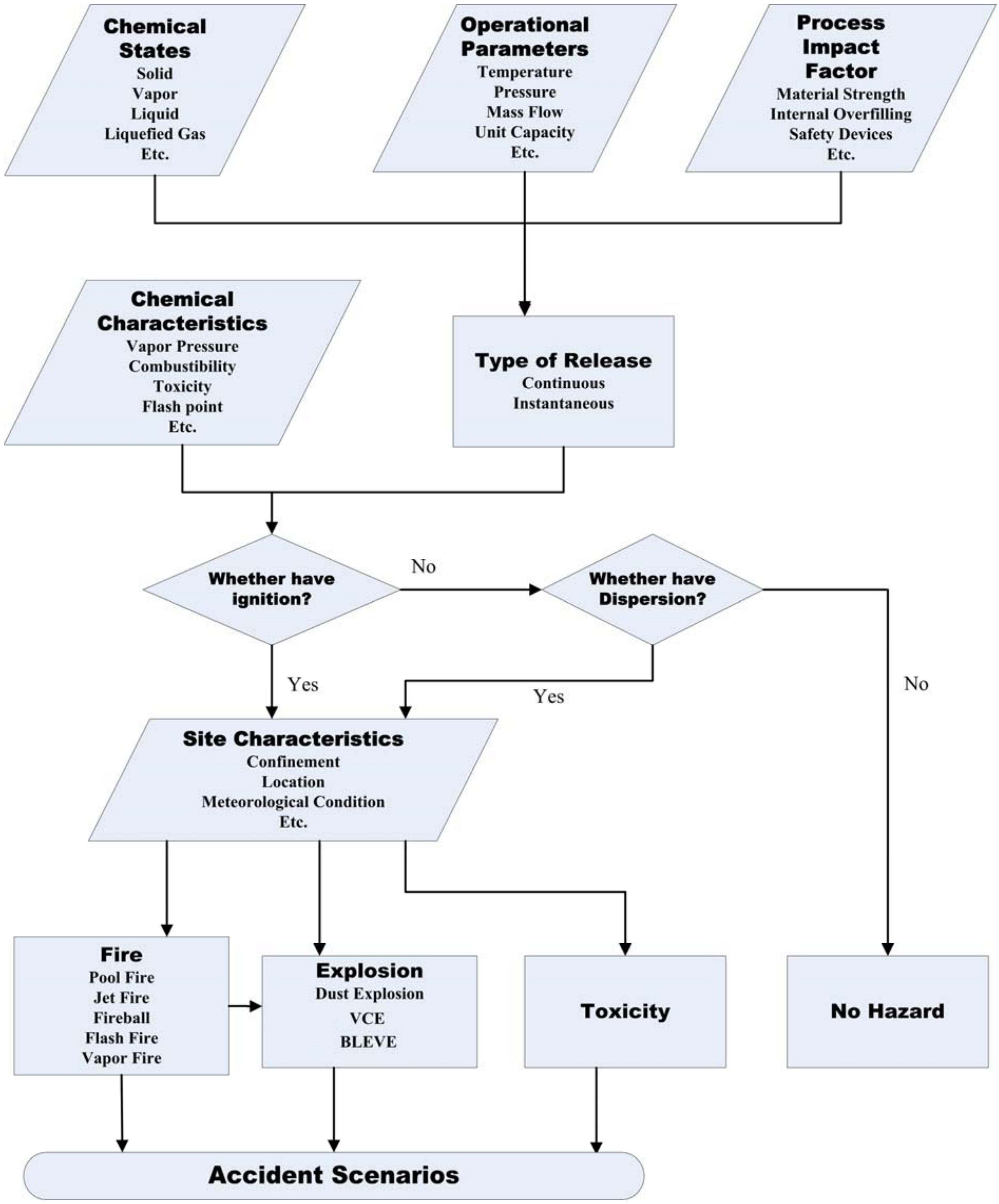

Figure 2.1 Framework of Creating Release Relevant Accident Scenarios

Darwiche (2009) discussed three main steps of constructing a Bayesian Network (BN): define relevant variables; define network edges; and assign conditional probability tables. On the basis of this and reflecting on mapping the hazard scenarios, the steps of the mapping algorithm are: 1) breaking hazard evolution into discrete nodes and defining nodes; 2) mapping causal relations into Bayesian network; 3) assigning conditional probability tables (CPT).

2.3.2 Identifying nodes

After envisaging hazard scenarios, the first step is to break the linear hazard evolution into discrete nodes which reflect every step in the hazard progression. Hazard scenarios are created by considering different aspects of relevant factors. Therefore, components in Figure 2.1 are all considered to be nodes, and each node represents one variable. Another issue is to properly define the states of variables. In fact, each aspect of a single variable can be interpreted as one node, the states of which are binary (such as true or false). For example, when defining the physical state of the contained chemical, we can set four nodes indicating solid, liquid, vapor, and liquefied gas respectively of which each node has two states “true” and “false”. However, this will significantly increase the number of nodes and thus may cause a high computational load due to the increasing complexity. To solve this problem, the nodes are allowed to have multiple states instead of being solely binary. The sub-states describing every aspect for the same variable are regarded as mutually exclusive and can be combined into one node. In this case, the state node can be represented as one with four states.

2.3.3 Classifying nodes and mapping principles for nodes

Having these discrete nodes, the next step is to classify nodes so that the classified nodes can be matched with different principles when being mapped onto a BN. Nodes are classified as evidence, intermediary, and query (Darwiche, 2009). In this case, the evidence nodes are the inputs based on observations or real-time parameters. The query nodes are the final outcomes, which refer to the predicted hazards. The intermediary nodes connect the evidence nodes and query nodes and are the transitional steps in hazard evolution.

Node mapping is associated with parent, child, and leaf node which indicate three main positions in a cause-effect chain. A parent node has no prior node connected, such as node "operation temperature" in Figure 2. A child node is the opposite of a parent node, such as node "type of release" in Figure 2. A leaf node has no child node, such as node "toxic" in Figure 2. The mapping principles are illustrated as follows. Firstly, the evidence nodes are the inputs and must only be parent nodes. Secondly, the query nodes are inferred based on the evidence nodes and intermediary nodes, and therefore must be child nodes but not necessarily leaf nodes because query nodes may also affect each other. For example, smoke produced by fire or explosion may also lead to toxicity. Lastly, the intermediate nodes mostly stand for the main transitional steps in hazard evolution. They are the core of the model's logic and directly influence the BN's reasonableness and reliability. The intermediary nodes are positioned in the middle and cannot be leaf nodes. Also note that, conditional probability tables can be updated for all nodes and this part belongs to the system update and maintenance; however, when using the model for hazard identification, only the input in the evidence nodes can be changed. The intermediary nodes only show computational process and cannot be set as evidence.

2.3.4 Mapping causal relations among nodes

Next is to map causal relations among these discrete and classified nodes in the BN, i.e. to define edges. The basic rule is to decide the direct cause and impact for each node. Overall, the causal relations for the three types of nodes are: the evidence node is the direct cause of the intermediary node, and the intermediary node directly affects the query node. Starting from the evidence nodes, determine their impacts sequentially to initialize the BN structure. Recheck out each node again to confirm whether any other causal relations exist. In addition, the evidence nodes are independent from each other; hence, no edges should be added among these nodes.

2.3.5 Assigning conditional probability tables

The last step is to assign conditional probability tables (CPT). The conditional probability is also known as quantitative degree of belief which defines uncertainty. This probability can be objective deduction, such as frequency or extracted data through certain approaches, such as maximum likelihood estimation, or simply subjective belief (Darwiche, 2009). In the current work, subjective belief is used as the focus here is to present the overall framework. Again, the probabilities used here are only for predictive purpose and used only for anticipating the likelihood of occurrence. A future work will be dedicated solely to determine the conditional probability based on expert survey. The CPTs can be updated at any time by means of either obtaining direct data or through prediction using the Bayesian update mechanism based on historical records (Rathnayaka et al, 2012).

2.4 Proposed Generic BN Model

Based on the mapping algorithm, the accident scenarios generated in Figure 2.1 are mapped into a generic BN. Figure 2.2 shows a generic BN rendered by means of GeNIe, a simulation software developed by the Decision Systems Laboratory used for implementing graphical decision-theoretic methods (Druzdzel, 1999). In this model, there is a total of 25 nodes including 16 evidence nodes, 6 intermediary nodes, and 3 query nodes. To better illustrate the proposed BN model, causal relations and node classifications are shown as Table 2.1. Table 2.2 illustrates each node and its corresponding states. To simply and effectively capture the current situation of each node, qualitative description is used for expressing the state. As Table 2.2 shows, state description can be binary, or discrete events that represent an aspect of the current node.

The generic model tries to encompass all possible evolution scenarios associated with release or release relevant cases rather than listing all possibilities for any range. It provides a framework for the direction of deviations. However, credible scenarios vary for each specific situation and may be affected by the physical properties of substance, plant geometry, area congestion, human interactions, and so on. Therefore, an update on the basis of the generic model is needed. The update can lead to either a structural change or an updated CPT. To conclude, the goal of integrated updates targeting a certain circumstance is to achieve more reliable and comprehensive results.

Table 2.1 Nodes Illustration in Generic Bayesian Network

No.	Node	Parent Node	Child Node	Node Classification
1	Operation Pressure	N/A	Type of Release; Fire	Evidence Node
2	Operation Temperature	N/A	Type of Release	Evidence Node
3	Operation Mass Flow	N/A	Type of Release	Evidence Node
4	Unit Capacity	N/A	Type of Release	Evidence Node
5	Material Strength	N/A	Mechanical Failure	Evidence Node
6	Overflow	N/A	Mechanical Failure	Evidence Node
7	Chemical Combustible	N/A	Ignition	Evidence Node
8	Ignition Source	N/A	Ignition	Evidence Node
9	Substance Vaporization	N/A	Vapor Cloud Formation; Dispersion	Evidence Node
10	Substance State	N/A	Vapor Cloud Formation; Fire; Explosion	Evidence Node
11	Confinement	N/A	Fire; Explosion	Evidence Node
12	Toxicity of Released Substance	N/A	Toxicity	Evidence Node
13	Atmospheric Condition	N/A	Toxicity	Evidence Node
14	Quantity Released	N/A	Toxicity	Evidence Node
15	Distance	N/A	Toxicity	Evidence Node
16	Location	N/A	Toxicity	Evidence Node
17	Smoke	Fire; Explosion	Toxicity	Intermediary Node
18	Mechanical Failure	Material Strength; Overflow	Type of Release	Intermediary Node
19	Type of Release	Operation Pressure; Operation Temperature; Operation Mass Flow; Unit Capacity; Mechanical Failure	Vapor Cloud Formation; Fire; Dispersion	Intermediary Node
20	Ignition	Chemical Combustible; Ignition Source	Fire; Explosion	Intermediary Node
21	Vapor Cloud Formation	Type of Release; Substance Vaporization; Substance State	Fire; Explosion	Intermediary Node
22	Dispersion	Type of Release; Substance Vaporization	Toxicity	Intermediary Node
23	Fire	Substance State; Operation Pressure; Type of Release; Ignition; Vapor Cloud Formation; Confinement	Smoke	Query Node
24	Explosion	Substance State; Vapor Cloud Formation; Fire; Ignition; Confinement	Smoke	Query Node
25	Toxicity	Dispersion; Toxicity of Released Substance; Atmospheric Condition; Quantity Released; Distance; Location	N/A	Query Node

Table 2.2 Nodes and Corresponding States

No.	Node	States
1	Operating Pressure	High; Low
2	Operating Temperature	High; Low
3	Operating Mass Flow	High; Low
4	Unit Capacity	High; Low
5	Material Strength	High; Medium; Low
6	Overflow	True; False
7	Chemical Combustible	True; False
8	Ignition Source	Hot Surface; Flame; Mechanical Spark; Electrical Spark; Lightening Stroke; No Ignition Source
9	Substance Vaporization	High; Low; None
10	Substance State	Solid; Liquid; Vapor; Liquefied Gas
11	Confinement	High; Medium; Low
12	Toxicity of Released Substance	High; Medium; Low; None
13	Atmospheric Condition	Stable; Unstable
14	Quantity Released	Large; Small
15	Distance	Very Far; Far; Near
16	Location	Urban; Rural
17	Smoke	True; False
18	Mechanical Failure	Rupture; Hole; Crack; No Observation
19	Type of Release	Continuous; Instant
20	Ignition	True; False
21	Vapor Cloud Formation	True; False
22	Dispersion	True; False
23	Fire	Pool Fire; Fireball; Flash Fire; Vapor Fire; Jet Fire; No Fire
24	Explosion	Dust Explosion; VCE; BLEVE; No Explosion
25	Toxicity	True; False

2.4.1 Two types of release

The first step when an initiating cause begins to evolve is to decide the release of materials. Chemical state, operational parameters and process impact factors together determine the type of release, namely, continuous release and instantaneous release. A continuous release refers to a steady release that has a large amount of chemical supply in comparison to the rate of release. A continuous release reflects a scenario where hazards do not occur immediately until the release accumulates up to a certain level over a period of time. In contrast, an instantaneous release refers a sudden release of a large amount of material within a very short period. An instant scenario refers to a hazard scenario based on the instant release. The type of release mostly depends on the type of mechanical failure; for example, a material crack will probably cause a continuous release, while a rupture can result in an instant release.

