



# **LNG TRANSPORTATION CHAIN: AN INTERPRETED RISK ASSESSMENT FROM SHIP TO END USER**

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# LNG TRANSPORTATION CHAIN: AN INTERPRETED RISK ASSESSMENT FROM SHIP TO END USER

By

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"Being optimistic and exercise is the best thing we can do in everyday of our life"

Frank Guldenmund

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## Executive Summary

At present, due to new concerns about securing energy supply a new global gas market for liquefied natural gas (LNG) is developing. However, LNG's property as a flammable cryogenic fluid is a big concern as well as safety of LNG transportation. Therefore, this research deals with the safety of LNG transportation, particularly from the import terminal to the filling station by tanker truck/train. There are three major motivations behind this research: (1) the policy requirements from the EU, (2) the requirement of Antea Group, and (3) the limited amount of safety studies at present of the LNG transportation chain.

The problems this thesis addresses are the different factors affecting the safety of LNG, addressing the critical risks, risk perception and different values. Considering these problems, the objectives of this thesis are identifying accident scenarios especially critical scenarios, understanding their causes, consequences and mitigation measures. Also, understanding differences of risk perception and dominant values which will influence the future of the LNG transportation chain.

Besides literature review, interviews were an important tool in this thesis, especially for creating the accident scenarios. 61 accident scenarios were created and using Cause-Consequence Analysis (CCA), the accidents were analyzed. Thereafter, a Risk Assessment Matrix (RAM), was used to identify the probability and severity levels of each of the scenarios. The validity of the results from the RAM was done using replicative validity. Finally, the dominant value(s) influencing the LNG transportation chain were analyzed using RAMSHEEP.

On the analysis of LNG accidents, it was found prior to 2004, most of the LNG accidents occurred at the LNG import terminals. While, since the past decade, the occurrence of accidents has shifted to the LNG tanker truck transportation and to the LNG filling stations. Which is due to the comparatively longer operational period and learning curve of terminals. Moreover, the presence of more uncontrolled factors with the LNG tanker trucks and the LNG filling stations makes accidents more prone in these two phases. However, for the occurrence of a major accident, the presence of four factors is necessary. These four factors are (1) operational failure, (2) enough amount of LNG release, (3) failure of instrumentation system, and (4) the presence of an ignition source. The absence of even one factor can only lead to a minor accident or even no accident at all.

Moreover, it was found that only safe designs or current regulations will not guarantee operational safety since real accident characteristics can be different from the design (expected) safety features and regulations have loopholes. Finally, ESD was found to be an important equipment to ensure safety.

From the CCA study it was found that most of the accidents occur due to the leakage of LNG. However, each phase of the LNG transportation chain (i.e. import terminal phase, LNG tanker

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truck/train transportation phase, and filling station phase) was found to have its own characteristics which can lead to different accidents. The single major cause of an accident was found to be human factors and the major consequence was damage to the operational and instrumentation equipment. Better procedures (including regulations, training, testing, maintenance etc.) were found useful to mitigate an accident. Finally, the results were found to be quite valid.

On comparison of the RAM from LNG expert interviews and the RAM from the literature, it was found that there is a consensus on the critical risk which is the collision of the LNG tanker truck with the other vehicles while riding. However, some risks were found to match in the two RAMs while some did not. Individual risk perceptions were found to be an important influencer of the rating of the risks which were influenced by three potential influencing factors. Firstly, the shared knowledge of LNG safety (e.g. education, training) among the LNG experts. Secondly, the same sense of controllability regarding the LNG safety systems and other safety assurances. Finally, the influence of historical data on the perception of the interviewees.

To deal with the critical risk, the first basic strategy to prevent the adverse outcome from this LNG tanker truck collision is to ensure that the whole systems are well functioned and matched with the current LNG safety standards (e.g. containment system consists of a double-walled tank with a combined vacuum and insulation system). This method can be considered as reactive methods but the effective strategy is to maintain a balance between the reactive and proactive methods (i.e. regular inspection and maintenance). However, the safety researchers agree that a reliable strategy to prevent the LNG truck accident is a well-trained driver. Hence, the extensive safety education should be regularly provided to both experienced and novice drivers to reduce the LNG truck accident and increase their awareness of the risk.

On assessment of the values, the most dominant value according to the stakeholders' rankings are listed in descending order of safety, reliability & availability, economics, maintainability, environment, and politics. These values were found to be related to each other. However, to have a sustainable future of the LNG transportation chain, multi-values should be integrated.

Finally, it was found that different stakeholders give their important to the critical risks differently based on their (important) values. The critical risks are important for both the private companies, and the government and academic institutions since one of their core values is safety. However, the critical risks are less important for the citizens since their core values are reliability and availability.

For future research in this field, more interviewees from different backgrounds must be involved in the research. The new phases of LNG transportation chain i.e. transportation by tanker truck/train and the LNG filling station are newer and can have possible unexpected accident scenario or unknown adverse outcomes, which must be studied. Lastly, LNG rules and regulations must be harmonized internationally.

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# Contents

<b>CHAPTER 1 : INTRODUCTION.....</b>	<b>1</b>
1.1 OVERVIEW OF LNG TRANSPORTATION CHAIN.....	1
1.2 RESEARCH MOTIVATIONS .....	1
1.3 PROBLEM STATEMENTS .....	2
1.4 SCOPE OF STUDY .....	3
1.5 RESEARCH OBJECTIVES.....	3
1.6 RESEARCH QUESTIONS .....	4
1.7 RESEARCH FRAMEWORK .....	5
<b>CHAPTER 2 : LITERATURE STUDY.....</b>	<b>6</b>
2.1 HAZARD, ACCIDENT SCENARIO, AND RISK .....	6
2.1.1 <i>Hazard</i> .....	6
2.1.2 <i>Accident scenario</i> .....	7
2.1.3 <i>Risk</i> .....	7
2.2 RISK PERCEPTION.....	8
2.2.1 <i>Psychometric paradigm</i> .....	9
2.3 GENERAL HAZARDS OF LNG .....	10
2.3.1 <i>Asphyxiation</i> .....	11
2.3.2 <i>Freeze burns</i> .....	11
2.3.3 <i>Brittle fracture</i> .....	11
2.3.4 <i>Fire</i> .....	12
2.3.5 <i>Vapor Cloud Explosion (VCE)</i> .....	14
2.3.6 <i>Boiling Liquid Expanding Vapor Explosion (BLEVE)</i> .....	15
2.3.7 <i>Rapid Phase Transition (RPT)</i> .....	15
2.3.8 <i>Overpressure due to rollover</i> .....	16

---

<b>CHAPTER 3 : METHODS AND TECHNIQUES.....</b>	<b>17</b>
3.1 DATA COLLECTION METHODS .....	17
3.1.1 Literature Review .....	17
3.1.2 Interview.....	17
3.1.3 Accident Scenario Identification .....	17
3.1.4 Cause-Consequence Analysis (CCA) .....	18
3.1.5 Risk Assessment.....	19
3.2 VALIDITY .....	22
3.3 VALUES.....	22
3.3.1 Value Assessment .....	22
3.3.2 Stakeholder Analysis .....	24
3.3.3 Dealing with conflicting values: reasoning about values .....	25
3.3.4 Radar Chart Approach.....	25
<b>CHAPTER 4 : LNG ACCIDENT ANALYSIS .....</b>	<b>26</b>
4.1 INTRODUCTION.....	26
4.2 RECORDED LNG ACCIDENTS.....	26
4.3 DISCUSSION.....	27
4.3.1 Occurrence of major accidents .....	27
4.3.2 Only safe designs do not guarantee operational safety .....	28
4.3.3 Regulations have loopholes.....	28
4.3.4 ESD system plays an important role .....	29
4.4 CONCLUSION .....	30
<b>CHAPTER 5 : CAUSE- CONSEQUENCE ANALYSIS.....</b>	<b>31</b>
5.1 INTRODUCTION.....	31
5.2 CCA FOR THE OVERALL ACCIDENTS IN THE LNG TRANSPORTATION CHAIN.....	31
5.3 CCA VALIDITY AND DISCUSSION.....	33
5.4 CONCLUSION .....	34

---

<b>CHAPTER 6 : RISK ASSESSMENT AND INTERPRETATION .....</b>	<b>37</b>
6.1 RAM FROM THE LNG EXPERT INTERVIEWS .....	37
6.2 VALIDITY OF THE RAMS.....	39
6.2.1 <i>The critical risk</i> .....	39
6.2.2 <i>Matching risks</i> .....	39
6.2.3 <i>Non-matching risks</i> .....	40
6.3 DISCUSSION: RISK PERCEPTION AND THE INFLUENCING FACTORS .....	40
6.3.1 <i>Preference: low-risk answers were predicted</i> .....	41
6.3.2 <i>Shared safety knowledge in the professional culture</i> .....	41
6.3.3 <i>Controllability and Availability Heuristic</i> .....	41
6.4 RECOMMENDATIONS: DEALING WITH THE CRITICAL RISK.....	42
6.4.1 <i>Strategy to prevent the worst-case scenario</i> .....	42
6.4.2 <i>Applicability of intervention technologies</i> .....	43
6.5 CONCLUSION .....	44
6.5.1 <i>How can the individual risk perceptions be explained?</i> .....	44
6.5.2 <i>How to deal with the critical risk in the LNG transportation chain?</i> .....	44
<b>CHAPTER 7 : VALUES .....</b>	<b>46</b>
7.1 INTRODUCTION.....	46
7.2 VALUE ASSESSMENT OF LNG TRANSPORTATION CHAIN.....	46
7.2.1 <i>Stakeholder Analysis</i> .....	46
7.2.2 <i>Individual stakeholders' values assessment</i> .....	48
7.2.3 <i>Values combination result</i> .....	50
7.2.4 <i>Conclusions: reasoned and weighted average judgement</i> .....	52
7.3 DISCUSSION AND RECOMMENDATIONS .....	53
7.3.1 <i>Bridging between values and the critical risk</i> .....	53
7.3.2 <i>Value integrity: proposition for the future sustainable LNG</i> .....	54
7.4 CONCLUSION .....	55