2.4.2 Fire and explosion scenario evolution

Release of a material may lead to fire, explosion, and toxicity. Fuel, oxygen, and ignition are the three components relevant to fire and explosion scenarios. Because most process equipment is exposed to open air, an abundance of oxygen is assumed. Hence, fuel and ignition are the two foci in this model. The chemical state of the released material indicates the type of fuel which, in turn, determines the ultimate scenario. For example, a liquid fuel most likely will lead to pool fire when meets ignition, and solid fine particles may lead to dust explosion. Additional attention needs to be paid to the type of release because that also influences the final type of hazard. For example, when igniting a vapor, continuous release with a steady momentum may cause jet fire, while a sudden release may lead to a fireball. On the other hand, ignition is dependent on ignition source and chemical combustibility, and thus becoming the child node of these two. The node Vapor cloud formation is included because it is a key factor in identifying vapor fire and VCE. When a vapor cloud encounters ignition, the probability of vapor fire and VCE will significantly increase. Confinement is one of the factors that distinguish fire and explosion scenarios. High confinement will increase the likelihood of an explosion, while decrease the likelihood of a fire. Another special case is BLEVE that can occur with external heating without any source of ignition. This case occurs depending on the external temperature and the flash point of the liquid. Typically, liquefied gas easily leads to BLEVE when heated externally; consequently, for liquefied gases, the probability of BLEVE is higher when no ignition exists.

2.4.3 Toxic scenario evolution

Regarding the toxic scenario, the most important factor for causing toxicity is dispersion, which is decided by the type of released material and its vaporization. An instant release is more likely to induce dispersion than continuous release due to its potential large amount. Besides, a liquid with no vaporization can hardly cause dispersion. Smoke produced by fire or explosion is considered to be readily dispersed and thus directly affects toxicity. Besides dispersion, other factors affecting toxicity are chemical properties, location, atmospheric conditions, and quantity released.

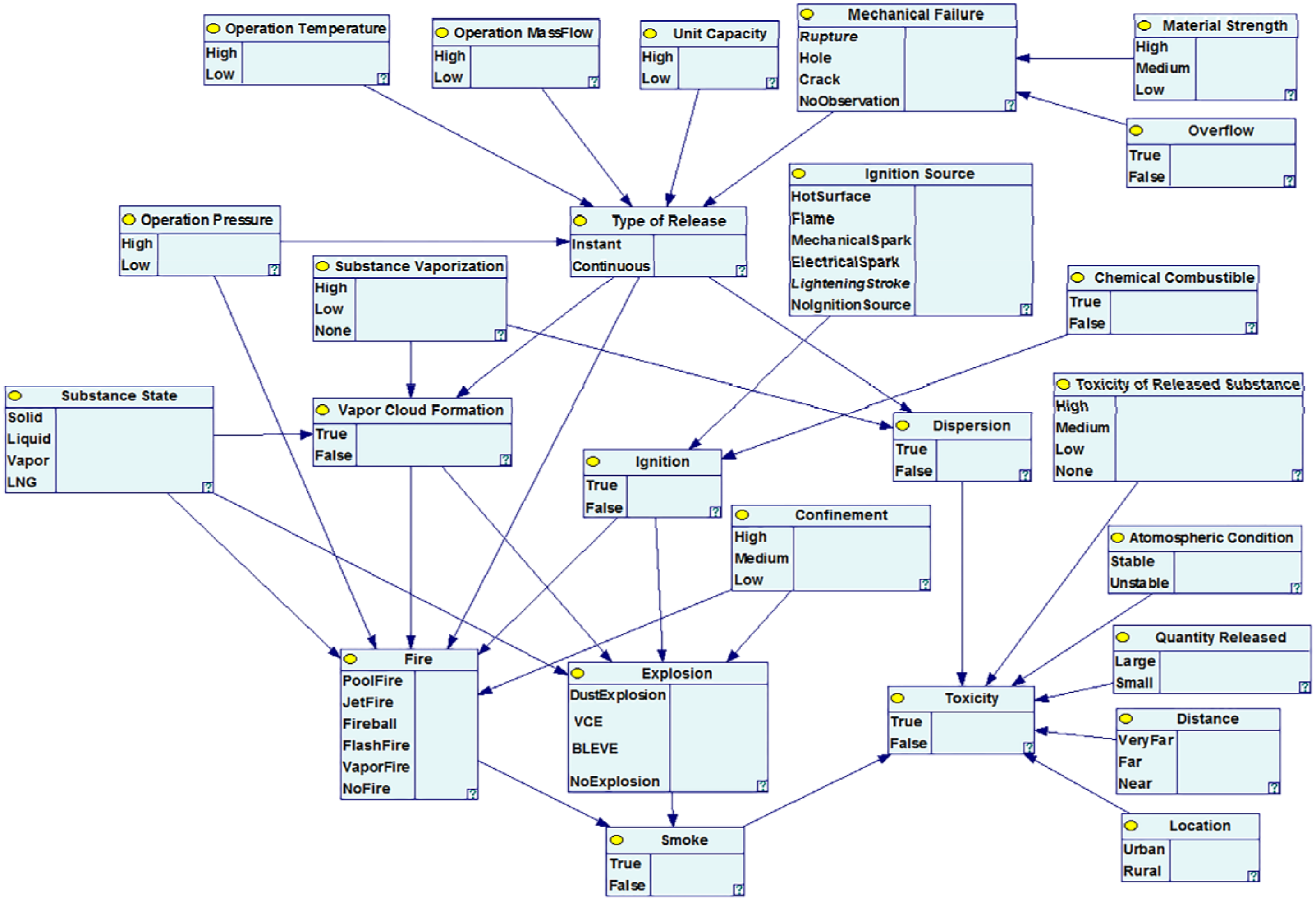

Figure 2.2 Generic Bayesian Model of Dynamic Hazard Identification

2.5 Case Studies

The following case studies are used to verify the rationale and demonstrate applicability of the proposed model. The case studies are based on accident reports cited from the US Chemical Safety Board because they are thoroughly investigated with sufficient details in the public domain. Root causes identified in the reports are used as evidence for the BN model. The outcomes of the BN model are then compared with the ultimate scenarios described in the reports.

2.5.1 Case Study 1

Accident Description: A fire occurred on August 6, 2012 in Richmond, California due to the ignition of a vapor cloud. The pipe in the crude unit containing light gas oil suddenly ruptured because of the decreased pipe thickness caused by sulfidation corrosion. The released hydrocarbon vaporized and formed a vapor cloud. The vapor cloud was then ignited and resulted in a vapor fire. The particulates in the smoke travelled a long distance and caused serious inhalation problems for people around the plant (CSB, 2015).

BN Model Simulation Results: According to the description above, 11 pieces evidences are set as follows: high temperature, high mass flow, high unit capacity, low material strength, high operating pressure, liquid state, high degree of vaporization, combustible chemical, ignition source, low confinement, low toxicity of released substance, high quantity released. Then, the simulation result for the fire scenario is shown in Figure 3.3.Three query nodes: fire, explosion, and toxicity show the final identified hazards in the Bayesian simulation. These three nodes weigh the same and should be considered separately. The most likely hazard should be assessed for fire, explosion, and toxicity scenarios respectively. For example, in this case, vapor fire has the highest probability in the fire category which means vapor fire is most likely to occur. In the explosion category, no explosion exists in terms of the ranking of probability. In the toxicity category, the probability of toxicity is more than 50%, which means toxicity is also likely to occur. Overall, vapor fire and toxicity are the most credible hazard to occur.

2.5.2 Case Study 2

Accident Description: A vapor cloud explosion occurred on November 22, 2006 in Danvers, Massachusetts. An open steam valve on the tank heater continuously heated the flammable liquid that was contained in the tank, thus vaporizing the liquid. As a result, vapor gradually released and formed a vapor cloud. Finally, the vapor cloud was ignited and caused vapor cloud explosion occurred in a congested area (CSB, 2008).

BN Model Simulation Results: the Evidence set is as follows: high temperature, high mass flow, high unit capacity, low material strength, high operation pressure, liquid state, high degree of vaporization, combustible chemical, ignition source, high confinement, low toxicity of released substance, large quantity released, and a far distance due to the exposure occurring far from the accident site. The simulation result for the explosion scenario is shown as Figure 3.4, where a VCE and toxicity are the most credible scenarios, with 48% and 61% possibilities respectively.

2.5.3 Case Study 3

Accident Description: An ammonia toxic release occurred on August 23, 2010 in Theodore, Alabama. A refrigeration coil suddenly ruptured because of a sharp pressure built-up caused by hydraulic shock, leading to a large quantity release of toxic ammonia. The ammonia dispersed and made people at 0.25 miles downwind suffer from inhalation problems (CSB, 2015).

BN Model Simulation Results: Evidence includes high operation pressure, temperature, mass flow, high unit capacity, vapor state, high degree of vaporization, chemical combustible, low material strength, no ignition source, medium toxicity of released chemical, short distance of exposure from accident site, and large quantity released. The simulation result for the toxic scenario is shown as Figure 2.5, where toxicity is much more likely to occur (72%) than fire (11%) and explosion (17%).

On the whole, the results predicted by the BN model all agree with the description in the accident report. The results validate the model for explosion, and toxic cases; this demonstrates the applicability of the model for identifying hazards in other cases.