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<b>CHAPTER 8 : CONCLUSION AND RECOMMENDATION .....</b>	<b>56</b>
8.1 CONCLUSION .....	56
8.2 REFLECTION .....	60
8.3 RECOMMENDATION FOR THE FUTURE STUDY .....	63
<b>REFERENCES.....</b>	<b>65</b>
APPENDIX A. GATE TERMINAL FIELD REPORT .....	78
APPENDIX B. 61 ACCIDENT SCENARIOS FROM LITERATURE REVIEW .....	88
APPENDIX C. QUESTIONS FOR LNG INTERVIEWS .....	109
APPENDIX D. STAKEHOLDER’S LIST IDENTIFICATION FOR VALUE .....	113
APPENDIX E. CHRONOLOGICAL LIST OF LNG ACCIDENTS .....	114
APPENDIX F. SUMMARY OF LNG HAZARDS.....	122
APPENDIX G. DETAILED OF CCA IN EACH PHASE OF THE LNG CHAIN .....	125
APPENDIX H. LNG EXPERT INTERVIEWS .....	131
APPENDIX I. DETAILED ANALYSIS OF RAM FROM LNG EXPERT INTERVIEWS .....	132

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## TABLE OF FIGURES

FIGURE 1: THE THREE TRANSPORTATION PHASES OF LNG .....	3
FIGURE 2: RESEARCH FRAMEWORK AND ITS DETAILS .....	5
FIGURE 3: POOL FIRE HAZARDS WHEN LNG IS SPILLED ON WATER .....	14
FIGURE 4: CAUSES OF OVERALL ACCIDENTS.....	31
FIGURE 5: CONSEQUENCES OF OVERALL ACCIDENTS .....	32
FIGURE 6: COMPARISON OF CAUSES OF THE LNG ACCIDENTS FROM TWO SOURCES .....	33
FIGURE 7: COMPARISON OF CONSEQUENCES OF THE LNG ACCIDENTS FROM TWO SOURCES .....	34
FIGURE 8: RAM FROM THE LNG EXPERT INTERVIEWS.....	37
FIGURE 9: PROPORTION OF RISK LEVELS THROUGHOUT THE LNG TRANSPORTATION CHAIN .....	38
FIGURE 10: COMPARISON OF RAMS.....	39
FIGURE 11: VALUE RANKING OF PRIVATE COMPANY STAKEHOLDERS.....	48
FIGURE 12: VALUE RANKING OF GOVERNMENT AND ACADEMIC INSTITUTION STAKEHOLDERS .....	49
FIGURE 13: VALUE RANKING OF CITIZEN STAKEHOLDERS .....	49
FIGURE 14: AVERAGE VALUE RESULTS FROM EVERY STAKEHOLDER.....	50
FIGURE 15: PROPOSITION OF VALUE INTEGRITY FOR SUSTAINABLE LNG TRANSPORTATION CHAIN	54
FIGURE 16: GATE TERMINAL AREA FROM TOP VIEW.....	79
FIGURE 17: JETTY OF GATE TERMINAL .....	80
FIGURE 18: FIXED UNLOADING ARM SCHEMATIC AT LNG IMPORT TERMINAL.....	81
FIGURE 19: WORKING ENVELOPES OF A FIXED UNLOADING ARMS OPERATING .....	81
FIGURE 20: PROCESS DIAGRAM OF LNG UNLOADING .....	84
FIGURE 21: CAUSES OF ACCIDENT SCENARIOS IN IMPORT TERMINAL.....	125
FIGURE 22: CONSEQUENCES OF ACCIDENT SCENARIOS IN IMPORT TERMINAL .....	126
FIGURE 23: CAUSES OF ACCIDENT SCENARIOS IN TANKER TRUCK/TRAIN TRANSPORTATION .....	126
FIGURE 24: CONSEQUENCES OF ACCIDENT SCENARIOS IN TRUCK/TRAIN TRANSPORTATION .....	127
FIGURE 25: CAUSES OF ACCIDENT SCENARIOS IN FILLING STATIONS .....	128
FIGURE 26: CONSEQUENCES OF ACCIDENT SCENARIOS IN FILLING STATIONS .....	128
FIGURE 27: CAUSES OF GENERAL ACCIDENTS.....	129
FIGURE 28: CONSEQUENCES OF GENERAL ACCIDENTS.....	130

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# Chapter 1 : INTRODUCTION

At present, due to new concerns about securing energy supply a new global gas market for liquefied natural gas (LNG) is developing (IEA, 2004; Victor, Jaffe, & Hayes, 2006). The global energy trends forecast that in inter-regional gas trade, the demand for LNG will increase to 84% by 2030 (Mokhatab, Mak, Valappil, & Wood, 2014). With this perspective, LNG will become part of a global market and can replace oil (Umbach, 2010). Literature study done for this thesis found excellent safety records along the LNG chain over the last 40 years (Lin, Zhang, & Gu, 2010).

Despite the many advantages of LNG, a big concern is its property as a flammable cryogenic fluid. Moreover, the relatively new LNG network, with its own unique operational characteristics poses concerns compared to longer running networks such as oil & gas. Furthermore, the involvement of many stakeholders increases the complexity and uncertainty of the LNG network. Foss (2003) summarizes that LNG itself poses a little danger as long as it is stored within storage tanks, piping, and equipment designed for use at LNG cryogenic conditions. But an uncontrolled LNG leakage from their designed equipment can be hazardous and flammable.

## 1.1 Overview of LNG transportation chain

A typical LNG chain starts at gas extraction from a well field. The gas is then sent to a processing plant where it is purified. The natural gas is then cooled down to  $-161^{\circ}\text{C}$  in liquefaction stages until it is liquefied. After that, liquid LNG is stored in storage tanks and can be loaded and shipped from an exporting terminal to an importing/receiving terminal by an LNG bunker ship. LNG is then unloaded from the ship to a storage tank. After this, either the liquid LNG is re-gasified, compressed and sent to a gas grid via a pipeline distribution, or remains in its liquid state to use as fuel for heavy-duty vehicles. In this case, LNG will be distributed to an LNG filling station either by rail transportation (by an LNG tanker train) or road transportation (by an LNG tanker truck).

## 1.2 Research motivations

This research deals with the safety of LNG transportation, particularly from the import terminal to the filling station by tanker truck/train. There are three major motivations behind this research, namely: the policy requirements from the EU, the requirement of Antea Group, and the limited amount of safety studies at present of the LNG transportation chain. This motivation is explained below:

Firstly, the transportation of LNG is directly affected by recent policies such as the LNG Blue Corridor (UN, 2003), and the Green Deal LNG Rhine and Wadden (Nationaal LNG Platform, 2013). At present, the Netherlands and her neighbor countries (supported by the National LNG

Platform), are not only enthusiastically developing LNG transportation networks, but also planning other LNG infrastructures (such as LNG filling stations), to support the growth of LNG as a vehicle fuel. Secondly, this research focus is required by Antea Group, who are the initiators of this study. Finally, despite the expected intensive use of LNG in the near future, the focus of the majority of available scientific literature related to LNG safety is mostly on liquefaction process at the export terminal, regasification at the import terminal, or gas distribution at the pipeline network. Little literature could be found relating to the safety of transportation by the tanker truck/train and at the filling station. Overall, this thesis aims to understand the safety issues in the transportation chain.

### **1.3 Problem statements**

#### **1.3.1 Safety study requires considering different factors**

Intensive use of liquid LNG as fuel for heavy-duty vehicles is expected in the near future. However, this is accompanied by limited experience with LNG transportation. Secondly, the risk of LNG transportation is derived from unique hazard characteristics of LNG, which lead to different consequences when compared to the transportation of the other fuels like oil & gas (Foss, 2003). Besides the traditional adverse consequence of fire, LNG operational activities pose unique adverse consequences. Finally, due to the cryogenic property of LNG, special equipment for LNG transportations are required. The usage of different equipment (e.g. single-walled tanker truck or double-walled tanker truck) leads to different consequences.

#### **1.3.2 Critical risks in the LNG transportation chain**

According to Ale (2009), for technologies having a small period of existence and many influencing factors (technical, human and organizational), it is not possible to clearly determine and identify all the risks.

The term ‘critical’ in this thesis does not mean that risk research is uncritical<sup>1</sup>. Rather it means that we focus on risks that require most critical attention or on the risk with high impact and high probability of occurrence. (Lane, Klauser, & Kearnes, 2012). Moreover, it is more efficient to evaluate these critical risks than evaluate all possible risks that could occur with the most likely scenarios (Lane et al., 2012).

#### **1.3.3 Risk perception**

According to Adams (1995), we are all seeking to manage risk with our guess. Different people perceive the same risk in a different way. Thus, they may rate the probability and the severity differently. They also interpret the consequences of the same scenario differently. Therefore, variation in individual risk perceptions can be a problem.

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<sup>1</sup> Uncritical as in the notion of not being analytical or unscientific.

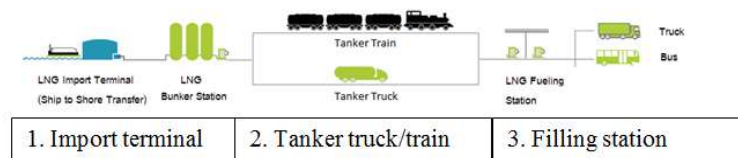
### 1.3.4 Different values lead to different futures

According to Wagner & Van Gelder (2013), although safety value is very important, in real life, safety is only one of the many values such as Reliability, Availability, Maintainability, Safety (and security), Health, Environment, Economics and Politics (RAMSHEEP). Moreover, Willoughby (1990) asserts that the most dominant value is very important since it mostly influences the decision of the stakeholders regarding the future of the business (Willoughby, 1990).