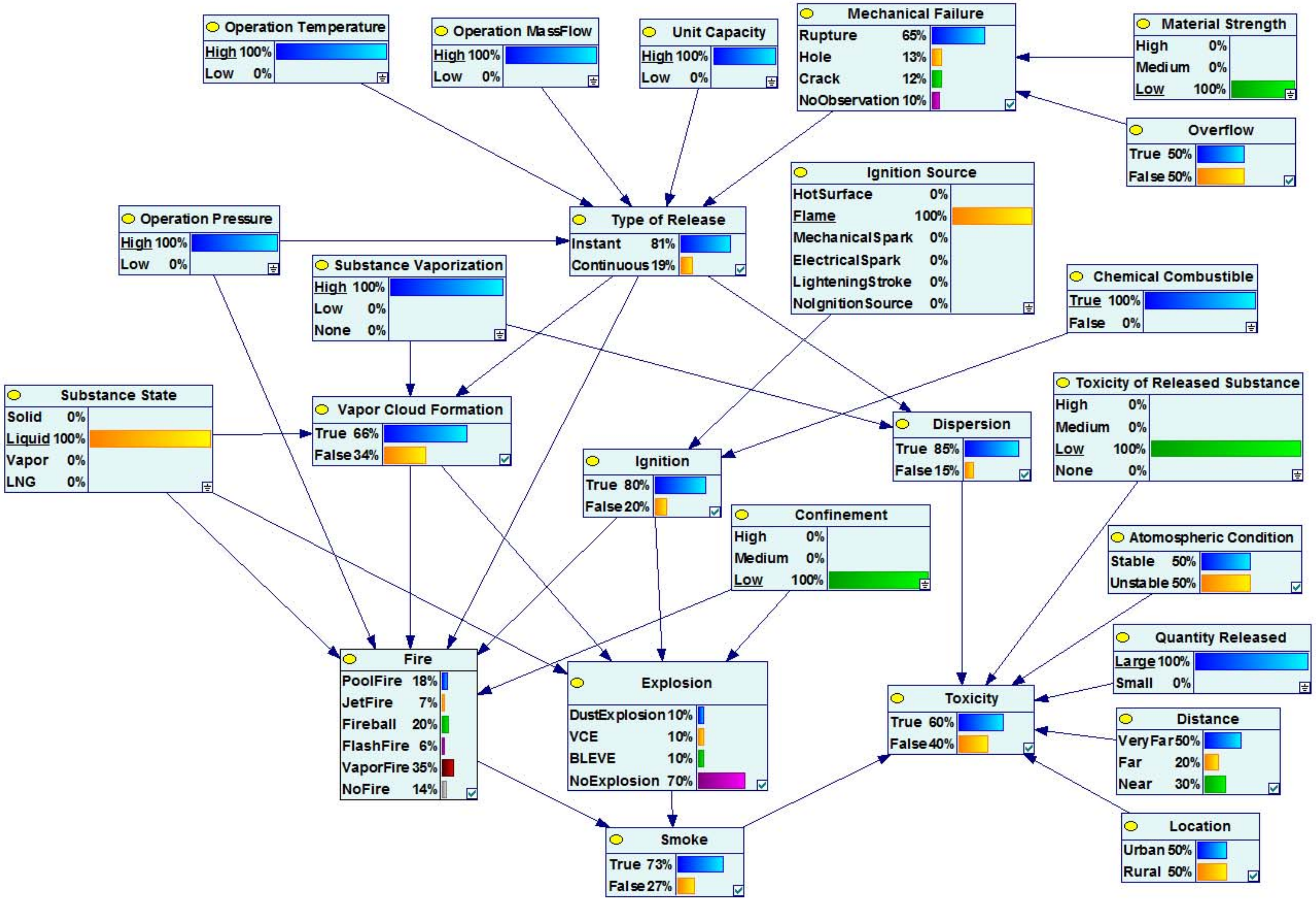

Figure 2.3 Bayesian Simulation Results in Study 1

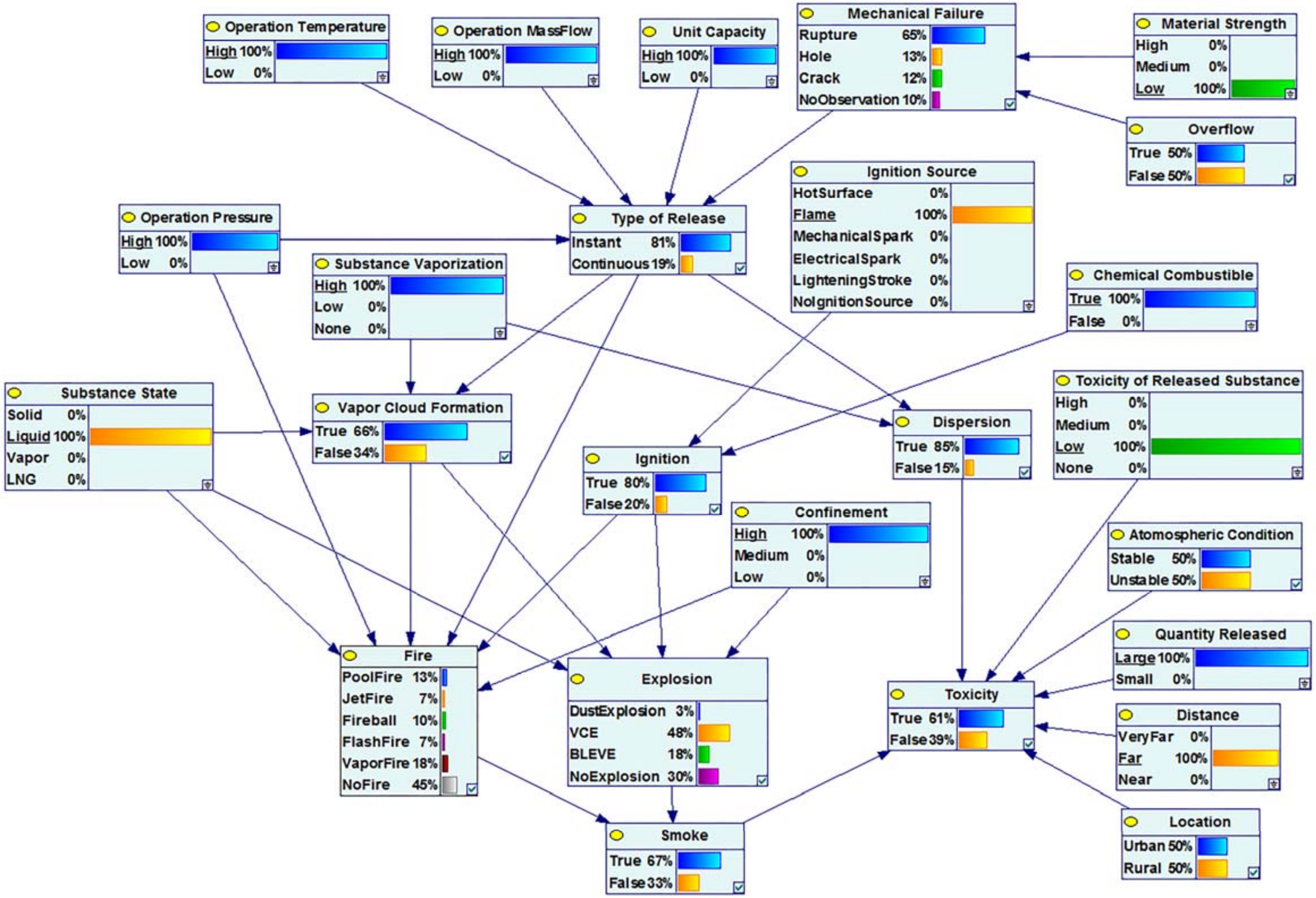

Figure 2.4 Bayesian Simulation Results in Study 2

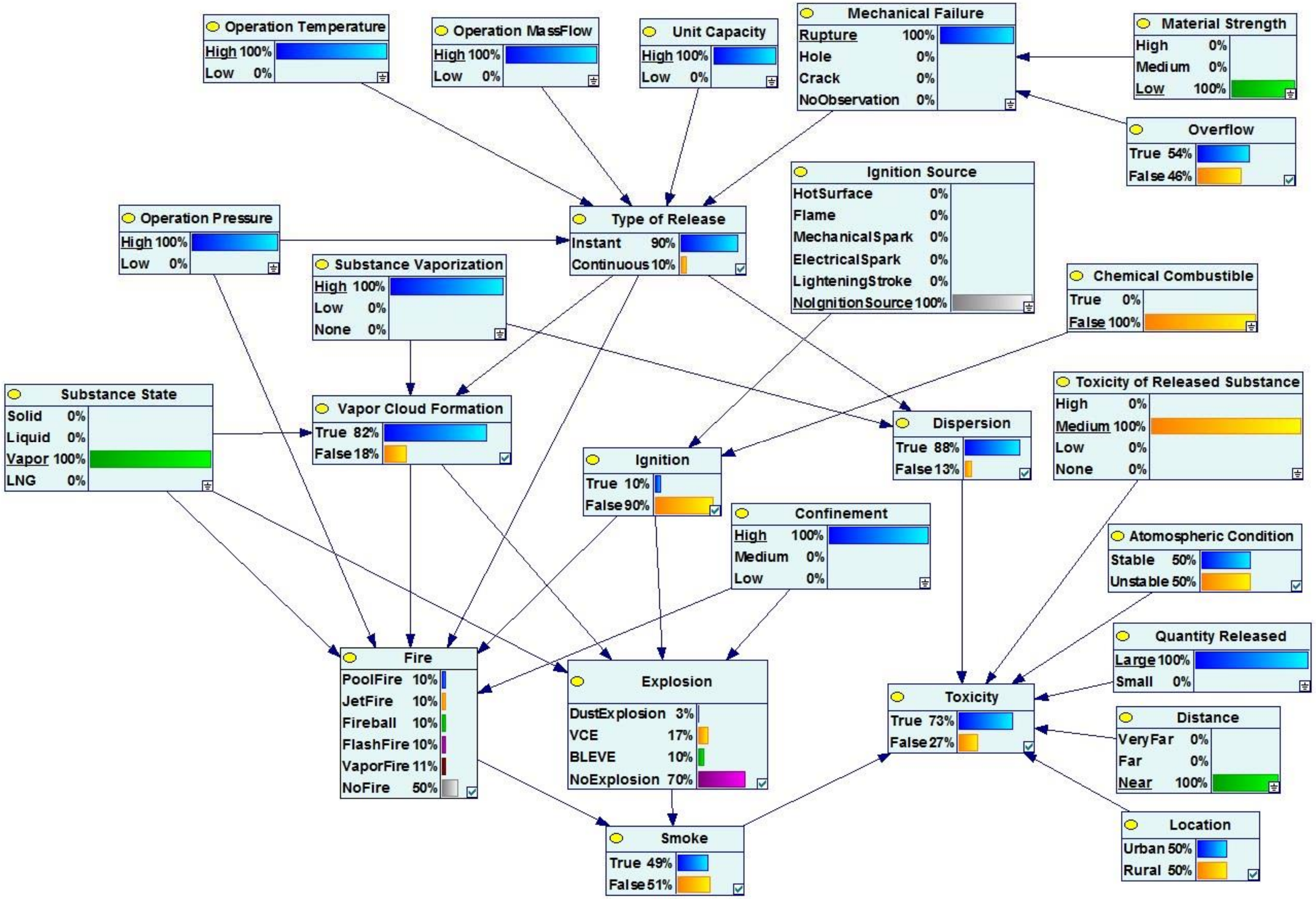

Figure 2.5 Bayesian Simulation Results in Study 3

2.6 Sensitivity Analysis

The results above are summarized as Table 2.3 shows, where hazards with dominant probabilities can be seen in all the case studies. In order to further analyze how sensitive the identified results are when subjected to any change in the input parameters, sensitivity analyses are conducted.

Table 2.3 Bayesian Simulation Results for Three Scenarios

Hazard Category	Hazard Type	Study 1	Study 2	Study 3
Fire	Pool Fire	18%	13%	10%
	Jet Fire	7%	7%	10%
	Fireball	20%	10%	10%
	Flash Fire	6%	7%	10%
	Vapor Fire	35%	18%	11%
	No Fire	14%	45%	50%
Explosion	Dust Explosion	10%	3%	3%
	VCE	10%	48%	17%
	BLEVE	10%	18%	10%
	No Explosion	70%	30%	69%
Toxicity	Toxicity	60%	61%	72%
Most Credible Hazard		Vapor Fire; Toxicity	VCE; Toxicity	Toxicity

The focus is on studying the parameters which greatly influence fire and explosion scenarios. The toxic scenario is precluded because fire and explosion can both lead to toxicity. An ignition source is assumed to exist due to its necessity in both fire and explosion scenarios. The target parameters to be investigated are narrowed to four parameters: material strength, overflow, confinement and operating pressure. The overflow and material strength are considered as one group of parameters because they concurrently determine the type of release through deciding the type of mechanical failure. The steps of conducting the sensitivity analysis are as follows. Firstly, generate scenarios by combining different states of input parameters. Secondly, choose an input parameter as the investigation target and classify the scenarios in terms of the state of this parameter. Lastly, check out if the result is sensitive subject to the inputs.

The first purpose of the sensitivity analysis is to find the parameters that mainly distinguish fire or explosion scenarios. The sensitivity analyses for confinement, pressure, material strength and internal overfilling are conducted respectively. Scenarios described here are a combination of states leading to an event. The common evidences set for all scenarios are Vapor (for node Substance State), High (for node Vaporization), Flame (for node Ignition Source), and True (for node Chemical Combustible). Evidence varied for each scenario is illustrated in Table 2.4. The simulation results are shown in Figure 2.6 (a) ~(c), where the horizontal axis refers to the number of created scenarios and the vertical axis refers to the probability of hazards. In Figure 2.6 (a), the first scenarios are created under a low confinement condition, the middle ones are under medium confinement, and the last ones are under high confinement. A clear trend can be seen: as the confinement begins to increase, the probability of fire decreases while the probability of explosion increases. On the other hand, in pressure sensitivity analysis and material strength and overflow sensitivity analysis, as shown in Figure 2.6 (b) and (c), no clear order has been found. Therefore, confinement becomes the main factor in determining the fire or explosion scenario. A high confinement condition results in an explosion scenario, while low confinement leads to a fire scenario.

Sensitivity analyses of pressure, material strength and overflow are also conducted under certain conditions of confinement to see how sensitive a certain type of fire or explosion is. The conditions for causing fireball, jet fire, and flash fire are studied. Information about the created scenarios is shown in Table 5, and the result is depicted as Figure 2.7. The first four scenarios are envisaged under high pressure, and the last four scenarios are under low pressure. Vapor fire is not considered in this analysis as vapor fire occurs irrespective of conditions as long as a vapor is ignited. As shown in Figure 7, under the condition of low confinement, fire ball and jet fire are both more likely to occur at high pressure, while a flash fire is more likely to happen at low pressure.

Information about overflow and material strength scenarios is listed in Table 2.6 and the results are shown in Figure 2.8. A total of 24 scenarios are created and they are separated into eight groups. Four of the groups are in a high confinement condition and the remaining four are in a medium confinement condition. Within each group, scenarios are created with varying material strength while keeping other conditions the same. Each group represents three scenarios with material strength varying from high to low; for example, 1 and 4 represent high material strength, 2 and 5 medium, 3 and 6 low and so on. As the results in Figure 2.8 show, the following conclusions can be drawn:1) the factor of material strength has more impact than the factor overflow on the probability of an ultimate identified hazard; 2) a high confinement condition leads to a higher probability of explosion than a medium condition does; 3) low material strength makes the probability of explosion higher than medium material strength does, and as does the medium material strength to high material strength.

Table 2.4 Scenarios Created for Sensitive Analysis for Fire and Explosion Scenarios

Evidence		Scenarios											
Node	**State**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 7**	**Scenario 9**	**Scenario 8**	**Scenario 6**	**Scenario 10**	**Scenario 11**	**Scenario 12**
Material Strength	High	□	□	□				□	□		□		
	Low				□	□	□	□		□		□	□
Overflow	TRUE		□	□		□	□		□	□	□		□
	FALSE	□			□			□				□	
Operation Pressure	High			□	□				□	□	□	□	□
	Low	□	□			□	□	□					
Site Confinement	High										□	□	□
	Medium						□	□	□	□			
	Low	□	□	□	□	□							
Most Credible Hazard		**Fire**	**Fire**	**Fire**	**Fire**	**Fire**	**Explosion**	**Explosion**	**Explosion**	**Explosion**	**Explosion**	**Explosion**	**Explosion**
	P(Fire) %	**32**	**28**	**28**	**30**	**33**	**21**	**21**	**22**	**20**	**14**	**15**	**16**
	P(Explosion) %	**10**	**10**	**10**	**10**	**10**	**34**	**33**	**31**	**35**	**44**	**47**	**49**

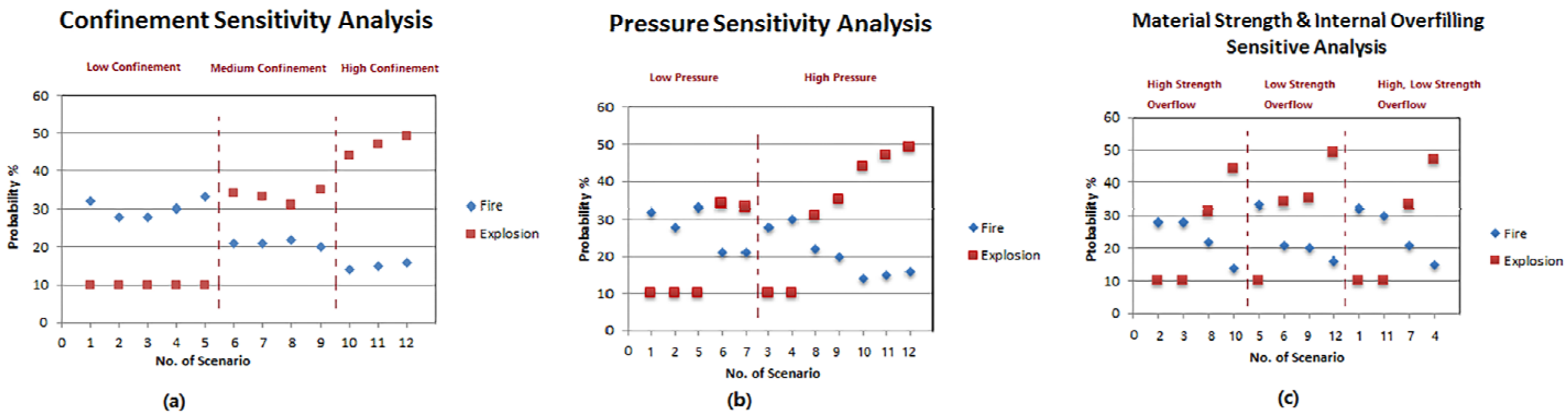

Figure 2.6 Sensitivity analysis for distinguishing fire and explosion scenarios

Table 2.5 Scenarios Created for Pressure Sensitivity Analysis

Evidence		**Scenarios**							
Node	**State**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**	**Scenario 8**
Site Confinement	High								
	Medium								
	Low	✓	✓	✓	✓	✓	✓	✓	✓
Material Strength	High	✓		✓				✓	✓
	Low		✓		✓	✓	✓		
Overflow	TRUE	✓	✓			✓			✓
	FALSE			✓	✓		✓	✓	
Operation Pressure	High	✓	✓	✓	✓				
	Low					✓	✓	✓	✓
	Most Credible Hazard	**Fire**	**Fire**	**Fire**	**Fire**	**Fire**	**Fire**	**Fire**	**Fire**
	P(JetFire) %	**24**	**16**	**28**	**18**	**10**	**10**	**10**	**10**
	P(Fireball)%	**22**	**27**	**19**	**26**	**10**	**10**	**10**	**10**
	P (Flash Fire)%	**6**	**6**	**6**	**6**	**23**	**25**	**32**	**28**