A very important value is that the LNG transportation operation should be sustainable. Since different values are often complementary to each other, stakeholders must trade-off and balance their decisions. A sustainable operation is not limited to a single value like safety but also considers other values such as reliability, cost, etc. Therefore, the decision making of stakeholders regarding values may not be always simple and straightforward. For example, if an LNG organization is more concerned with the safety value, it has to balance this safety value with other values like economics (high cost). Finally, there are various stakeholders in the LNG transportation chain such as private companies, government and academic institutions, citizens, etc. Therefore, the problem is of these various stakeholders and their different values and its impacts on the future of the LNG transportation chain.

## 1.4 Scope of study

For this thesis, the scope starts at unloading LNG from the ship, then continues at the import terminal, then transportation via the LNG tanker truck/train and ends at the filling station where the end users load the LNG into their vehicles. In this thesis, the end users are the ones who directly use the LNG filling station, including heavy-duty trucks and buses (Wolting & Vijgen, 2013). Figure 1 demonstrates the scope of this study:



**Figure 1: The three transportation phases of LNG**

In Figure 1, the LNG transportation chain is separated into three different phases: the LNG import terminal, the LNG tanker truck/train transportation, and the LNG filling station. Research objective

## 1.5 Research Objectives

The main objective of this thesis is to identify the potential accident scenarios and the critical risk that could occur in the LNG transportation chain. Related to this objective are sub-objectives:

1. To understand the LNG-related hazards, including causes and consequences, and to determine the proper measures to mitigate these hazards

2. To study factors of failure (cause) which can lead to the accident scenarios in the different phases through the LNG chain
3. To study the possible adverse consequences from those scenarios in different phases throughout the LNG chain, especially the critical accident scenarios which have a high severity and high probability of occurrence
4. To understand differences of individual risk perceptions and risks in the literature
5. To identify dominant value(s) of different stakeholders which will influence the future of the LNG transportation chain
  - A. To analyze the different stakeholders and their decision making on the values
  - B. To discuss the influence of the dominant value(s) on the critical risks and the future directions of the LNG transportation chain
  - C. To recommend the value(s) which can lead to a sustainable future in the LNG transportation chain

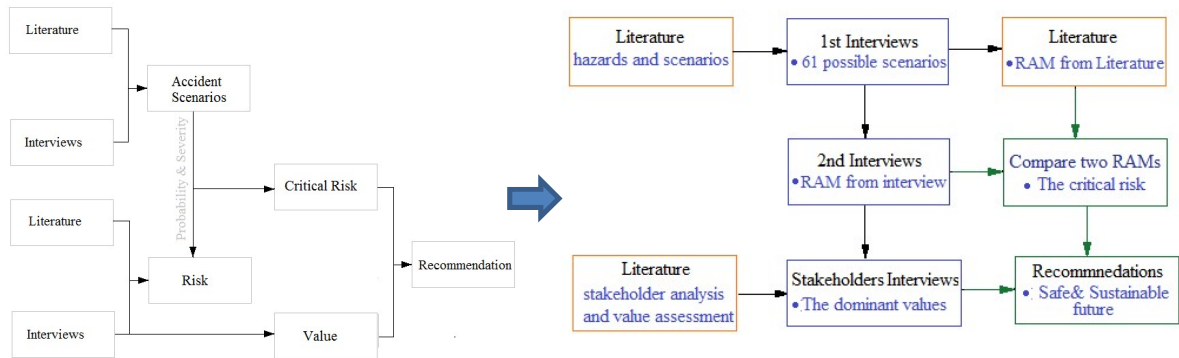
## 1.6 Research Questions

The main question in this thesis is: How to deal with the critical risk in the LNG transportation chain? To be able to answer the main question, several sub-questions are posed:

1. How does a major of LNG accident in the LNG transportation chain occur?
2. What are the major causes/consequences of LNG accidents?
  - 2.1 How can those accidents be mitigated?
3. Can the regulations be improved to ensure LNG operational safety?
4. Which equipment is the most important to ensure safety?
5. How can the individual risk perceptions be explained?
6. What are the dominant values in the LNG transportation chain?
  - 6.1 How can these values influence the future of the LNG?
7. How important are the risk for stakeholders on the basis of their values?
8. What are the most critical risks for the transportation chain?

## 1.7 Research framework

The following research framework is used to answer the above research questions:



**Figure 2: Research Framework and its details**

As shown in Figure 2, this thesis starts with a literature review of the LNG transportation activities (chapter 2), methods and techniques (chapter 3), hazards of LNG, historical LNG accidents, and all LNG accident scenarios in each phase of the LNG chain (chapter 4). After finishing the literature review, the first round of interviews with LNG experts have been conducted and resulted in 61 potential accident scenarios.

In the next step, the second round of interviews with another group of LNG experts were conducted. Some LNG experts from the first interview are included too. The goal of the second phase of interviews is to identify the probability and severity levels of each of the 61 accident scenarios. From these interviews, the risk assessment matrix (RAM) of the 61 scenarios is generated. Also, another RAM based on the literature is created and cause-consequence analysis is applied to these accident scenarios (chapter 5).

Thereafter, both RAMs from the LNG expert interviews and from the literature are compared in order to analyze the matching and non-matching patterns. In this step, the critical risks in both RAMs are identified (chapter 6).

In the last step, various values are reviewed from both literature and interviews. For this value study, the interviewees are called ‘stakeholders’ since LNG experts are representatives of one stakeholder group. The dominant values of each group have been extracted. A discussion and analysis of the dominant value(s) influencing the critical risk and the future of the LNG transportation chain are performed. The value(s) which will lead to a safe and sustainable future of the LNG are presented (chapter 7). Finally, conclusions of the thesis and recommendations for future research are presented (chapter 8).



# Chapter 2 : LITERATURE STUDY

In this chapter, the relevant literature studied in thesis regarding the safety of the LNG transportation chain is described. Definitions of the most common terms within this study are defined and cited.

## 2.1 Hazard, accident scenario, and risk

In this safety thesis, three technical terms are usually referred, namely: hazard, accident, and risk. According to Adams (1995), since in everyday speech, these terms are often used interchangeably, causing confusion. To prevent this confusion, a distinction between these terms is presented in the following sections.

### 2.1.1 Hazard

A potentially damaging physical event, phenomenon or human activity, which may cause loss of life or injury, property damage, social and economic disruption (UNISDR, 2004).

Hazard is a potential source of damage, harm or adverse consequences to people, property or the environment under certain conditions (Flaus, 2013). In other words, a hazard is a condition, event, or circumstance that could lead/contribute to an unplanned/undesirable event in the (near) future (Ale, 2009). Hence, by its nature, ‘hazard’ involves something that could potentially be harmful and the conditions leading to it might be hidden (Usman, Olorunfemi, Awotayo, Tunde, & Usman, 2013).

In the occupational safety-related literature, the term ‘occupational hazard’ is particularly used for a hazard experienced in the workplace (IAPA, 2007). Occupational hazard refers to a potential damage of any machine, equipment, process, material substance (e.g. chemical) or physical factor at a workplace. It can be divided into a few main subtypes such as chemical, biological, ergonomic, psychological, physical hazards etc. (*Oxford Handbook of Occupational Health*, 2013).

For the LNG transportation chain, hazards can be classified into three broad groups (Rice, 2012):

1. Natural hazards: caused by external natural phenomena such as earthquake, tsunami, floods, landslides.
2. Chemical hazards: caused by the chemical properties of the materials such as their flammability, explosiveness, corrosiveness.

3. Physical hazards: caused by the property of the working environment that can harm the worker, e.g. cold stress, asphyxiation, etc.

Because of the nature of LNG and the LNG transportation activities to cause potential harm, especially on exposure to people, property, or the environment; LNG and the LNG transportation activities are considered hazards.

### 2.1.2 Accident scenario

An unexpected, unplanned event in a sequence of events that occurs through a combination of causes resulting in physical damage (injury or disease to an individual), damage to property, damage to business processes or any combination of these effects (Stranks, 2006).

An accident is characterized as being unforeseeable, unintended, unplanned, or unexpected (Stranks, 2006). Due to its characteristics and the resulting damages, the occurrence of an accident is highly dangerous to humans, properties, and businesses (Shappell et al., 2007)

Thus, to prevent an accident, it is necessary to examine all potential causes which are lying underneath the event of an accident. The causes of any accident can be grouped into categories such as human error, operational failure, equipment/instrumentation failure, inferior material, procedural error, management error, or weather phenomena (Shappell & Wiegmann, 2000; Shappell et al., 2007).

According to European Commission (2015)<sup>2</sup>, the examination of causes leading to an accident must be done in a safety report. An accident scenario is defined as “a specific sequence of events from an initiating event to an undesired consequence (harm)” (Rausand, 2013). Moreover, this safety report should include all possible accident scenarios with necessary measures to limit the consequences to humans and the environment (Fidler & Wennersten, 2007). Therefore, these recommendations from the European Commission for analyzing and preventing accidents have been considered in this thesis.

### 2.1.3 Risk

The combination of the consequences of an accident scenario and the associated probability of its occurrence. Consequences are the negative effects of an accident scenario (European Commission, 2010).

According to Wagner & Van Gelder (2013), the definition of a risk can be expressed algebraically as the probability of failure of an accident scenario multiplied by the consequence of

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<sup>2</sup> Requirements for a safety report to prevent accidents and to limit their consequences for humans and the environment from the EU, Seveso II Directive (European Commission, 2015).

that scenario. Specifically, according to e.g. Aven (2012), risk is captured by the triplet of accident scenario ( $s_i$ ), probability of that scenario ( $p_i$ ), and the consequence of that scenario ( $c_i$ ):

$$\text{Risk} = (s_i, p_i, c_i)$$

### 2.1.3.1 Types of risk

There are two types of risks: inherent and residual. Inherent risks are defined as the risks that an activity would pose if they were not treated. While residual risks are the risks that remain after treatments/controls have been applied to the various activities (Monahan, 2008). The risks that were assessed in the RAM were residual in nature, this was because analysis and mitigation of inherent risks have already been prescribed in literature and regulations. Furthermore, analyzing inherent risks neither carried any novelty nor did it increase the knowledge space of the community (PGS Publications, 2013).

To assess these (residual) risks, there are various techniques available of which HAZOP (Hazard and Operability Study) is considered to be the most successful (Ale, 2009). However, the use of a well-defined system of activity and effective development of keywords was found to be difficult because of the variety of stakeholders and their often related but distinct work processes. Moreover, conducting HAZOP exercises with these different stakeholders at the same place and the same time required immense personnel and financial resources, which were unavailable (Cowan, 2005). Hence, as the closest alternative to HAZOP, the Risk Assessment Matrix (RAM) was used. Actually, the last stage of a HAZOP study is the ranking of the risks using a RAM (Galante, Bordalo, & Nobrega, 2014).

The risks were plotted on a matrix with the X-axis as a consequence and the Y-axis as a probability. The least to highest ranking of the probability ranges extended from rare to unlikely to possible to likely to almost certain. Similarly, the least to highest ranking of the range of impacts extended from insignificant to negligible to moderate to extensive to significant. Although these rankings were qualitative, they can be interpreted to be in 20% intervals e.g. for probability it was 0-10%: rare, 30%: unlikely, 50% :possible, 70%: likely and 90%: almost certain (Köster, 2010).

## 2.2 Risk Perception

According to Sjöberg, Moen, & Rundmo (2004), a differentiation between reality and possibility is a shared view in every risk concept. There is a consensus in the safety literature of risk definitions consisting of the probability of an adverse situation and the magnitude of its consequences. Although this definition may be enough for calculation of engineering aspect, it might mislead for the societal risk aspect (Rayner & Cantor, 1987); since the concept of risk is closely related to uncertainty and the term of uncertainty can also be applied to individual psychological constructs (human mind and value) which are influenced by society and culture (Boholm, 1998). Therefore, to understand how people understand risk is to understand risk perception (Sjöberg et al., 2004). In other words, we study risk perception theory in order to understand why different people evaluate risk in a different way.

Risk perception is the subjective assessment of accidents and consequences and several theories have been proposed to explain it. Currently, two important theories have been proposed to explain risk perception: the psychometric paradigm and cultural theory (Sjöberg et al., 2004). However, this thesis will only use the psychometric paradigm since amongst risk perception researchers it is more accepted and less controversial than others (Douglas, 1992; Handmer & James, 2007). The psychometric paradigm is explained briefly below.

### **2.2.1 Psychometric paradigm**

The psychometric paradigm is developed from psychology and decision sciences fields. According to this approach “Risk does not exist ‘out there’, independent of our minds and cultures, waiting to be measured” (Slovic, 1992). In this paradigm, the term ‘our mind’ refers to risk being inherently subjective that is influenced by psychological, social, institutional, and cultural factors (Slovic, 1992).

For the psychometric paradigm in this thesis, the following keywords can help explain the risk perception through an individual’s cognitive processes.

#### **2.2.1.1 Preference**

According to Starr (1969) and Slovic, Peters, Finucane, & Macgregor (2005), preference is used to explain which risks are considered acceptable. Preference can be measured as the degree to which people are willing to accept the risk. Another word that is closely related to preference is benefit. Some academic papers describe that people seem to accept risk if they also had clear benefits: the more people perceived a benefit, the more people tolerate risk (Slovic, Fischhoff, & Lichtenstein, 1982; Starr, 1969).

#### **2.2.1.2 Safety Climate**

According to Guldenmund (2000), the term safety climate or safety culture is part of an organizational climate or organizational culture which reflects the employees’ shared perceptions and understandings of safety. These perceptions and beliefs are themselves influenced by various organizational characteristics, such as strategy, structure, management and production processes, people and hazards in that organization (Guldenmund, 2000). Similar observations were found in the paper of Keown (1989) which explains that perceptions of risk are likely to vary between different places dependent upon what people chose to discuss, what cultural norms are viewed as important, and what technical and legal opportunities existed for control and regulation of risk. In other words, risk perception is assumed to vary due to the effect of cultural, environmental, and governmental influences (Keown, 1989).

#### **2.2.1.3 Controllability**

People perceive a situation as less risky if they consider that the situation can be controlled. Moreover, they tend to believe that they are in control. In other words, controllability can be explained by the notion that people often think that the probability of an accident scenario is small. This term of sense of controllability is related to unrealistic optimism (Sjöberg et al., 2004).

#### **2.2.1.4 Availability Heuristic**

According to Sjöberg et al. (2004), based on information available to an individual, people tend to use that information to estimate risk in a given situation. This individual risk estimation strategy relates to the psychological factor called ‘availability heuristic’. In other words, the availability heuristic means that people determine the probability and severity of a situation occurring by how readily they can remember a similar occurrence of an event. This recollection will influence the individual’s risk perception.

### **2.3 General Hazards of LNG**

LNG consists of around 90% methane with other light hydrocarbons (e.g. ethane, propane and butane) and with 1% nitrogen. LNG is a cryogenic liquid, created by cooling natural gas to a temperature below its boiling point of about -162°C. By turning natural gas into LNG, the volume is reduced 600 times. LNG is stored and transported normally around atmospheric pressure (Woodward & Pitbaldo, 2010).

LNG as a cryogenic liquid does not burn or explode, but the release of LNG, especially within the flammable range of an ignition source can cause fire or explosion. Hazards of LNG will cause damage when the LNG releases. These hazards are generally from three of its properties (Foss, 2003):

1. Cryogenic temperatures
2. Dispersion characteristics
3. Flammability characteristics

The potential consequences<sup>3</sup> of an LNG accidental release are considered as the primary safety concerns for the LNG transportation chain since the LNG release can present the unique hazards to nearby people and property. There are seven common potential hazards from LNG and the LNG transportation chain: freeze burns, asphyxiation, brittle fracture, fire hazard, BLEVE, RPT (Rapid Phase Transition) and overpressure due to rollover. The latter three hazards are specifically associated with the physical conditions of LNG during storage and transport while the former four hazards are associated with the general properties of LNG. (California Energy Commission, 2004).

According to Appendix E and Appendix F, we can conclude that the historical accidents in the LNG transportation chain occurred due to the properties of LNG and its hazard. In other words, LNG properties and the hazards of LNG and its transportation activities are directly related to the accident.

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<sup>3</sup> These consequences are affected by many factors including: the amount released, wind speed, wind direction, the surface that LNG releases on, surface temperature, air temperature, and location of ignition sources.

The following hazards of LNG transportation chain which lead to an accident in the transportation chain include asphyxiation, freeze burns, brittle fracture, pool fire, jet fire, flash fire, VCE, RPT, BLEVE, and overpressure due to rollover:

### **2.3.1 Asphyxiation**

LNG is neither carcinogenic nor toxic. However, in the case of an LNG release, exposure to the center of a vapor cloud in an enclosed or semi-enclosed area can result in asphyxiation. This asphyxiation causes a decrease of inhaled oxygen when LNG vapor mixes with air. The concentrations of around 50% by volume (methane in air) will cause obvious suffocation symptoms like difficulties in breathing and rapid breathing at the same time as the ability to respond deteriorates and muscle coordination weakens. Moreover, prolonged breathing of the LNG vapor may cause dizziness, nausea, unconsciousness, and eventually lung damage. The risk of asphyxiation increases much more due to LNG being colorless and odorless. Thus, a risk of dying from asphyxiation for the operators working in confined spaces (in low oxygen concentrations areas) is much higher than the others (California Energy Commission, 2004; Thorndike, 2007)

### **2.3.2 Freeze burns**

The cryogenic property of LNG presents thermal hazards to personnel. Although momentary skin contact can be harmless, extended contact will cause severe frostbite or freeze burns. The prolonged exposure skin contact with LNG results in effects similar to thermal burns. The frozen symptoms caused by inadequate blood circulation from hypothermia. Frostbite symptoms on the surface of contacted skins would develop from itching and pain, to permanently insensitive; and finally loss of feeling (the tissue dead). However, the risk of cryogenic burns through accidental exposure can be reduced by the use of appropriate protective clothing. The protection can range from loose fitting fire resistant gloves and full face shields to special extra protection multi-layer clothing depending upon the risk of exposure (Woodward & Pitbaldo, 2010).

Another potential freeze burn damage scenario is when LNG spill on water. Since LNG weighs less than half as much as water, it floats on fresh water (or seawater). Therefore, LNG would immediately freeze any living organisms present in shallow water ecosystems (California Energy Commission, 2004).

### **2.3.3 Brittle fracture**

The extremely low temperatures are hazardous to metals. While stainless steel will remain ductile, the low temperature can change the structure of most ordinary metals and alloys due to which their ductility, as well as impact strength, will decrease and become brittle and fractures. If LNG releases and comes into contact with the steels, rapid cooling would make stress and eventually cause cracking. Standard ship carbon steel (of all grades) must, therefore, be protected and insulated from any possible exposure to an LNG spillage (California Energy Commission, 2004; Hamilton, 2012).

Although the cryogenic property of LNG would damage humans and materials [see Appendix F], LNG evaporates completely and cleanly without a residue. Hence, an LNG spill leaves minimal environmental impact (freezing effects only) (Marks, 2003).