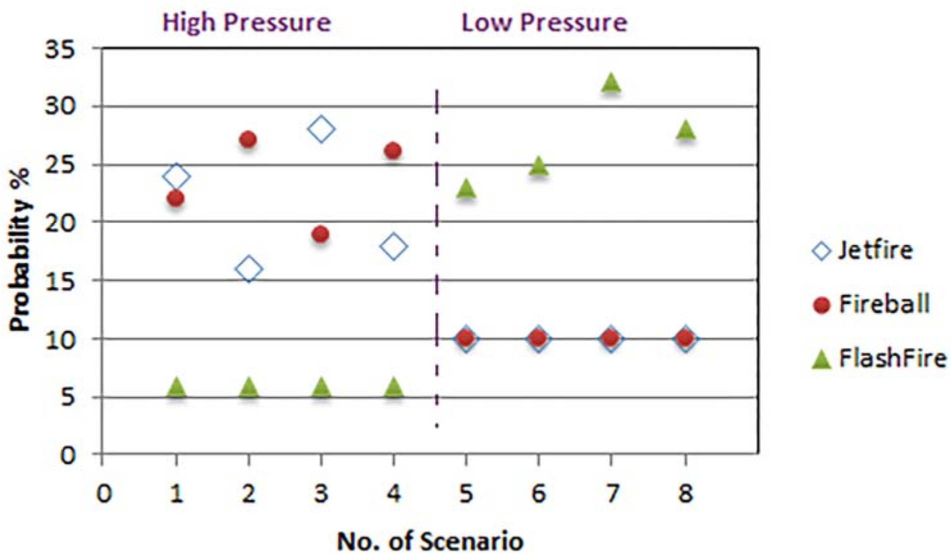

Figure 2.7 Pressure sensitivity analysis

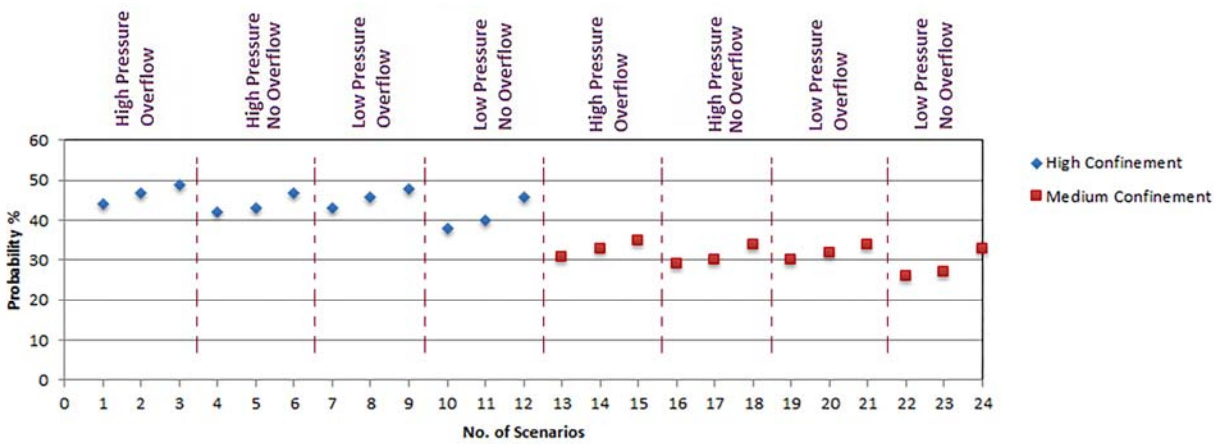

Figure 2.8 Overflow &material strength sensitivity analysis

Table 2.6 Scenarios Created for Material Strength & Overflow Sensitivity Analysis

Evidence		Scenarios											
Node	**State**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**	**Scenario 8**	**Scenario 9**	**Scenario 10**	**Scenario 11**	**Scenario 12**
Site Confinement	High	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Medium				✓	✓	✓						
	Low												
Operation Pressure	High	✓	✓	✓	✓	✓	✓					✓	✓
	Low							✓	✓	✓	✓	✓	✓
Material Strength	High	✓			✓			✓			✓		
	Medium		✓			✓			✓			✓	
	Low			✓			✓			✓			✓
Overflow	TRUE	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	
	FALSE				✓	✓	✓				✓	✓	✓
	Most Credible Hazard	**Explosion**	**Explosion**	**Explosion**	**Explosion**	**Explosion**	**Explosion**	**Explosion**	**Explosion**	**Explosion**	**Explosion**	**Explosion**	**Explosion**
	P(Explosion) %	**44**	**47**	**49**	**42**	**43**	**47**	**43**	**46**	**48**	**38**	**40**	**46**
Node	**State**	**Scenario 13**	**Scenario 14**	**Scenario 15**	**Scenario 16**	**Scenario 17**	**Scenario 18**	**Scenario 19**	**Scenario 20**	**Scenario 21**	**Scenario 22**	**Scenario 23**	**Scenario 24**
Site Confinement	High												
	Medium	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Low												
Operation Pressure	High	✓	✓	✓	✓	✓	✓					✓	✓
	Low							✓	✓	✓	✓	✓	✓
Material Strength	High	✓			✓			✓			✓		
	Medium		✓			✓			✓			✓	
	Low			✓			✓			✓			✓
Overflow	TRUE	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	
	FALSE				✓	✓	✓				✓	✓	✓
	Most Credible Hazard	**Explosion**	**Explosion**	**Explosion**	**Explosion**	**Explosion**	**Explosion**	**Explosion**	**Explosion**	**Explosion**	**Explosion**	**Explosion**	**Explosion**
	P(Explosion) %	**31**	**33**	**35**	**29**	**30**	**34**	**30**	**32**	**34**	**26**	**27**	**33**

2.7 Conclusions

The current work proposes a methodology for dynamic hazard identification by mapping hazard scenarios into a Bayesian network. The methodology helps to construct a dynamic simulation model that enables real time hazard identification. Given a set of input parameters during an operation, the model is able to identify the most probable hazards by assessing the likelihood of each hazard scenario in terms of a probability ranking. The model is dynamic because the structure is flexible enough to accommodate different processes; the input parameters can also be conveniently updated at any time. An advantage of this model is that it facilitates real time hazard identification to accommodate parameter variations. A generic model is also presented to further explain this dynamic method. In order to verify the adaptability of the generic model, three case studies of fire, explosion, and toxic dispersions are conducted by comparing the simulation results with the root causes identified in investigation reports. A sensitivity analysis is also conducted to investigate how sensitive the identified hazard is to the change of input parameters. Results show that confinement has the largest influence on the occurrence of a fire or explosion, and a high confinement condition more likely results in an explosion scenario. Pressure influences the type of fire to a great extent. Material strength and an overflow of equipment influence the probability of explosion significantly, with the material strength having larger influence. Further, this method is dynamic not only because it facilitates coping with real time changing parameters, but also because the conditional probability tables can be updated easily with the latest knowledge and experience, and thus improving the accuracy of identification. The update of prior probabilities will be the focus in the next stage of work.

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2.8 Reference

Assael, M. J., & Kakosimos, K. E. (2010). *Fires, explosions, and toxic gas dispersions: Effects calculation and risk analysis*. CRC Press.

Batres, R., Fujihara, S., Shimada, Y., & Fuchino, T. (2014). The use of ontologies for enhancing the use of accident information. *Process Safety and Environmental Protection*, *92*(2), 119-130.

Bobbio, A., Portinale, L., Minichino, M., & Ciancamerla, E. (2001). Improving the analysis of dependable systems by mapping fault trees into Bayesian networks. *Reliability Engineering & System Safety*, *71*(3), 249-260.

Center for Chemical Process Safety (CCPS), & LASTCenter for Chemical Process Safety (CCPS). (1999). *Guidelines for consequence analysis of chemical releases* (Vol. 1). Wiley-AIChE.

CCPS (Center for Chemical Process Safety). *Guidelines for Hazard Evaluation Procedures* (3 ed.). John Wiley & Sons, 2011.

Chen, X., Zhu, H., & Chen, J. (2011). Hazard Identification and Control in the Pre-Blasting Process. *Journal of Coal Science & Engineering, 17*(3), 331-335.

Crawley, F., & Tyler, B. (2015). *HAZOP: Guide to best practice*. Elsevier.

Crowl, D. A., & Louvar, J. F. (2001). *Chemical process safety: fundamentals with applications*. Pearson Education.

CSB US Chemical Safety Board. *Chevron Refinery Fire.* Retrieved from http://www.csb.gov/chevron-refinery-fire/

CSB US Chemical Safety Board. *Millard Refrigerated Services Ammonia Release* . Retrieved from http://www.csb.gov/millard-refrigerated-services-ammonia-release/

CSB US Chemical Safety Board. *CAI / Arnel Chemical Plant Explosion.* Retrieved from http://www.csb.gov/cai-/-arnel-chemical-plant-explosion/

Darwiche, A. (2009). *Modeling and reasoning with Bayesian networks*. Cambridge University Press.

Druzdzel, M. (1999, July 18-22). SMILE: Structural Modeling, Inference, and Learning Engine, and GeNIe: A Development Environment for Graphical Decision-Theoretical Models: Proceedings of *the Sixteenth National Conference on Artificial Intelligence (AAAI-99),* Orlando, Florida, 1999, American Association for Artificial Intelligence.

Ericson, C. A. (2015). *Hazard analysis techniques for system safety*. John Wiley & Sons.

Friedman, N., Geiger, D., & Goldszmidt, M. (1997). Bayesian network classifiers. *Machine learning*, *29*(2-3), 131-163.

Geiger, D., Verma, T. S., & Pearl, J. (2013). d-separation: From theorems to algorithms. *arXiv preprint arXiv:1304.1505*.

Kalantarnia, M., Khan, F., & Hawboldt, K. (2009). Dynamic risk assessment using failure assessment and Bayesian theory. *Journal of Loss Prevention in the Process Industries*, *22*(5), 600-606.

Khan, F. I., & Abbasi, S. A. (1998). Multivariate hazard identification and ranking system. *Process Safety Progress*, *17*(3), 157-170.

Khan, F. I. (2001). Use maximum-credible accident scenarios for realistic and reliable risk assessment. *Chemical engineering progress*, *97*(11), 56-65.

Khan, F., Husain, T., & Abbasi, S. (2001). SAFETY WEIGHTED HAZARD INDEX (SEeHI) A New, User-friendly Tool for Swift yet Comprehensive Hazard Identification and Safety Evaluation in Chemical Process Industries. *Process Safety and Environmental Protection,* 65-80.

Khakzad, N., Khan, F., & Amyotte, P. (2012). Dynamic risk analysis using bow-tie approach. *Reliability Engineering & System Safety*, *104*, 36-44.

Khakzad, N., Khan, F., & Amyotte, P. (2013). Dynamic safety analysis of process systems by mapping bow-tie into Bayesian network. *Process Safety and Environmental Protection*, *91*(1), 46-53.

Khakzad, N., Khan, F., Amyotte, P., & Cozzani, V. (2014). Risk management of domino effects considering dynamic consequence analysis. *Risk Analysis*, *34*(6), 1128-1138.

Kim, D., Moon, I., Lee, Y., & Yoon, D. (2003). Automatic generation of accident scenarios in domain specific chemical plants. *Journal of Loss Prevention in the process industries*, *16*(2), 121-132.

Kletz, T. A. (1997). HAZOP—past and future. *Reliability Engineering & System Safety*, *55*(3), 263-266.

Kletz, T. A. (1999). The constraints on inherently safer design and other innovations. *Process Safety Progress*, *18*(1), 64-69.

Knegtering, B., & Pasman, H. (2013). The safety barometer: How safe is my plant today? Is instantaneously measuring safety level utopia or realizable?. *Journal of Loss Prevention in the Process Industries*, *26*(4), 821-829.

Mannan, S. (2012). *Lees' Loss prevention in the process industries: Hazard identification, assessment and control*. Butterworth-Heinemann.

McCoy, S. A., Wakeman, S. J., Larkin, F. D., Jefferson, M. L., Chung, P. W. H., Rushton, A. G., Lees, F.P., & Heino, P. M. (1999). HAZID, a computer aid for hazard identification: 1. The STOPHAZ package and the HAZID code: an overview, the issues and the structure. *Process Safety and Environmental Protection*, *77*(6), 317-327.

Nolan, D. (1994). *Application of HAZOP and What-if Safety Reviews to the Petroleum, Petrochemical and Chemical Industries*. William Andrew Publishing/Noyes.

Paltrinieri, N., Tugnoli, A., Buston, J., Wardman, M., Cozzani, V. Dynamic Procedure for Atypical Scenarios Identification (DyPASI): A new systematic HAZID tool (2013)

Journal of Loss Prevention in the Process Industries, 26 (4), pp. 683-695

Paltrinieri, N., Wilday, J., Wardman, M., Cozzani, V. Surface installations intended for Carbon Capture and Sequestration: Atypical accident scenarios and their identification (2014) Process Safety and Environmental Protection, 92 (1), pp. 93-107

Paltrinieri, N., Tugnoli, A., Cozzani, V. Hazard identification for innovative LNG regasification technologies (2015) Reliability Engineering and System Safety, 137, art. no. 006, pp. 18-28 Wilday, J., Paltrinieri, N., Farret, R., Hebrard, J., Breedveld, L.