#### **2.3.4 Fire**

When an LNG vapor cloud (the mixing cloud between methane, ethane, and propane) encounters with an ignition source (e.g. open flame, internal combustion engine, sparks) within the range of flammability, an ignition cloud could occur. However, the LNG vapors do not get ignited as easily as those of other common fuels, such as gasoline or propane, since the cloud contains condensed humidity from water vapor. Therefore, only the portion of the vapor cloud (e.g. at the edge of the cloud) has concentrations in the flammable range burns. Moreover, the range of flammability which supports the LNG ignition is between the ranges of 5% to 15% of the vapor concentration. The LFL (Lower Flammability Limit) for methane is 5% (50,000 ppm) concentration in the air while the UFL (Upper Flammable Limit) limit is 15% (150,000 ppm) concentration in air. These limits are important since, at a methane concentration of more than UFL, the air becomes saturated and does not cause a fire. Similarly at a concentration of less than LFL, the oxygen in the air is too less to cause ignition (Foss, 2003; MIACC, 2007).

As per calculations and experiments when LNG spills, the air trapped has only enough heat capacity to partly evaporate the liquid (aerosol). After it has partly evaporated, the remaining LNG spills over to form a liquid pool (Mokhatab et al., 2014).

If there is no ignition, the LNG will vaporize rapidly, spread, and carry downwind with no injurious effects after diluting below flammable limits. If there is ignition, LNG fire is typically smoky, i.e. they absorb a large amount of heat. Therefore, the heat from the ignited LNG vapor cloud is dangerous because of its tremendous radiant heat output, forming a hazard for nearby people and objects.

In an ignition case, there are four different forms of LNG fire hazards deriving from the ignited vapor. Each form has its own fire characteristics (e.g. ignitability, flammability, heat release, and flame spread) which lead to different consequences. These potential fire risk scenarios are flash fire, jet fire, pool fire, and vapor cloud explosion (American Bureau of Shipping, 2012; Marks, 2003). These four cases are explained below:

##### **2.3.4.1 Flash fire**

A flash fire hazard can occur when LNG vapor clouds are ignited without generating any overpressure. The ignited cloud will flash back across all its flammable part within the flammable range: the transient fire can burn both forward to the cloud front and back to the release point. It will then burn until the entire gas is consumed. Although one of the general characteristics of flash fire is extreme rapidity of flame spread, experiments show that the LNG flash fires propagate at the speed of 10 to 20 m/s. This LNG propagation speed is considered as relatively slow (Mokhatab et al., 2014) The duration of the flash fire is not long, normally lasts no more than a few tens of seconds. This flash fire can stabilize after sometime as a jet fire or pool fire from the leak origin.

Flash fires do not cause secondary ignition or burn to people outside but it can result in serious consequences or even be fatal to people inside the flash fire region (MIACC, 2007).

#### **2.3.4.2 Jet Fire**

Since LNG facilities usually operate at low pressures, hence the release of compressed LNG from storage tanks is unlikely. However, in certain operations, such as LNG vaporization, unloading, and transportation through equipment such as HP pump or high-pressure piping, LNG is subjected to high pressures (typically over 2 bars). Under this high pressure, if LNG vapor leaks out (especially through a small hole) and gets ignited, a jet fire could result (Woodward & Pitbaldo, 2010).

The direction and size of the jet fire are mainly affected by LNG leakage patterns, whereas the flame dispersion is directly affected by the atmospheric and wind distribution. Out of these factors, wind distribution is the most important factor. However, for the continuity of the jet fire, the ventilation condition is the most important factor. In other words, a highly ventilated space has a low chance of the continuous jet fire (Raj, 2007).

There are two issues of concern with jet fires: radiation from the jet and direct impingement upon an object. For structures, both aspects are important. However, for humans, the latter is more dangerous, since it always results in death. Given the known outcome of impingement, protection is usually based on experimentally determined heat flux rather than on calculations. Protection structures like: firewalls are based on these experiments and are rated for the time duration of survival (e.g. 30 minutes). Finally, since radiant jet fires are much more dynamic, to determine their different outcomes, detailed modeling and calculations are conducted (Wagner & Van Gelder, 2013).

#### **2.3.4.3 Pool fire**

For large spills, air cannot transfer enough heat to vaporize much LNG so a part of the spill is likely to end up in a liquid pool. A pool fire may also result after a flash fire since the flash fire could burn back toward the evaporating pool of spilled LNG. This burning will result in quickly evaporating natural gas immediately above the pool, giving the appearance of a burning pool or pool fire (California Energy Commission, 2004). This bright, diffusion flame forms above the pool of vaporizing LNG. Furthermore, this can burn turbulently or statically. Important parameters influencing LNG spread and pool formation are heat flux, pool geometry, and turbulence. The rate of burning of pool fires does not depend on the material i.e. it burns with the same rate on water as on steel (Mary Kay O'Connor Process Safety Center, 2008).

The main concern of LNG pool fire is its generation of significant thermal radiation with the surface emission power above 200kW/m<sup>2</sup> (even a person wearing protective clothing<sup>4</sup> cannot

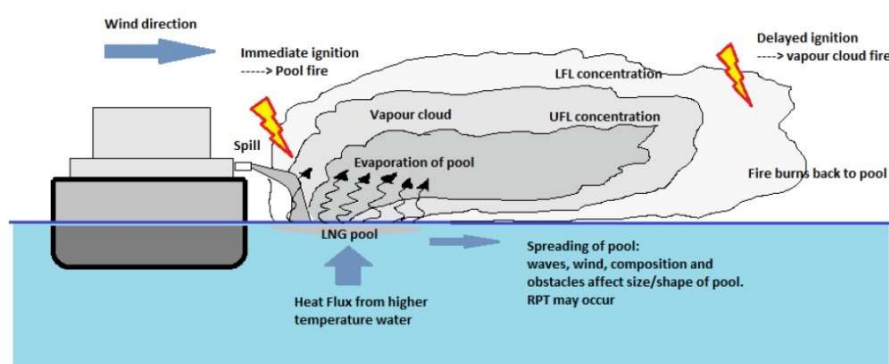
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<sup>4</sup> Protective capacity = 12 kW/m<sup>2</sup>



withstand this for a long time). Besides harming people, the heat fluxes expected from an LNG pool fire would severely degrade the structural strength, especially LNG container. This thermal degradation can damage both the outer and inner hulls of the storage tanks (Sun, Guo, & Pareek, 2014; U.S. Department of Energy, 2012)

However, this pool of fire diameter decreases soon in size due to combustion and eventually small pool remains. This property is important for the containment of fire: if the spill occurs inside a properly designed enclosure, the pool fire can be contained and controlled to burn itself out. Whereas in an outside confined area, the burning pool fire is free to flow. The Figure 3 below shows how the formation of LNG pool fire takes place (Johnson, 1992; Woodward & Pitbaldo, 2010).



**Figure 3: Pool fire hazards when LNG is spilled on water**

From Figure 3, we can see that the pool fire (and flash fire) will reach distances far from the point of leakage, depending on the amount of liquid spilled (Natacci, Ikeda, & Martins, 2010).

### 2.3.5 Vapor Cloud Explosion (VCE)

In the case of an explosion, the gas cloud size and distribution are mostly decided by leakage pattern. It means that the extent of gas dispersion is a determinant for the explosion since it affects explosion intensity and extent of the damage. Besides gas dispersion, a vapor cloud gets exploded when the amount of mass in concentrations is between the LFL and the UFL.

However, a vapor cloud will explode only if ignited inside an enclosed area or an area with a high density (congested) of obstacles. Experiments have confirmed that LNG is not explosive when ignited in unconfined open areas (Woodward & Pitbaldo, 2010).

The effects of this explosion would still be limited to local areas, due to relatively low explosion pressures. As discussed in the previous section, a flash fire can occur if an LNG vapor cloud is released into the atmosphere and ignited. However, the LNG facility being designed as very open structure, the frequency of occurrence of an explosion is very low. However, the confinement of the vapor cloud can occur e.g. within the spaces of the ship or nearby buildings

onshore or a chemical process plant in the vicinity. The resulting explosion can also generate methane, which can produce damaging overpressures (Center for Chemical Process Safety, 2010).

The emergency shutdown facility is typically suitable for an LNG facility, it can be activated by one or more of the following sources: gas detection; fire detection; manual activation of both the ship to be bunkered and the bunkering installation; break-away detection; electrical power failure; detection of an excessively high level in the fuel tank(s); high-pressure detection; detection of an excessively large liquid flow; detection of the filling arm/filling hose leaving its safe working zone (Woodward & Pitbaldo, 2010).

### **2.3.6 Boiling Liquid Expanding Vapor Explosion (BLEVE)**

Boiling Liquid Evaporating Vapor Explosions (BLEVEs) are large flammable envelopes occurring only with pressurized liquids and are the most extreme form of VCE. In an LNG facility, the normal mechanism for occurrence is due to the pressure vessel being subjected to external fire impingement or it failing catastrophically due to some other cause. This quick and turbulent release of LNG, from its pressurized containment, causes gasses to flash, leading to the characteristic large fireballs. Moreover, with a low volume of air being contained in the fireball, the pressurized LNG burns across the entire external envelope and rises rapidly. This fireball typically lasts for 20 to 40 seconds (Planas, Pastor, Casal, & Bonilla, 2015) .

Given, the special conditions required for a BLEVE to occur, it cannot easily occur in the large open spaces. Moreover, mostly LNG tanks do not have high operating pressures and even if LNG releases from the inner tank, the outer concrete shell of the LNG storage tank will provide an efficient barrier in case of this event (International Group of Liquefied Natural Gas Importers, 2009).