Rathnayaka, S., Khan, F., & Amyotte, P. (2012). Accident modeling approach for safety assessment in an LNG processing facility. *Journal of Loss Prevention in the Process Industries*, *25*(2), 414-423.

Villa, V., Paltrinieri, N., Cozzani, V. Overview on dynamic approaches to risk management in process facilities (2015) Chemical Engineering Transactions, 43, pp. 2497-2502

Villa, V., Paltrinieri, N., Khan, F., Cozzani, V. Towards dynamic risk analysis: A review of the risk assessment approach and its limitations in the chemical process industry (2016) Safety Science, 89, pp. 77-93.

Wang, Y. F., Xie, M., Ng, K. M., & Habibullah, M. S. (2011). Probability analysis of offshore fire by incorporating human and organizational factor. *Ocean Engineering*, *38*(17), 2042-2055.

Wilday, J., Paltrinieri, N., Farret, R., Hebrard, J., & Breedveld, L. (2011). Addressing emerging risks using carbon capture and storage as an example. *Process Safety and Environmental Protection*, *89*(6), 463-471.

Yuan, Z., Khakzad, N., Khan, F., & Amyotte, P. (2015). Risk analysis of dust explosion scenarios using Bayesian networks. *Risk analysis*, *35*(2), 278-291.

Chapter 3. Layout Optimization of A Floating Liquefied Natural Gas Facility Using Inherent Safety Principles

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Abstract

This paper presents a layout optimization methodology for the topside deck of a floating liquefied natural gas facility (FLNG) using inherent safety principles. Natural gas is emerging as a clean energy, and a large amount of natural gas exists in the proven offshore area, thus making it an energy source with huge potential in today's and the future market. FLNG facilities tap natural gas from an offshore well by floating, compressing it into liquefied natural gas (LNG), and offloading it to LNG carriers after temporary storage. In addition, FLNG facilities enable long-distance as well as multi-location transportation. The FLNG facility requires compact design due to limited space and high construction costs, and thus faces a more challenging situation where the design has to concurrently guarantee economic profits and a safe operational environment. Therefore, the layout of the topside deck, which includes production, storage, and other functions plays a paramount role in designing an FLNG facility. This papers optimizes the layout of an FLNG topside deck by implementing inherent safety principles. The objective is to design a topside deck layout which achieves the largest extent of inherent safety with optimal costs. Details of the principles and their application for layout optimization are also provided.

Keywords: Floating LNG facility; topside layout design, layout optimization, inherent safety principles

3.1 Introduction

Natural gas has emerged as a clean energy with a low capex in recent years [1]. The International Energy Agency has predicted that the demand for natural gas will continue to increase for the next decades and replace coal as the second main fuel [2], thus making natural gas play an important role in today's energy markets. Liquefied natural gas (LNG) is the liquid form of natural gas at the temperature of approximately -160 Celsius at atmospheric pressure. Its competitive volume, which only takes up 1/600th of its gas form, facilitates larger storage capacity and long distance transportation. With this notable feature and the increased exploration of offshore gas reserves due to the depletion of traditional fossil fuels onshore, floating liquefied natural gas (FLNG) facilities are being developed as a new offshore architecture that combines the functions of floating, production, storage, and offloading (FPSO). More specifically, they are turret-moored facilities which provide liquefaction process, temporary storage as well as offloading towards LNG carriers [3]. Besides, FLNG facilities are particularly adapted to deep water and are served in remote areas where the infrastructure of production and transportation are inadequate [4].

Although FLNG facilities have been less used compared to other offshore facilities, they are still a favorable solution when dealing with offshore gas fields [5]. To date, the FLNG industry has made continuous breakthroughs, and the world's first and largest FLNG facility developed by Shell has finished construction and will start production in 2016. Meanwhile, much research has been conducted to develop FLNG layout, process, mooring systems, and LNG tankers [1,5-7]. FLNG facilities require a compact layout that raises risk potential to a new height. For example, other than hazards triggered by the flammability of LNG, clearances among equipment are smaller compared to land conditions, and knock-on effects are more likely to take place; in addition, the living quarter is closer to the process area, and emergency escape is limited to an isolated situation surrounded by water. Moreover, atypical scenarios caused by innovative technologies need to be identified [8]. Typical FLNG risks, such as ship collision and LNG spills were discussed in [9], and representative LNG accidents of recent decades, which have brought significant loss of life and injuries, were outlined in [8]. Therefore, risk assessment is of vital importance during the design stage to spot risk potential and discover design limitations. To date, risk assessment has been adopted to FLNG studies via using either simulation or qualitative and quantitative analysis. [10-12].

An index approach was developed by [13] to assess plant layouts from an inherent safety perspective. Layout plays a key role in the FLNG facility. It decides area and equipment arrangements and influences accident magnitude and propagation routes of hazards. Therefore, an optimal layout can greatly enhance plant safety and effectively mitigate hazards. [14] also demonstrated that safety could be improved by proper layout design. On the other hand, inherent safety is a proactive way of eliminating hazards inherently and emphasizes safety integrity rather than relying on passive measures. Firstly proposed by Trevor Kletz in 1978, the aspects of the inherent safety have evolved since then. One important development in this field is the index-based approach for evaluating process safety. Inherent safety indices and the comparison among different approaches are available in [15-19]. Layout optimization at the conceptual stage can also be considered as inherent safety improvement out of the design itself. This paper conducts a layout optimization of the FLNG facility by means of the inherent safety method. When dealing with this new concept, FLNG, the proposed work shows a new way of thinking that sets safety as a starting point and tries to balance costs of safety measures with unexpected extra costs brought by potential risks. It also provides an alternative layout assessment in which safety becomes the primary issue and the assessment is achieved by means of conceptualizing safety into an index form. Using inherent safety principles helps ensure the integrity of FLNG, thus making the production and operational systems inherently safer. Part of this work was presented at the OMAE conference [20], and this paper will provide more details on the application of the inherent safety methodology as well as optimizing the layout of FLNG topside deck design.

3.2 FLNG Layout Design

3.2.1 FLNG Layout Framework

The Layout plays a paramount role when designing facilities. It decides areas and equipment arrangements. It also determines the area with the highest population density, accessibility of plants, and emergency response plan [13]. Further, it influences pipeline complexity that associates with costs and the route of propagating hazards. Offshore units require compact layouts, thus leading to a higher risk of hazard escalation (chains of hazards). Therefore, layout design of offshore units not only requires taking into account challenging offshore conditions, but also minimizing risks as much as possible. Planning the overall site and the process area layout are the two parts of the plant layout design [21]. The present work started with selecting an appropriate LNG process adapting to offshore conditions, then determined physical locations of equipment in the LNG process area, lastly arranged blocks of areas on the topside deck of an FLNG facility. The framework of layout optimization is as shown in Fig. 3.1.

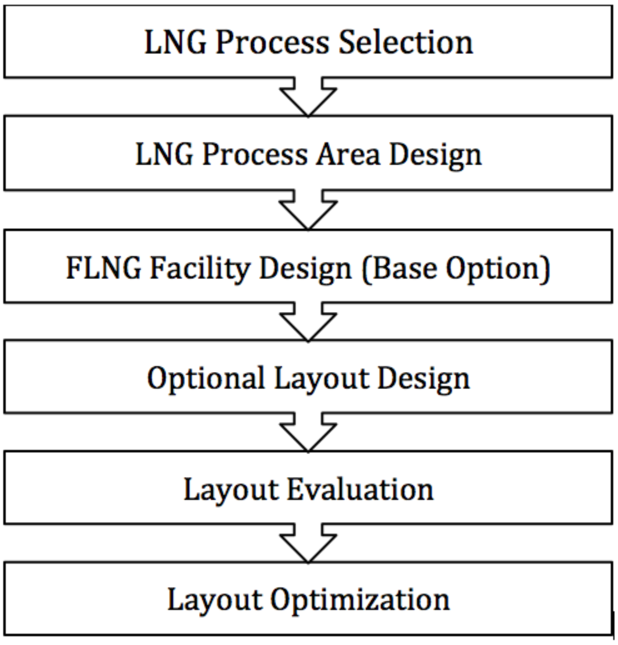

Figure 3.1 FLNG Layout Optimization Framework

3.2.2 LNG Process Selection

[1] described four process components that exist on the FLNG facility. Liquefaction process is considered as the most important process which might influence the whole facility's performance. Thus, the determination of the LNG process is a key element of the FLNG facility design. [22] pointed out several LNG process criteria including compactness, modular design, operation problems and process efficiency due to the limited space under offshore conditions. Descriptions of different liquefaction techniques can be found in existing literature [1,6,23]. [6] made a comparison of five liquefaction processes (C3MR, DMR, Liquefin, SMR-SP, and SMR-DP) from seven criteria (namely energy consumption; feasibility and design of cryogenic exchangers,

compressors, and water cooled exchangers; ease of operation; references; and loss of production) and drew a conclusion that DMR, C3MR, and Liquefin were the most adoptable considering extreme climate conditions and capacities.

Among these liquefaction techniques, Shell's dual mixed refrigerant (DMR) process has been adopted by the Sakahalin LNG project and the Shell Prelude FLNG projects [24]. It enjoys the highest efficiency [25], competitive production capacity and low capital costs compared to other processes [24]. Therefore, in this study, we chose the DMR as the liquefaction technology. The DMR process has two liquefaction cycles, precooling mixed refrigerant cycle and mixed refrigerant cycle, with different mixed refrigerants, respectively. The mixed refrigerant is firstly chilled in the pre-cooling cycle and together with the precooling mixed refrigerant chills the natural gas thoroughly to a liquid phase [23]. The DMR process on the FLNG mainly consists of raw gas treatment and liquefaction processes, shown below in Fig. 3.2, in which the Pre-Mixed Refrigerant Module1, Pre-Mixed Refrigerant Module 2, and Mixed Refrigerant Module all belong to the liquefaction process. [25] studied optimal DMR process operation conditions; [26, 27] investigated an optimal layout for the FLNG facility by comparing the required power of several pre-proposed layouts, and the optimal layout had the highest efficiency. The current work started with the selected liquefaction process and proposed block design for an FLNG facility topside layout.

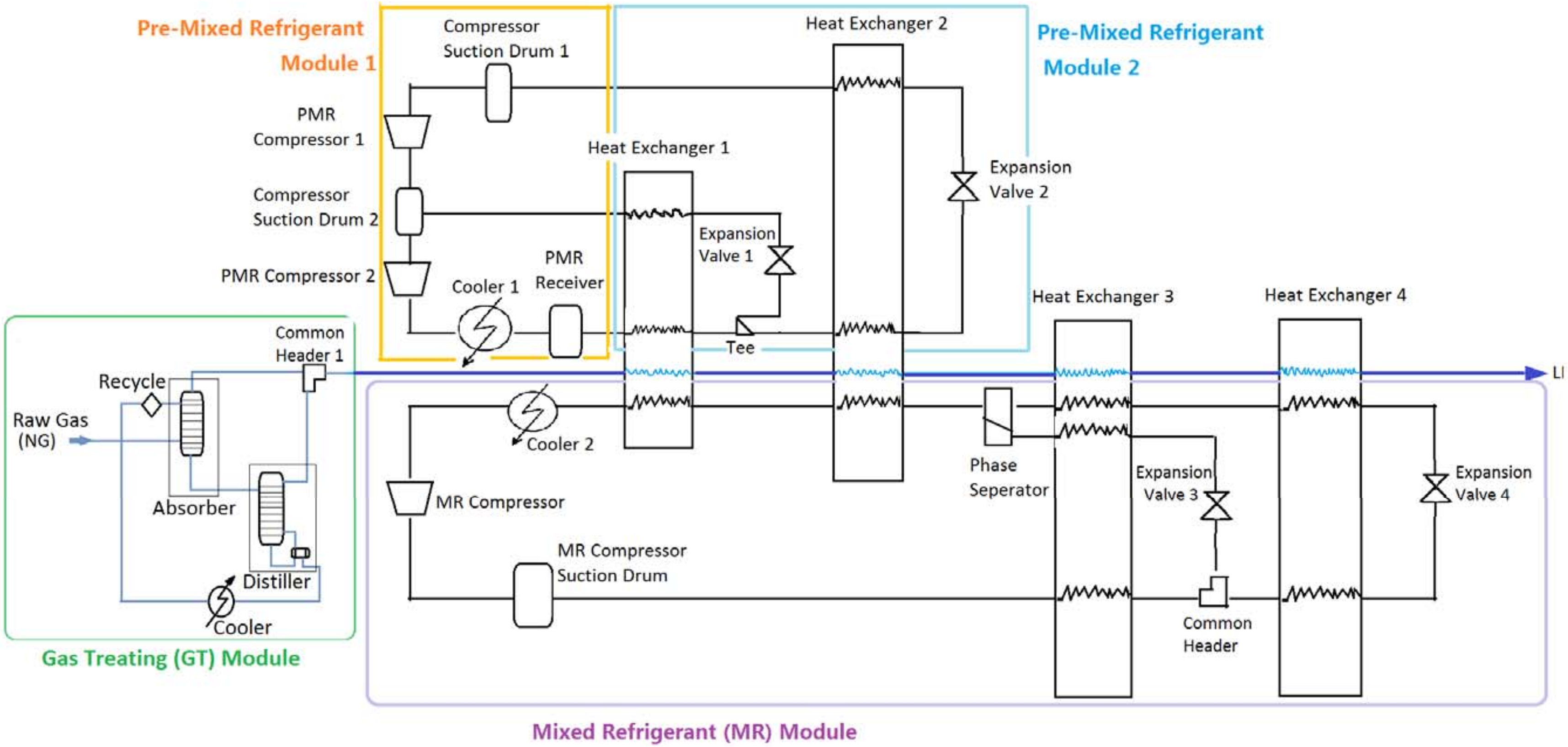

Figure 3.2 DMR Liquefaction Process on the FLNG facility

3.2.3 Process Area Design

The core factor of an FLNG is to optimize a modular design for liquefaction process equipment [1], thus indicating the importance of layout design work. The design work firstly finished the deck design of the process area, and then made arrangement for different areas of the FLNG facility. In the first stage, design methodology and constraints mainly were according to [7]. For example the centerlines of each piece of equipment were perpendicular to x axis and y axis; and this work was used as a reference to determine the physical location and dimension of the equipment to ensure the feasibility and adaptability of the design in practice. However, changes and modifications were also made in order to fit the new situation. The liquefaction process was separated into four process modules. These were gas treating module (GT), pre-mixed refrigerant module1 (PMR 1), pre-mixed refrigerant module 2 (PMR 2), and mixed refrigerant module (MR). The allocation of each module is shown in Fig. 3.3. Additionally, as the process area was regarded as the most cost intensive part, which concentrating 70% of the total capital cost [11], each module was designed as a multi-deck allocation in order to decrease the capital cost [7]. The example of design details of the MR module is illustrated in Fig. 3.3 and Table 3.1. Deck design details of the other modules are available in Appendix A.