### **2.3.7 Rapid Phase Transition (RPT)**

The transfer of LNG to and from an LNG carrier provides the potential for spillage of LNG onto the water. If it happens, enormous heat will be transferred and rapidly convert to the gaseous phase. The transition causes LNG to expand in volume expands around 600 times, releasing, in turn, a large amount of energy usually in the form of a physical expansion, called a rapid phase transition (RPT). On the other hand, RPT can occur when a liquid rapidly changes phase to vapor. The vapor generation leads to greatly increase in volume and pressure resulting in an air or waterborne blast wave/pressures (Cleaver et al., 1998; Hamilton, 2012).

Although there is no immediate combustion, this explosion can be devastating to any living organisms or buildings nearby. At the same time, this explosion is unlikely to damage large structural elements such as a vessel or a jetty. The intensity of this explosion is limited to sonic velocity and the damage although serious is mostly limited to local physical regions of LNG/water mixing zones (Gavelli, Chernovsky, & Kytomaa, 2005). However, the RPTs have not yet resulted in any LNG major accident (Woodward & Pitbaldo, 2010).

### **2.3.8 Overpressure due to rollover**

Rollover is a potential risk to the safety of the LNG tanks during the LNG storage process. This hazard can occur when new LNG from the cargo ship transfers to an LNG onshore storage tank which has been partially filled. The different liquid densities from the two LNG sources cannot fully mix, the liquid layer adjacent to a liquid surface becomes denser than the layers beneath. This formation of layers of LNG with different densities is called LNG stratification.

Due to evaporation, the density of the upper layer gets heavier due to the continuous evaporation of methane vapor, which is a lighter hydrocarbon component of LNG. Due to heating of the tank walls the LNG at the bottom continues to evaporate. Finally, densities of both layers become same and the two layers suddenly begin to mix. This combined with the heat accumulated in the bottom layer produces a large amount of boil-off gas. This boil-off leads to large amounts of vapor expansion and consequent increase in internal tank pressure. This phenomenon is known as rollover. (Baker & Creed, 1995; Tamura, Nakamura, & Iwamoto, 1998).

The main hazard of a rollover is the rapid release of large amounts of vapor which may lead to over-pressurization of the LNG storage tank. It is also possible that the tank relief system may not be able or adequate to handle the rapid pressure build up in the tank. As a result, the storage tank will fail. Besides the damage to the tank leading to the rapid release of large amounts of LNG, rollover incident may lead to fire and explosions (Bashiri & Fatehnejad, 2006).

# Chapter 3 : METHODS AND TECHNIQUES

## 3.1 Data Collection Methods

In this thesis, not only the potential accident scenarios in the LNG transportation chain are analyzed, but also, the important values for the involved stakeholders will be determined. The methods to achieve these objectives are a literature review followed by cause consequence analysis, risk matrices and value radar diagrams. These methods are supplemented by interviews and field visits. Selection and description of these methods are described in the following sections.

### 3.1.1 Literature Review

The first method used in this research is a literature review. This literature review included several both electronic and printed academic documents such as scientific papers, journal, accident investigation reports, magazines, company literature. The primary literature obtained was through TU Delft library, journal search engines such as sciencedirect.com and scholar.google.com. Moreover, the web was also crawled upon to find specific information. Finally, this research being participatory and iterative, literature was also obtained from the involved stakeholders.

The advantage of this method is that it is not only inexpensive but is also an excellent method of creating a solid foundation to base the research upon. At this stage of the thesis, besides understanding the process and various intricacies involved in the handling of LNG, there was another objective: hazard identification.

### 3.1.2 Interview

The second data collection method in this thesis is face-to-face interviews using checklists and open questions. The interview structure is non-linear and free-flowing, with the interviewee at the centre of the interview. The interview consisted not only of the main questions [see Appendix C] but was also accompanied by additional clarifying questions. According to DiCicco-Bloom & Crabtree (2006) and Barriball & While (1994), by using such an individual interview, the participation of the interviewees increases and he/she is able to express clearly his/her opinion. New unexpected information can be introduced, especially for topics that are yet unavailable in the literature (DiCicco-Bloom & Crabtree, 2006). Therefore, this method was found useful to explore the interviewee's perspective and to explore the relevant issues (e.g. hazards, accident scenarios, and risks).

### 3.1.3 Accident Scenario Identification

After understanding LNG property and its related hazards, possible accident scenarios throughout the LNG transportation chain will be examined. In order to systematically identify the possible accident scenarios in the LNG transportation chain, the literature and LNG historical

accidents is reviewed. Also, the primary information is supported by interviews with the LNG experts.

#### **3.1.4 Cause-Consequence Analysis (CCA)**

For a system such the LNG transportation chain which has multiple causes of accidents, Cause-Consequence Analysis (CCA) is recommended (Ericson, 2005). Moreover, it is a proven tool for analyzing occupational accidents which fits well with this study (Center for Chemical Process Safety, 2011; Ericson, 2005).

According to Ericson (2005), CCA can range from extensive graphical logic trees displaying interrelationships between causes and consequences based on their initiating event or can be simple. However, determination of initiating event or complex interrelations is not required in this thesis since the purpose of this thesis is management of risk at the more practical level, which is understandable by all stakeholders. Furthermore, this analysis must be at the tangible and realistic level which corresponds well with the scope of this thesis, so the analysis should not be too broad, nor too narrow (the accident scenarios will not be analyzed for very low-level hazards; such as minute system components like a loose screw/bolt). Therefore, given the robustness and ease in communicating results, a textual description of particular accidents of CCA is used in this thesis.

To create the CCA, firstly the 61 accident scenarios are reviewed in the literature [Appendix B] and their causes and consequences are determined. These accident scenarios are classified as per their phase of occurrence (e.g. import terminal phase, road transportation phase, and filling station phase). Secondly, the causes and consequences in each accident scenario are grouped into categories. Thirdly, the proportion of the cause and consequence categories for each phase of the LNG transportation chain is determined. Fourthly, the proportion of the cause categories for each phase of the LNG transportation chain are plotted in a pie-chart. Similarly, the consequence categories for each phase of the LNG transportation chain are plotted in another pie-chart [see Appendix G]. Finally, the overall causes and consequences throughout the LNG transportation chain are plotted and validated with the historical accident data [see Appendix E and Appendix F].

The causes are classified into the following six categories:

1. Equipment or instrumentation failure: failure of operational equipment or instrumentation and control independently and randomly without the influence of an external factor.
2. External weather phenomena: accident due to extreme weather phenomena such as snow, storm, waves etc.
3. Human Error: this is one of the factors of human fallibility, it is due to the person and focuses on the errors of operators such as forgetfulness, inattention, or moral weakness (Reason, 2000b).
4. Inferior material quality: this cause separates equipment failure occurring independently to that due to the usage of inferior quality materials.

5. Procedural error: this is the other factor of human fallibility and relates to errors caused due to the conditions under which operators work. Poor procedures mean poor defenses to avert errors or their effects.
6. Terrorism: can be considered as human factor, but since it is a security threat i.e. done with an intention of harm, it is separated from human factor.

The causes due to human error (no.3) and procedural error (no.5) actually share same characteristics, thus they can be considered together as human factors (Reason, 2000a). However, these two factors are analyzed separately.

Similarly, the consequences are classified into seven categories. These are the most severe consequence that could occur in case a particular accident does occur:

1. Asphyxiation: lack of oxygen to the lungs due to the prolonged breathing of the LNG vapor. Other consequences in this category are dizziness, nausea, unconsciousness
2. Business process loss: refers to discontinuity of the LNG process, it could range from chemical process interruption to transportation interruption, which eventually hinders business revenues
3. Equipment damage: refers to damage of any operational equipment in the plant. It could refer from equipment such as loading arms to hoses to instruments connected to the tanker truck
4. Fire: refers to not only the combustion of LNG but related consequences that could cause a fire such a BLEVE, RPT, etc.
5. Freeze burn: refers to the burns caused when LNG contacts with human skin
6. Rollover: does not refer to rollover of LNG in the storage tank but the rollover of the LNG tanker truck or train after an accident on the highway or railway
7. Structural damage: refers to damage of structures in the LNG plant e.g. foundations, dispensers etc.

A synthesis of the CCA throughout the LNG transportation chain is done in Chapter 5. Using CCA in accident identification, the causes, and consequences of various accidents are known, but not their probabilities.

### **3.1.5 Risk Assessment**

Till now the focus has been on identification of hazards and accident scenarios, the next stage in this thesis relates to risk assessment. The risk is the measure of consequences and probability (Ale, 2009).

According to Adams (1995), an extensive study and identification of the risks (in this thesis: the LNG transportation chain) must be undertaken, because this can enable the creation of safety measures to manage these risks. Furthermore, according to Ale (2005), these identified risks must be decreased by implementing appropriate safety measures till the risks are as low as reasonably achievable (ALARA).

Risk assessment not only helps to determine the probability and severity of occurrence but also helps to determine mitigation measures in terms of risk levels. Interviews were held with LNG experts to fill the missing probability and severity data in the literature.

### 3.1.5.1 Risk Assessment Matrix

After performing the CCA, the identified risks are classified into a RAM (Risk Assessment Matrix). In the end, the potential severity and probability of occurrence of an accident are expressed in a 5x5 risk matrix. A five scale matrix is better than a three scale matrix since the risk comparison can perform better with less ambiguity and the results can also be clearly communicated (Curtis & Carey, 2012). Moreover, the five scale matrix provides enough range to distinguish the difference between categories; greater precision with larger risk matrices is typically unwarranted (Curtis & Carey, 2012).

In this thesis, five levels for identification of probability of occurrence are explained in Table 1 and five levels for identification of severity are explained in Table 2 (Committee for the Prevention of Disasters, 2005; Det Norske Veritas, 2011; Yataghène, Tallec, & Roue, 2005).

**Table 1: Definition of probability levels<sup>5</sup>**

Rating	Descriptor	Probability of occurrence	Frequency
1	Rare	Highly unlikely, but it may occur in exceptional circumstances. It could probably never happen or recur.	$\geq 10^{-4}$ /year
2	Unlikely	Not expected to happen or recur, but there is a slight possibility it may occur at some time.	$10^{-3}$ /year to $10^{-4}$ /year
3	Possible	The event might happen or recur at some time as there is a history of casual occurrence.	$10^{-2}$ /year to $10^{-3}$ /year
4	Likely	There is a strong possibility the event will occur as there is a history of frequent occurrence. However, it is not a persisting circumstance.	$10^{-1}$ /year to $10^{-2}$ /year
5	Almost Certain	Very likely. The event is expected to occur in most circumstances as there is a history of a regular occurrence. Possibly frequently.	$<10^{-1}$ /year

**Table 2: Definition of severity levels**

Rating	Descriptor	Severity/ Consequence Descriptors			
		People	Property	Environmental	Damage (€)
1	Insignificant	<ul style="list-style-type: none"> <li>Accident with first aid treatment</li> </ul>	<ul style="list-style-type: none"> <li>Minor damage</li> <li>Vandalism to asset</li> </ul>	<ul style="list-style-type: none"> <li>Emission internally</li> </ul>	<ul style="list-style-type: none"> <li>10,000</li> </ul>

Rating	Descriptor	Severity/ Consequence Descriptors			
		People	Property	Environmental	Damage (€)
		<ul style="list-style-type: none"> <li>Minor injury</li> <li>No permanent injury</li> </ul>			
2	Negligible	<ul style="list-style-type: none"> <li>Accident with medical treatment</li> <li>Lost time from workplace</li> </ul>	<ul style="list-style-type: none"> <li>Minor damage</li> <li>Loss of &lt; 5% of total assets</li> </ul>	<ul style="list-style-type: none"> <li>Emission slightly exceeding permit agreement:</li> <li>≤ 10% above permit agreement</li> <li>≤ 2 year</li> </ul>	<ul style="list-style-type: none"> <li>Between 10,000 to 100,000</li> </ul>
3	Moderate	<ul style="list-style-type: none"> <li>Accident with lost workday</li> <li>Hospitalization</li> </ul>	<ul style="list-style-type: none"> <li>Damage</li> <li>Loss of &lt;20% of total assets</li> </ul>	<ul style="list-style-type: none"> <li>Emission exceeding permit agreement:</li> <li>&gt;10 % above permit agreement</li> <li>&gt; 2 x year</li> </ul>	<ul style="list-style-type: none"> <li>Between 100,000 to 1,000,000</li> </ul>
4	Extensive	<ul style="list-style-type: none"> <li>One fatality</li> <li>Multiple major injuries</li> </ul>	<ul style="list-style-type: none"> <li>Extensive damage</li> <li>Loss &lt; 50% of total assets</li> </ul>	<ul style="list-style-type: none"> <li>Emission exceeding permit agreement with environmental damage</li> </ul>	<ul style="list-style-type: none"> <li>Between 1,000,000 to 10,000,000</li> </ul>
5	Significant	<ul style="list-style-type: none"> <li>Multiple fatalities</li> </ul>	<ul style="list-style-type: none"> <li>Destruction</li> <li>Complete loss of &gt; 50% of assets</li> </ul>	<ul style="list-style-type: none"> <li>Emission exceeding permit agreement with irreversible environmental damage</li> </ul>	<ul style="list-style-type: none"> <li>&gt;10,000,000</li> </ul>

### 3.1.5.2 Risk region description

Although traditional risk matrix is shaded in three colors of red, yellow and green, Cox (2008) recommends using more colors to expand the analysis space. With more colors different ratings can be assigned to quantitatively different risks. Furthermore, it helps to assign proportionate ratings to risks and to decrease the ambiguity (Cox, 2008).

Hence, the risk matrix in this thesis has five distinct levels of risk which were shaded in five different colors. The risk degree increases from level 1: low to level 5: very high.

The risk value for each scenario is calculated as the product of consequence and likelihood values, as illustrated in a matrix. The shading of the matrix visualizes the different risk levels. Based on the acceptance criteria, risks levels of 5-very high and 4-high are considered as unacceptable risks. In other words, these unacceptable risks are considered as the critical risks and any scenario of this risk level must be treated in order to have its risk reduced to an acceptable level (Ayob, Mukherjee, Kajuputra, Wong, & Salleh, 2014).



## 3.2 Validity

To ascertain the validity of the results, replicative validity was used. Replicative validity is the most fundamental form of validity and ensures that the generated model data matches with already observed data from the real system (Zeigler, Praehofer, & Kim, 2000). In this thesis, this matching was done between possible 61 accident scenarios [Appendix B] with the historical data [Appendix E and Appendix F]. This matching was done by graphically comparing the overall causes of accidents with the historical data. The percentage share of factors causing the various accidents and their consequences were compared. Also, the validity was conducted between the two RAMs from the literature and the interviews [Error! Reference source not found.]. This comparison was conducted between the average probability and severity levels from the interviewees' rankings and those levels from the academic sources [Appendix B].

The second part of this thesis will be related to values of the stakeholders. Value assessment tool and other methodologies are explained in the next section.

## 3.3 Values

To assess the important values of different stakeholders in the LNG transportation chain, some techniques and methods are used. These techniques are explained below.

### 3.3.1 Value Assessment

According to Schwartz (2006), the value are defined as desirable, trans-situational goals, varying in importance, that serves as guiding principles in people's lives. The important feature of values is an individuals' motivational goal. In order to evaluate and communicate value, value assessment tool is used (Schwartz, 2006).

Various value assessment tools are usually found in social studies. The tools are used mostly in the field of psychology and anthropology such as personal value assessment (PVA), Myers-Briggs Type Indicator (MBTI), or Value Orientations Method (VOM) (Gallagher, 2001). However, these value assessment tools originate from the field of social studies and their applicability to the field of safety study is claimed as ambiguous (Corrigan, Bunting, Jones, & Gunstone, 2013). Hence in this thesis where technical and societal aspects are combined, the value assessment tool is adopted from a closer field of safety studies i.e. risk-driven infrastructure management. This highlighted tool is RAMSHEEP (Wagner & Van Gelder, 2013).

#### 3.3.1.1 RAMSHEEP

According to Koppes (2015), RAMSHEEP is a methodology to tackle various values. The objective of RAMSHEEP is to assess more insight into the system, in this case the LNG transportation chain. RAMSHEEP has four characteristics, which are suitable with this thesis. They are described below:

1. It is an unambiguous assessment tool, which can clearly identify the values in a holistic and comprehensive view when applied to the large and complex system like the LNG transportation chain.
2. It has been developed from the technical aspect to the combination of the safety aspect and societal aspect.
3. It can clearly compare different value in each stakeholder group as well as compare different values among different stakeholder groups.
4. It can concisely communicate information and results to both the interviewee (during interview) and the reader.

In this thesis, RAMSHEEP is used as a tool to assess the main values of the LNG transportation chain based on different perspectives of stakeholders. The results from this tool will indicate the main driving values of the LNG chain. With this value assessment, the value conflicts among different stakeholders can be further managed and the important values for sustainable future of the LNG transportation chain can be introduced.

According to Wagner & van Gelder (2013), RAMSHEEP as the name indicates consists of reliability, availability, maintenance, safety, security, health, environment, economics, and politics. The details, explanation of each value is given in Table 3:

**Table 3: RAMSHEEP Explanation**

No.	Value	Definition
1	Reliability	<ul style="list-style-type: none"> <li>• It indicates the failure probability of a system due to which its functions could not be fulfilled. Reliability directly related to the frequency of failure. More often a system fails, the lower reliability is (Wagner &amp; Van Gelder, 2013).</li> <li>• The degree to which a system/an assessment tool produces stable and consistent results (Phelan &amp; Wren, 2006).</li> </ul>
2	Availability	It indicates the time duration in which the system is functional and its functions can be fulfilled (Wagner & Van Gelder, 2013).
3	Maintainability	The ease with which the system could be maintained over time (Wagner & Van Gelder, 2013).

No.	Value	Definition
4	Safety (and security) <sup>6</sup>	<ul style="list-style-type: none"> <li>The absence of human injuries during operating, using and maintaining the system (Steenbergen, Gelder, Miraglia, &amp; Vrouwenvelder, 2013).</li> <li>Safety, freedom from danger, invulnerability, protection, safekeeping, shielding (The Oxford English Dictionary, 1989).</li> </ul>
5	Health	The objective argument of good health with respect to the physical, mental and societal views (Wagner & Van Gelder, 2013)
6	Environment	Influence of the system on its direct environment (Wagner & Van Gelder, 2013).
7	Economics	A reflection of the cost vs. benefit analysis which provides an insight into the economics value which enables shareholders to make a responsible choice (Wagner & Van Gelder, 2013).
8	Politics	A rational decision on all the above values, including also some politics, to achieve the individual strategic objectives (Wagner & Van Gelder, 2013).

### 3.3.2 Stakeholder Analysis

According to Schmeer (2000), the term ‘stakeholders’ is derived from the interest, or stake which actors have in a certain business<sup>7</sup>. Stakeholders can be defined as individuals, groups (e.g. private organizations, government and academic institutions), or different groups and individuals whose involve in the certain business.

To approach stakeholder analysis, the relevant stakeholders are identified. The relevant stakeholders can be divided into two groups as internal stakeholders and external stakeholders. The internal stakeholders are the individuals or groups directly associated with the business and they also have the primary responsibility towards that business. While the external stakeholders are the individuals or groups that are not part of the business but they get affected by the business’s activities (Schmeer, 2000).