SolidWorks was used in order to examine the feasibility of the proposed deck design, meaning the examination of inequality restraints of non-overlapping, emergency and working space areas [7]. The example of the isometric view of the MR module using the SolidWorks is shown as Fig. 3.4.

Table 3.1 Design variables of equipment arrangements of the MR module

Equipment		Centroid Coordinate		Dimension			Deck Belonging
No.	Name	xi(m)	yi(m)	Length (m)	Width (m)	Height (m)	
1	MR Phase Separator	20.35	21.85	3.5	3.5	9	deck B,C
2	Heat Exchanger3	20.35	12.75	4.7	4.7	42	deck A, B,C,D,E
3	Heat Exchanger4	20.35	3.05	4.7	4.7	42	deck A,B,C,D,E
4	Expansion Valve3	7.5	13	0.1	0.1	0.15	deck C
5	Expansion Valve4	7.5	3	0.1	0.1	0.15	deck D
6	MR Compressor Suction Drum	14.35	21.85	4.5	4.5	8.5	deck B,C
7	MR Compressor	6.5	12.15	17.3	6	6.4	deck C
8	Cooler for MR Compressor	6.5	12.15	3	2	3	deck B
9	Overhead Crane	6.5	13	23	16	6	deck D
10	Cooler2	5	13	3	2	5	deck E
		Deck width =23 m		Deck length = 33.3 m		Deck area = 765.9 m2	

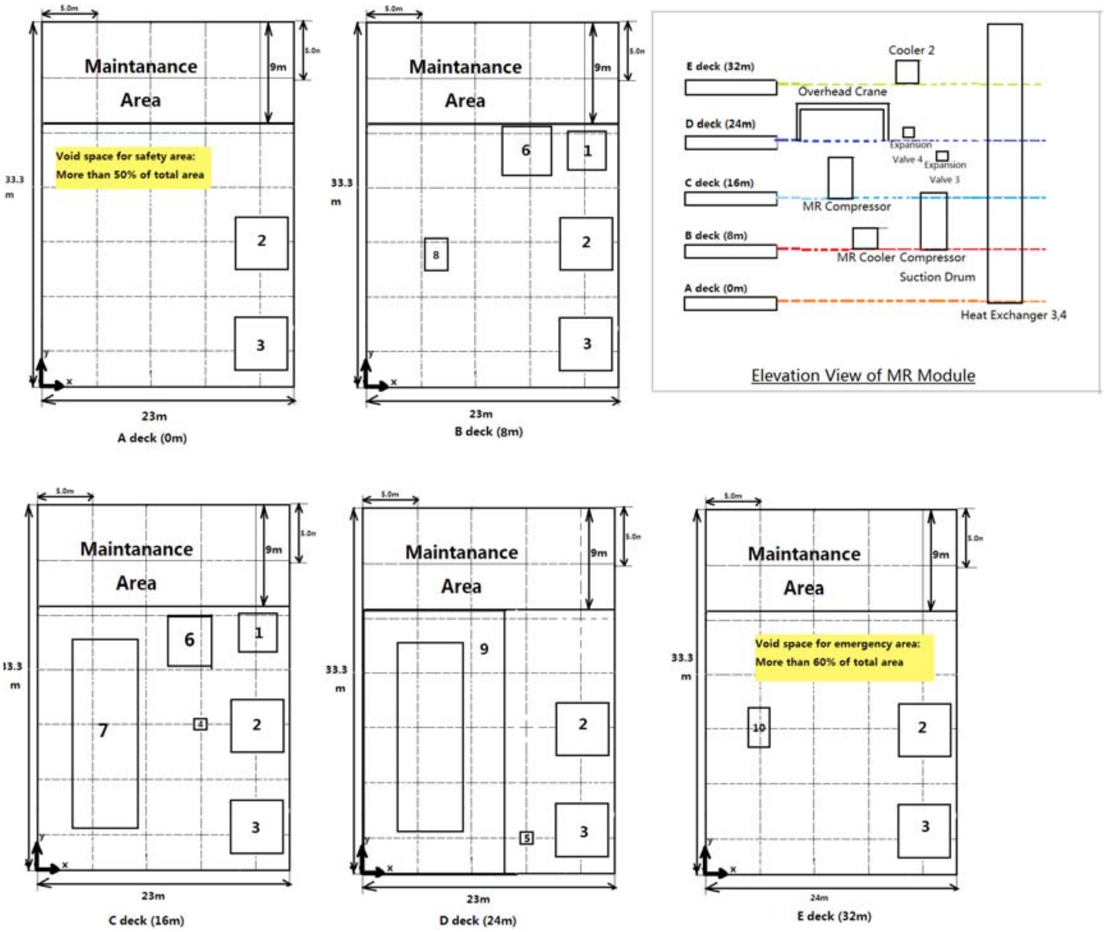

Figure 3.3 Plan view of the MR module

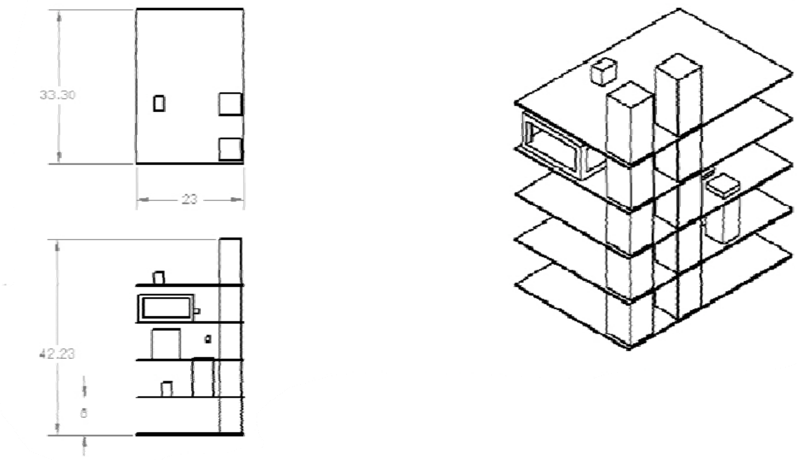

Figure 3.4 Isometric view of the MR module

3.2.4 FLNG Facility Topside Layout Design

Catastrophic events are generally caused by hazard escalation; however, a proper layout could effectively prevent this from happening due to the precaution of safe distances among equipment. Spaces setting among units were discussed in [28,29]. However, hazard prevention and mitigation for offshore production facilities need additional consideration regarding a new surrounding environment and tactics [30]. The current work arranged area blocks of process, storage, living quarter, water treatment, and control room. Nine areas are listed as Fig. 5 shows, where the process area is divided into four modules. Areas of four process modules were consistent with previous discussion results. Distances between each area were set as 15m [31], and 20m for the process area due to its higher risks. The dimensions of control room and storage areas were set with the reference from [32]; walkways were designed according to the example of the offshore production unit in [30]. On the other hand, topside design not only involves the dimensional set of each area, but also concerns the spatial layout of the physical location. In order to better guarantee the safety of the crew's working and living environment, areas with higher risks should be as far as possible from those with lower risks [33]. Therefore, the living quarter, which has a high population density, was arranged to be far from the process area; moreover, firewalls were added to protect the crews in case of fire emergency.

Based on the design requirements and regulations of offshore facilities, a base layout of a topside deck was drafted in SolidWorks as shown in Fig. 3.5 (a). SolidWorks was used due to the convenience of dimension adjustments. The process modules were attached to each other and took up approximately half the space of the topside deck, and the rest of the area were located below. Further, the living quarter was placed at the bottom so as to be far away from the process area. Meanwhile, underlying risks emerged as a consequence of saving space. The process area was highly likely to suffer hazard escalation due to the connected configuration. However, at this point, no quantitative and sufficient evidence indicated this attachment could cause the mentioned risk. Thus, two more layouts were proposed to make the comparison with the base layout.

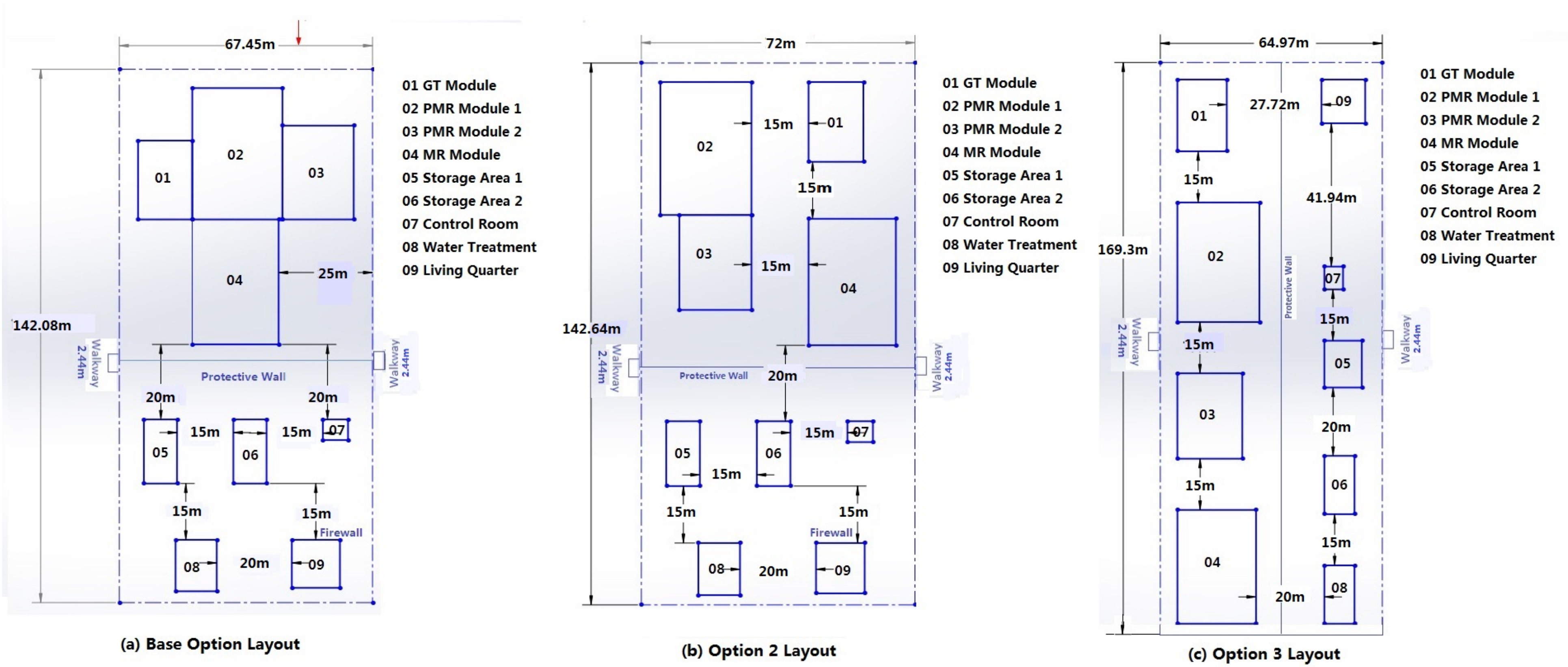

Figure 3.5 Three layouts for FLNG topside deck

With the consideration of the effectiveness of hazard prevention, control, and applicability to offshore conditions [34], the inherent safety method is found to be the most appropriate way to improve layout safety. As mentioned earlier, inherent safety method intrinsically enhances safety rather than relying on passive measures, and the basis of implementing this method is to apply the so-called inherent guidewords. [13] discussed three dominant guidewords regarding layouts. These were attenuation, simplification, and limitation. Applying the attenuation guideword changes the arrangement of units contributing to reducing the likelihood of hazard escalation; the simplification guideword impacts spatial organization that ameliorates the complexity of pipelines and process flow; the limitation guideword has similar effects as the attenuation guideword which aims to mitigate and eliminate hazard escalation; however, the limitation guideword considers both inherent measures and passive measures while the effect of the attenuation guideword is only attained by using inherent measures [13].

The application of these guidewords to the base layout and two optional layouts is shown as Fig. 3.5 (b) and (c). In Option 2, PMR Module 1 and PMR Module 2 were placed along the length (x-axis), unlike the base layout where those were placed along the width (y-axis). The GT Module and MR Module were separated and kept parallel to two pre-cooling modules. The arrangements of the remaining were almost the same as the base layout. Due to the partial segregation, total width of the facility increased from 67.45m to 72m. In Option 3, all of the four process modules were placed along the length; physical locations of other areas changed accordingly. Compared to the base layout, and total width decreased from 67m to 64.97m, total length increased from 142.08m to 169.3m. Additionally, the living quarter in this layout was at the top right corner and kept almost 30m from the GT module which was considered as the nearest threatening source.

3.3 Layout Optimization Method

The purpose of the majority layout optimal solutions is to minimize costs. The traditional way of optimizing layout is either to use mathematical algorithms or programming the shortest distance of flow across units. Research regarding identified types of layout optimization can be found in the literature [35-38]. However, while considering how to use optimal layout to save costs, vulnerability to loss from accidents due to safety issues cannot be ignored. Kletz pointed out safety can be as well achieved without spending much money [39]. [40] investigated a case study which substantiated that inherent safety could be balanced with good cost performance when taking expected loss into consideration, such as environmental loss.

The current work investigated layout optimization from the inherent safety perspective, and the method used in layout evaluation chose an index-based approach incorporating an integrated inherent safety index (I2SI) and domino hazard index (DHI). I2SI is a comprehensive method of inherent safety assessment, which was proposed by [40] and was revised with an addition of cost evaluation [41]. It provides a quantitative feedback of the applicability extent of inherent safety and also builds up a connection between inherent safety and costs estimation. Further, domino hazard index, a sub-index of the inherent safety index, [42] was used to assess the possibility of the domino hazard (hazard escalation) of each layout. [43] concluded a domino hazard could be prevented by appropriately changing plant layouts. Therefore, studies have hitherto verified plant layouts do influence safety from both the safety and cost perspective. Details of indices calculation procedure and relevant costs of safety measures used in the current work can be found in [18,40-42]. The framework of layout evaluation is depicted in Fig. 3.6, where the index calculation procedure can be summarized into a pyramid-shaped structure. In order to obtain the three main indices, sub-indices of the lower layers should be calculated first. For example, hazard index (HI) and inherent safety potential index (ISPI) are required before calculating the I2SI, because the I2SI is a quotient of the HI and the ISPI. Each index has its own function, and details are available in previously mentioned literatures. The sub-indices in the lower layer should be considered first before obtaining the indices on the upper layer, and the layout evaluation can be finally realized by calculating the layers from the bottom to the top.

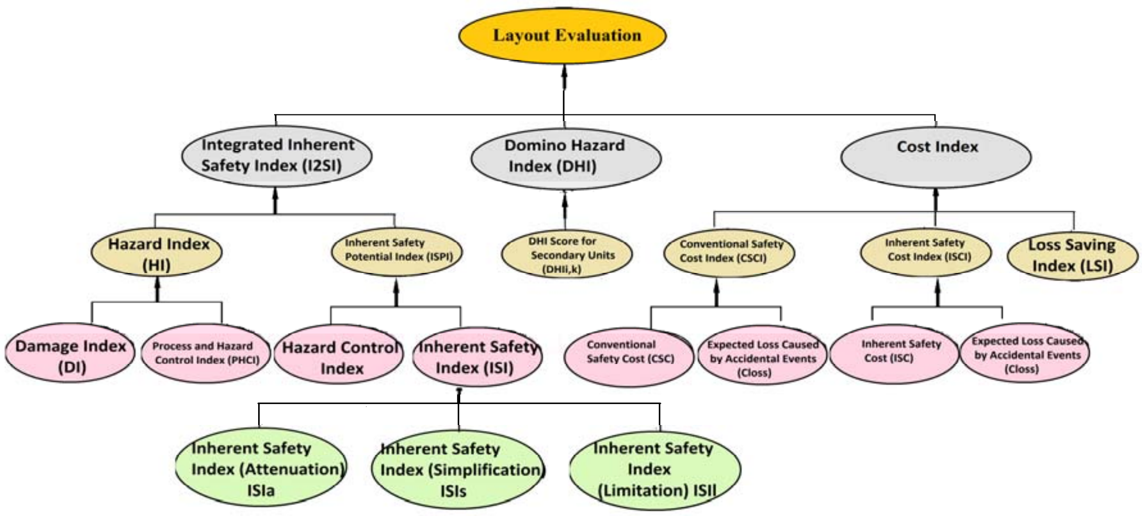

Figure 3.6 Framework of layout evaluation

3.4 Result discussion

Risk in the process area is much higher compared to other areas due to extreme operating conditions or hazardous materials; therefore, the process area should be a focus, and the following work was completed based on assessing the layout safety of the process area. In this area, potential risks should be avoided as much as possible in order to ensure safety; however, in this particular case, liquefied natural gas can only be obtained by liquefaction, which means the risks brought by the cooling operational process cannot be prevented. Thus, safety measures are still required though inherent safety has been applied. Assessing the extent of applying the inherent safety concept is based on the hazardous impacts on surrounding units given an accident scenario for one certain unit. An explosion scenario was assumed to take place on a compressor, and a fire scenario was assumed for the rest of the equipment. Safety scores were posed for each individual unit to better understand quantifying inherent safety and its influence on each unit. Table 2 shows the final results of the I2SI and DHI for three layout options. The inherent safety index (ISI) as an intermediate step of I2SI index method is also introduced in Table 3.2. The computed ISI for the base option was less than 5. Due to the minimum value of ISI is 5 [42], the ISI for all the equipment in the base option was considered to be 5 in this case. The larger the I2SI is, the more inherently safer the layout will be. On the other hand, a larger DHI value means a higher probability of suffering hazard escalation. Note that an assumption was made that costs of simplification remained the same while the complexity of the process increased. According to the results yielding from I2SI, DHI and cost indices, the analysis of each layout is as follows:

- Base layout

In the base layout, the process area was the smallest among the three layouts due to the connection of four process modules; however, the high likelihood of aggravating hazard escalation was proved by the highest value of DHI among the three layouts as shown in Table 3.2. On the other hand, the I2SI values were generally low (less than 1) for all equipment shown in Table 2, indicating it was not inherently safe enough compared to the other two. In the cost part, the cost of conventional safety was first calculated using the number and price of safety measures. The cost evaluation showed conventional costs were generally higher compared to the other two layouts as Table 3 shows. The increased cost is due to the more add-on measures that are needed to guarantee safe operational conditions.

Table 3.2 Layout Evaluation Results

		Base Option			Option 2			Option 3		
No.	**Unit**	**ISI**	**I2SI Base Option**	**DHI**	**ISI**	**I2SI Option 2**	**DHI**	**ISI**	**I2SI Option 3**	**DHI**
1	Absorber	5.00	0.36	3.10	12.25	0.87	2.10	12.24	0.87	2.1
2	Distiller	5.00	0.36	7.00	12.25	0.87	5.10	12.24	0.87	5.1
3	Cooler	5.00	0.39	1.90	23.43	1.85	0.00	23.43	1.85	0
4	Common Header	5.00	0.26	6.80	12.25	0.63	5.00	12.24	0.63	5
5	PMR Suction Drum1	5.00	0.34	15.00	1.89	0.13	15.00	1.73	0.12	15
6	PMR Suction Drum2	5.00	0.43	16.80	1.89	0.16	16.80	1.73	0.15	15
7	PMR Compressor1	5.00	0.31	6.00	7.15	0.44	4.00	21.21	1.32	3
8	PMR Compressor2	5.00	0.31	6.00	7.15	0.44	4.00	21.21	1.32	3
9	Cooler for Comp.1	5.00	0.39	3.80	21.21	1.67	2.00	21.21	1.67	2
10	Cooler for Comp.2	5.00	0.39	4.90	5.76	0.45	3.90	31.11	2.46	2
11	Cooler1	5.00	0.39	4.00	21.21	1.67	2.00	21.21	1.67	2
12	PMR Receiver	5.00	0.38	9.60	5.76	0.43	7.80	32.66	2.47	4.1
13	Heat Exchanger1	5.00	0.45	15.70	1.89	0.17	15.70	11.49	1.03	12.1
14	Heat Exchanger2	5.00	0.45	12.00	1.89	0.17	12.00	10.10	0.90	12
15	Expansion Valve1	5.00	0.54	4.20	1.89	0.21	4.00	12.24	1.33	3
16	Expansion Valve2	5.00	0.42	4.00	1.89	0.16	4.00	12.24	1.04	3
17	MR Phase Separator	5.00	0.68	20.80	23.43	3.19	10.00	142.86	19.43	0
18	Heat Exchanger3	5.00	0.58	10.20	10.13	1.18	10.00	10.10	1.18	10
19	Heat Exchanger4	5.00	0.58	12.00	10.13	1.18	12.00	10.10	1.18	12
20	Expansion Valve3	5.00	0.56	7.60	23.43	2.61	4.00	23.43	2.61	4
21	Expansion Valve4	5.00	0.56	3.00	10.13	1.13	3.00	10.10	1.12	3
22	MR Compressor Suction Drum	5.00	0.61	12.00	10.13	1.23	12.00	10.10	1.23	12
23	MR Compressor	5.00	0.34	5.00	10.13	0.69	5.00	10.10	0.68	5
24	Cooler for MR Compressor	5.00	0.67	5.90	10.13	1.36	5.90	10.10	1.36	5.9
25	Cooler2	5.00	0.33	2.80	10.13	0.66	2.80	10.10	0.66	2.8

- Option 2

In Option 2, partial process modules (GT module and MR module) were demarcated, and thus directly contributed to a decrease of DHI value as Table 3.2 shows. This decrease also implied that the segregation of equipment is an effective way to prevent hazard escalation. Additionally, ISIa and ISIl were significantly increased while the ISIs of some units slightly decreased as a consequence of higher complexity, leading to the increase of the total ISI value. PHCI, HCI, and DI values remained as the same with the base layout. In this layout, most of the equipment had larger values on the I2SI than the base option as shown in Table 3.2, which also clarifies that area segregation makes plants inherently safer. As to cost, the cost of inherent safety was smaller than that of the base option in the GT module and PMR Module 1; however, an increase is also shown in PMR Module 2 and MR module, mainly because of the high cost of some minor units, such as expansion valve and cooler. In order to better explain this variation, cost saving was then calculated to compare the safety costs of the base option and Option 2. Overall, additional costs on PMR module 2 and PMR module 1 were beyond the costs saved by the GT module and PMR module as shown in Table 3.3, thus making total costs of Option 2 surpassed the base option.

Table 3.3 Costs comparison for three layouts

	Base Option	Option 2		Option 3	
	Cost of Conventional Safety (1000$)	Cost of Inherent Safety (1000$)	Cost Saving (1000$)	Cost of Inhernet Safety (1000$)	Cost Saving (1000$)
GT Module	872	428	444	428	444
PMR Module 1	1250	960	290	762	488
PMR Module 2	1120	1780	-660	872	248
MR Module	1670	3350	-1680	2250	-580
		Total saving	-1606	Total Saving	600

- Option 3

In Option 3, all process modules were isolated in order to mitigate the hazard escalation of the process area. Generally, DHI values were the smallest and much lower than the other two options as shown in Table 3.2, which reflected that this layout was much safer due to the separation of process modules from the hazard escalation perspective. Three sub-indices changed dramatically due to different assigned DHI scores for each possible secondary unit. Process complexity and limitation effects remained the same, but overall most of the I2SI values were higher. From the cost perspective, the MR module was the only module which cost more than the base option. However, the total saving indicated Option 3 did save safety costs on the whole. Thus, Option 3 was so far considered as the most optimal layout.

3.5 Conclusion

The current work performed a layout optimization using the inherent safety principles given three layouts of the topside deck of an FLNG facility. The layout was optimized from the view of making plant inherently safer. Three layouts were designed in accordance with offshore regulations, and the main difference lay in the arrangement of four process modules in the process area. The process modules were the sub-parts divided from the dual mixed refrigerant which was selected as the liquefaction technique after comparing several technologies. The I2SI and Cost Index were the two main indices implemented to assess each layout. After analyzing the extent of inherent safety for each layout, Option 3 was found to be the best layout due to its largest extent of applying the inherent safety method proved by generally higher I2SI values and the best cost performance compared to the others. However, Option 3 was not satisfying in every aspect; for instance, it took the largest space due to the segregation of process modules. Nevertheless, safety is always at the first priority. Issues brought by safety risks could very well cost far more than the saved money. Meanwhile, the other two options can also enhance safety while keeping the current area by adding more safety devices; however, this also confronts the same expected accidental loss. Thus, on the whole Option 3 was the most optimal layout. More generally, module segregation could significantly enhance the safety inherently especially for an offshore structure where the space is limited and equipment is compact. The distances between modules could inherently prevent the domino hazard acting among modules. Further, costs brought by the segregation effect decreased in this case when concerning costs of safety measures and loss of expected accident events. However, using inherent safety principles takes no consideration of construction costs, and thus cannot assess the addition costs due to the increased area. Additionally, the influence of environmental force on layout, such as prevailing wind, need to be further discussed. Another limitation is the uncertainty of the feasibility of the proposed layouts. As previously mentioned, FLNG is a new concept, and so far no FLNG facilities have come into real production. Therefore, the relevant design information of FLNG is very limited for use as a reference. The proposed work introduces a new way of offshore layout design and optimization that is based on inherent safety. Additionally, ensuring inherent safety is believed to an optimal mechanism to enhance safer operation and prolong the lifetime of the plants by reducing the risks of accidents.

3.6 Reference

[1] Won, W., Lee, S. K., Choi, K., & Kwon, Y., 2014, "Current Trends for the Floating Liquefied Natural Gas (FLNG) Technologies," Korean Journal of Chemical Engineering, **31**(5), pp. 732-743.

[2] Gowid, S., Dixon, R., & Ghani, S., 2014, "Optimization of Reliability and Maintenance of Liquefaction System on FLNG Terminals Using Markov Modeling," International Journal of Quality & Reliability Management, **31**(3), pp. 293-310.

[3] Zhao, W., Yang, J., & Hu, Z., 2013, "Effects of Sloshing on the Global Motion Responses of FLNG," Ships and Offshore Structures, **8**(2), pp. 111-122

[4] Chakrabarti, S., 2005, *Handbook of Offshore Engineering,* Elsevier, Oxford, UK, Chap. 7.

[5] Ronalds, B. F., & Lim, E. F. H., 1999, “FPSO Trends,” SPE 56708, *SPE annual technical conference,* SPE, Houston, Texas.

[6] Paradowski, H., & Hagyard, P., 2003, “Compare Five LNG Process,” Hydrocarbon Engineering, pp. 31-37.

[7] Ku, N. K., Hwang, J. H., Lee, J. C., Roh, M. I., & Lee, K. Y., 2014, “Optimal Module Layout for a Generic Offshore LNG Liquefaction Process of LNG-FPSO,” Ships and Offshore Structures, **9**(3), pp. 311-332.

[8] Paltrinieri, N., Tugnoli, A., & Cozzani, V., 2015, “Hazard Identification for Innovative LNG Regasification Technologies,” Reliability Engineering & System Safety, **137**, pp. 18-28.

[9] Pitblado, R. M., & Woodward, J. L., 2011, “Highlights of LNG Risk Technology,” Journal of Loss Prevention in the Process Industries, **24**(6), pp. 827-836.

[10] Otsubo, K., Sotaro, M., Yaguchi, Y., Asanuma, T., & Maeda, K., 2014, “Gas Explosion Analysis for FLNG Plant Layout Design,” **19**(0), pp. 255-263.

[11] Dan, S., Lee, C. J., Park, J., Shin, D., & Yoon, E. S., 2014, “Quantitative Risk Analysis of Fire and Explosion on the Top-Side LNG-Liquefaction Process of LNG-FPSO,” Process Safety and Environmental Protection, **92**(5), pp. 430-441.

[12] Vanem, E., Antão, P., Østvik, I., & de Comas, F. D. C., 2008, “Analysing the Risk of LNG Carrier Operations,” Reliability Engineering & System Safety, **93**(9), pp. 1328-1344.

[13] Tugnoli, A., Khan, F., Amyotte, P., & Cozzani, V., 2008, “Safety Assessment in Plant Layout Design Using Indexing Approach: Implementing Inherent Safety Perspective: Part

1–Guideword Applicability and Method Description," Journal of hazardous materials, **160**(1), pp. 100-109.

[14] Ebrahimi, F., Virkki-Hatakka, T., & Turunen, I., 2012, "Safety Analysis of Intensified Processes," Chemical Engineering and Processing: Process Intensification, **52**, pp. 28-33.

[15] Rahman, M., Heikkilä, A. M., & Hurme, M., 2005, "Comparison of Inherent Safety Indices in Process Concept Evaluation," Journal of Loss Prevention in the Process Industries, **18**(4), pp. 327-334.

[16] Gangadharan, P., Singh, R., Cheng, F., & Lou, H. H., 2013, "Novel Methodology for Inherent Safety Assessment in the Process Design Stage," Industrial & Engineering Chemistry Research, **52**(17), pp. 5921-5933.

[17] Khan, F. I., & Abbasi, S. A., 1997, "Accident Hazard Index: A Multi-Attribute Method for Process Industry Hazard Rating," Process safety and environmental protection, **75**(4), pp. 217-224.

[18] Khan, F. I., Husain, T., & Abbasi, S. A., 2001, "Safety Weighted Hazard Index (SWeHI): A New, User-Friendly Tool for Swift Yet Comprehensive Hazard Identification and Safety Evaluation in Chemical Process Industries," Process Safety and Environmental Protection, **79**(2), pp. 65-80.

[19] Khan, F. I., Sadiq, R., & Amyotte, P. R., 2003, "Evaluation of Available Indices for Inherently Safer Design Options," Process Safety Progress, **22**(2), pp. 83-97.

[20] Xin, P., Ahmed S., Khan, F., 2015, "Inherent Safety Aspects for Layout Design of A Floating LNG Facility," OMAE2015-41669, *ASME 34th International Conference on Ocean, Offshore, and Arctic Engineering*, ASME, St John's, NL, Vol. 10, pp. V010T11A022.

[21] American Institute of Chemical Engineers, Center for Chemical Process Safety, 1995, *Guidelines for Safety Process Operations and Maintenance*, Center for Chemical Process Safety/AIChE, New York, USA, Chap. 3.

[22] Wood, D., Mokhatab, S., & Economides, M. J., 2007, "Offshore Natural Gas Liquefaction Process and Development Issues," SPE Projects, Facilities & Construction, **2**(04), pp. 1-7.

[23] Wang, X., & Economides, M., 2013*, Advanced Natural Gas Engineering*, Gulf Publishing Company, Houston, USA, Chap. 6.

[24] Nibbelke, R., Kauffman, S., & Pek, B., 2002, "Double Mixed Refrigerant LNG Process Provides Viable Alternative for Tropical Conditions," Oil & gas journal, **100**(27), pp. 64-66.

[25] Hwang, J. H., Roh, M. I., & Lee, K. Y., 2013, "Determination of the Optimal Operating Conditions of the Dual Mixed Refrigerant Cycle for the LNG FPSO Topside Liquefaction Process," Computers & Chemical Engineering, ***49***, pp. 25-36.

[26] Hwang, J., Lee, J. C., Lee, K. Y., & Roh, M. I., 2012, "Optimal Synthesis of LNG FPSO Liquefaction Cycles," ISOPE-I-12-134, *Twenty-second International Offshore and Polar Engineering Conference*, International Society of Offshore and Polar Engineers, Rhodes, Greece, pp. 17-22.

[27] Hwang, J., & Lee, K. Y., 2014, "Optimal Liquefaction Process Cycle Considering Simplicity and Efficiency for LNG FPSO at FEED Stage," Computers & Chemical Engineering, **63**, pp. 1-33.

[28] Mecklenburgh, J. C. (1973). *Plant layout: A guide to the layout of process plant and sites*, Wiley, New York.

[29] Center for Chemical Process Safety, 2003, *Guidelines for Facility Siting and Layout*, Center for Chemical Process Safety/AIChE, New York, USA, Appendix A.

[30] American Petroleum Institute, 2013, "Recommended Practice for Design and Hazard Analysis for Offshore Production Facilities Recommended Practice API-l4J, (2nd edition)," American Petroleum Institute, Washington DC.

[31] Terdre, N., 2011, "Safety, Offloading Issues Impact FLNG Vessel Size and Layout," Offshore, **71**(11).

[32] Chakrabarti, S., 2005, *Handbook of Offshore Engineering,* Elsevier, Oxford, UK, Chap. 10.

[33] Center for Chemical Process Safety, 2003, *Guidelines for Facility Siting and Layout*, Center for Chemical Process Safety/AIChE, New York, USA, Chap. 5.

[34] Khan, F. I., & Amyotte, P. R., 2002, "Inherent Safety in Offshore Oil and Gas Activities: A Review of the Present Status and Future Directions," Journal of Loss Prevention in the Process Industries, ***15***(4), pp. 279-289.

[35] Francis, R. L., & White, J. A., 1974, "*Facility layout and location: an analytical approach.* Englewood Cliffs," Englewood Cliffs, N.J., Prentice-Hall.

[36] Barbosa-Povoa, A. P., Mateus, R., & Novais, A. Q., 2001, "Optimal Two-Dimensional Layout of Industrial Facilities," International Journal of Production Research, ***39***(12), pp. 2567-2593.

[37] Patsiatzis, D. I., & Papageorgiou, L. G., 2002, "Optimal Multi-Floor Process Plant Layout," Computers & Chemical Engineering, ***26***(4), pp. 575-583.

[38] Sherali, H. D., Fraticelli, B. M., & Meller, R. D., 2003, "Enhanced Model Formulations for Optimal Facility Layout," Operations Research, **51**(4), pp. 629-644.

[39] Kletz, T., 2009, *What Went Wrong?: Case Histories of Process Plant Disasters and How They Could Have Been Avoided (5th Edition)*, Elsevier, Burlington, USA.

[40] Khan, F. I., & Amyotte, P. R., 2005, "I2SI: A Comprehensive Quantitative Tool for Inherent Safety and Cost Evaluation," Journal of Loss Prevention in the Process Industries, **18**(4), pp. 310-326.

[41] Khan, F. I., & Amyotte, P. R., 2004, "Integrated Inherent Safety Index (I2SI): A Tool for Inherent Safety Evaluation," Process Safety Progress, **23**(2), pp. 136-148.

[42] Tugnoli, A., Khan, F., Amyotte, P., & Cozzani, V., 2008, "Safety Assessment in Plant Layout Design Using Indexing Approach: Implementing Inherent Safety Perspective: Part 2–Domino Hazard Index and Case Study," **160**(1), pp. 110-121.

[43] López-Molina, A., Vázquez-Román, R., Mannan, M. S., & Félix-Flores, M. G., 2013, "An Approach for Domino Effect Reduction Based on Optimal Layouts," Journal of Loss Prevention in the Process Industries, **26**(5), pp. 887-894.

Chapter 4. Conclusions and Future Work

4.1 Conclusions

Risk-based design is a complementary approach to traditional design. It incorporates risk analysis to support decision-making and to lower risks to an accepted level. This thesis presents two risk-based tools including one dynamic hazard identification tool and one risk-based layout optimization technique. The proposed hazard identification model is adaptable to changing input parameters and able to make predictions accordingly for most likely hazards. The layout optimization technique adopts inherent safety method as a basis to evaluate different layouts through using inherent safety indices. The summary of each chapter is presented as follows.

Chapter 1 introduces risk-based design and the steps for conducting a risk-based design. Risk assessment, as the key element, is a focus. Hazard identification, probability analysis and consequence analysis are introduced in turns. Then the applications of risk-based design are reviewed followed by illustrating the research objectives and thesis outline.

Chapter 2 proposes a new methodology of hazard identification using the Bayesian network which helps to identify major hazards in real time. This methodology enables the construction of a dynamic hazard identification model which overcomes the drawbacks brought by the static feature in conventional approaches. The dynamic model enables the real time identification of hazards as well as information updates. In order to prove the feasibility and credibility of this method, three case studies of fire, explosion, and toxic scenarios are conducted. The simulation results from using the BN model are compared to the accident reports published on CSB websites and the results turn out consistency. In order to investigate the dominant probabilities shown in simulation results, sensitivity analysis is implemented to validate the generic model.

Chapter 3 demonstrates a risk-based method to improve safety inherently by performing layout optimization using inherent safety indices. The work firstly chooses an LNG process, followed by constructing an FLNG process area design as well as an FLNG topside layout design. Two optional layouts are also proposed with different arrangements of FLNG modules. Lastly, layout evaluation is performed in terms of the extent of inherent safety, and the layout with the best evaluated results is chosen as the optimized layout for an FLNG facility. The layout optimization process validates that the increase clearance between process modules can improve overall safety. Besides, the inherent safety has been proved a cost-effective method comparing to adding passive safety measures. However, the associated construction and maintenance costs caused by enlarging spaces should also be considered to balance with benefits.

Finally, the conducted research contributes to three publications as listed follows:

Xin, P., Khan, F., & Ahmed, S. (2016). Dynamic Hazard Identification and Scenario Mapping Using Bayesian Network. Paper accepted at *Process Safety and Environmental Protection*.

Xin, P., Khan, F., & Ahmed, S. (2015). Layout Optimization of a Floating Liquefied Natural Gas Facility Using Inherent Safety Principles. Paper accepted at *Journal of Offshore Mechanics and Arctic Engineering*.

Xin, P., Ahmed S., Khan, F., (2015). Inherent safety aspects for layout design of a floating LNG facility. International Conference on Ocean, Offshore, and Arctic Engineering (OMAE), St John's, ASME.

4.2 Future Work

In the future work, certain aspects can be improved for the presented tools.

The updating mechanisms in Bayesian network are encouraged so that results can be more credible and closer to the latest facts. In addition, frequency analysis and consequence analysis are also suggested to integrate so that the identified hazards can be better quantified.

In the layout optimization technique, impacts of environmental forces, such as prevailing wind, on FLNG layouts could be accounted when evaluating layouts. Furthermore, the feasibility of the proposed layouts can be further studied in the comparison of other existing naval architectures.

Appendix

Appendix Table 1 Deck design for GT module

Deck Design Variables for GT Module							
Equipment		Centroid Coordinate		Dimension			Deck Belonging
No.	Name	xi(m)	yi(m)	Length (m)	Width (m)	Height (m)	
1	Absorber	3.725	4.275	3.45	3.45	8	deck B,C
2	Distiller	11.45	4.275	2	2	13.8	deck B,C
3	Cooler	11.45	4.275	3	2	5	deck A
4	Common Header	11.45	10.5	1	1	1	deck D
		Deck width =14.45 m		Deck length = 21 m		Deck area = 303.45 m2	

Appendix Table 2 Deck design for PMR Module 1

Equipment		Centroid Coordinate		Dimension			Deck Belonging
No.	Name	xi(m)	yi(m)	Length (m)	Width (m)	Height (m)	
1	PMR Suction Drum1	8.5	24.5	3.65	3.65	4.65	deck B
2	PMR Suction Drum2	15.5	24.25	3.2	3.2	4.55	deck B
3	PMR Compressor1	8.5	13	19	6	5.8	deck B
4	PMR Compressor2	15.5	13	19	6	5.8	deck B
5	Cooler for Comp.1	8.5	13	3	2	3	deck A
6	Cooler for Comp.2	15.5	13	3	2	3	deck A
7	Overhead Crane for Compressor	12	13	23	16	6	deck C
8	Cooler1	12	13	8	2	5	deck D
		Deck width =24 m		Deck length = 35 m		Deck area = 840 m2	

Appendix Table 3 Deck design for PMR Module 2

Equipment		Centroid Coordinate		Dimension			Deck Belonging
No.	Name	xi(m)	yi(m)	Length (m)	Width (m)	Height (m)	
1	PMR Receiver	4.2	3.7	4.2	4.2	9.9	deck A,B
2	Heat Exchanger1	12.4	11.3	4.2	4.2	21.3	deck B,C,D
3	Heat Exchanger2	12.6	3.9	4.6	4.6	23	deck B,C,D
4	Expansion Valve1	8.8	11.3	0.1	0.1	0.15	deck D
5	Expansion Valve2	8.8	3.9	0.1	0.1	0.15	deck D
		Deck width =19 m		Deck length = 25 m		Deck area = 475 m2	