Later, goals, interests, and values of the relevant stakeholders are analyzed. The contribution from this step will support the value assessment and the recommendation in the future of LNG transportation chain.

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<sup>6</sup> The difference between security and safety is ‘security’ seems to refer to threats by deliberate human behavior, while ‘safety’ refer to threats from natural causes or human negligence. However, this distinction is not made in many official UN documents (Bailliet, 2009)

<sup>7</sup> The term ‘Business’ in this thesis refers to the operations or activities related to the LNG transportation chain.

### **3.3.3 Dealing with conflicting values: reasoning about values**

As mentioned above, different stakeholders focus on their own (different) values. Also, the stakeholders will make their decisions based upon (important) values in their minds (Wagner & Van Gelder, 2013). These different values will lead to different decisions and the different decisions will lead to different future of the LNG transportation chain. Therefore, to make the LNG transportation chain sustainable, the stakeholders must trade-off their different values [see 1.3.4] and balance their decisions (Willoughby, 1990).

According to Van De Poel & Royakkers (2011), selecting different values by different stakeholders can lead to a problematic situation. This problematic situation is called a ‘value conflict’. There are five approaches to deal with conflicting values: (1) cost benefit analysis; (2) multiple criteria analysis; (3) the determination of thresholds for design criteria; (4) reasoning about values; and (5) the search for new technical solutions (Van De Poel & Royakkers, 2011).

Among these five approaches, the ‘reasoning about values’ approach is selected since this approach fits well within the more qualitative approach taken in this thesis. According to Fulford, Carroll, & Peile (2011), the aim of this approach is not to decide who is right, instead it aims to expand our understanding of the various values in a given situation. Moreover, it can clearly identify the individual values as well as highlights the core conflicting values. This approach is also based on three ethical principles: (1) no danger or threat for humans; (2) minimum damage to the environment; and (3) to consider all stakeholders (especially the weak stakeholders who have the low significant capability to influence the operations of the operations/processes such as e.g. citizens). Considering these three principles, sustainable development of the LNG transportation chain can be successfully achieved (Van De Poel & Royakkers, 2011)

### **3.3.4 Radar Chart Approach**

For the RAMSHEEP method, a rating of these different values is necessary. To represent the different values visually simultaneously, it was found useful to use a radar chart. With a radar chart, the data collected from the 7 values could be represented easily. Moreover, by shading the areas lying inside the radar chart, it could be discerned the intersection of which values is more significant. That is which conjunction of values is more important for the stakeholders than the rest. The data points used on the radar chart represented graphically the average level of value perception of the stakeholders.

# Chapter 4 : LNG ACCIDENT ANALYSIS

## 4.1 Introduction

The operation of LNG cargo shipping began in 1959 (Woodward & Pitbaldo, 2010). The LNG shipping industry has excellent accident record, with the number of LNG accidents being 80% lower than the average number of marine accidents (Valsgard, Ostwold, Rognebakke, Byklum, & Sele, 2006).

However, the LNG facilities are expanding rapidly nowadays. There are 30 LNG importing countries with 126 LNG import terminals, including 17 new terminals under construction as of early 2015 worldwide (International Gas Union, 2015; Planas et al., 2015). Out of these numbers, around 30 LNG import terminals are located in Europe. New filling stations are also increasing at the same pace e.g. in the USA, the LNG filling station had increased by 400% by 2013. Similarly in the EU, 14 new LNG filling stations are being planned to be constructed by 2017 (Dembele et al., 2014).

This rise in demand for LNG has increased the operational activity in the LNG transportation chain. This increase in operational activity leads also to an increase operational failure, eventually leading to a rise in the number of accidents in the LNG transportation chain (Martin County Fire Rescue, 2015; Schubert, 2005; Whitney & Behrens, 2010).

In this chapter, historical of LNG accident and hazards of LNG will be explained.

## 4.2 Recorded LNG accidents

To understand the possible accident in the transportation chain, it is important to study the causes and consequences derived from the history of accidents. By analyzing the accidents; the cause and the resulting impact of these accidents can be understood. With this understanding, the various hazards and risk scenarios can be identified further in this thesis.

The table in Appendix E describes LNG accidents occurring over the LNG transportation chain in a chronological order.

### 4.2.1 Accident analysis

Before 2004, we can see most of the LNG accidents occurred at the LNG import terminals. While, since the past decade, the occurrence of accidents has shifted to the LNG tanker truck transportation and to the LNG filling stations. This relative shift can be explained with two reasons.

Firstly, the longer operational period of the LNG terminals (both export and import terminals) has provided more learning experiences from the past mistakes leading to better operational practices and better rules and regulations (Promban, 2015; Velgersdijk, 2015). For

example, since the 1971 LNG roll-over accident, many improved regulations and practices have been implemented to prevent recurrence of the similar accidents. Due to these improvements, the previous severe accidents, like rollover in LNG storage tank, are now considered only theoretical accidents (Promban, 2015). Considering the longer operational period of the LNG terminals with the shorter operational period of the LNG filling stations and the tanker truck transportation; the LNG terminals have more lesson-learned experiences.

Secondly, the increase in demand for LNG as a vehicle fuel has increased the number and frequency of both the LNG tanker trucks and the LNG filling station services. These two phases have more uncontrolled factors than the terminal phase since the operational environments of the LNG road transportation has more unpredictable factors. It is more open and dynamic. Therefore, the uncertainty in these two phases is higher (Brecher, Epstein, & Breck, 2015; Sperling, 1990).

Thus, given the aforementioned reasons, the transportation of LNG via road has greater safety concern compared with the LNG filling stations and the LNG terminals.

**NB:** According to the terminology defined by the LNG international commissions (CHIV International, 2012; DG MOVE, 2013), an LNG accident is considered to be one, which is caused directly due to the properties of LNG and its hazards. In other words, road or construction accidents involving LNG cannot be considered as LNG accidents. Therefore, only two LNG truck accidents are recorded in the table of LNG historical accident [see Appendix E]. If we don't consider this definition, since 1971, the real total number of a road accident involving LNG tanker truck reported in USA and Europe is 23<sup>8</sup> (Inland Transport Committee, 2015).

## 4.3 Discussion

Many kinds of literature claim that the LNG transportation chain has an excellent safety record (Alderman, 2010; Foss, 2003; International Group of Liquefied Natural Gas Importers, 2009). However, we can see from the LNG recorded accidents [see Appendix E and Appendix F] that the LNG transportation chain is not 100% safe. The observation from the LNG recorded accidents and the hazards of LNG transportation chain are discussed in this section.

### 4.3.1 Occurrence of major accidents

Major accidents in the LNG transportation chain will occur when all of the following four factors are present:

1. Operational failure
2. Enough amount of LNG release
3. Failure of instrumentation system
4. The presence of an ignition source

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<sup>8</sup> Out of this number, there were no loss of LNG from its containment (Inland Transport Committee, 2015).

Firstly, the major accidents are caused due to the operational failure. Operational failure refers not only to the failure of operational activities such as (un)loading operations, LNG storage, etc. but also refers to the failure of LNG transportation activities such as tanker truck collision. From the LNG recorded accidents, an operational failure is caused by many factors such as human errors or equipment failures [see Appendix E]. Secondly, the operational failure must cause an enough amount of LNG to spill/leak. Thirdly, there should be the failure of instrument and control system, including ESD system. Finally, these factors must be present in an area that is conducive to fire. Such an area is typically a confined area, where the methane concentration in air is between UFL and LFL [see 2.3.4]

The absence of even one factor can only lead to a minor accident or even no accident at all. Consider an accident involving the failure of transfer operation leading to an enough amount of spillage/leakage of LNG in a flammable area, but due to the presence of the instrumentation system, the occurrence of the potential accident will be detected and controlled in time, preventing a major accident to occur. Moreover, in the same case, if there is not an enough amount of spillage/leakage of LNG, even if it cannot be detected or controlled by the instrumentation system, this spillage/leakage will quickly evaporate and cause no major accident.

#### **4.3.2 Only safe designs do not guarantee operational safety**

Nowadays, the LNG facilities and the LNG vehicles have design features aimed at a high degree of safety which make the occurrence of an accident difficult. However, throughout the LNG transportation chain, the LNG road transportation has more uncontrolled factors than the LNG import terminals or the LNG filling stations since there are many vehicles ride on the roads day and night. The operational environments of the LNG road transportation have more unpredictable factors (Brecher et al., 2015; Sperling, 1990).

Hence, it is possible that the real accident characteristics can be different from the design (expected) safety features for the LNG tanker trucks. For example, for the LNG tanker truck accident from Appendix E, their insulations of the tanker were not effective because they were either knocked off or rapidly burned off due to the intense fire (Planas et al., 2015; Planas-Cuchi, Gasulla, Ventosa, & Casal, 2004). Therefore, the LNG road transportation poses a high concern for safety in the LNG transportation chain.

#### **4.3.3 Regulations have loopholes**

The current PGS and EU regulations for the LNG tanker truck transportation are considered as adequate for ensuring safety (Beemt, 2015; George, 2015; Velgersdijk, 2015). These regulations have reduced LNG accidents, especially accidents due to spillage and leakage from LNG tanker trucks. Since the current regulations require tanker trucks to meet stringent regulations such as the

usage of double-walled tanks<sup>9</sup>. Double walled tanks have two walls with a combined vacuum and insulation system that not only helps to keep the cryogenic LNG cool but also prevent leakage.

Although these international standards have been established, but due to existing national regulations in EU member states, these regulations have not been implemented similarly across the EU. This leads to non-uniform technologies across the EU. For example, the Netherlands being a new entrant to LNG field has equipment conformant to the newer regulations such as double walled tanks (Beemt, 2015). But older entrants such as Spain are still allowed to use existing single walled tanker trucks in their country. Because, in the EU, single walled tanker trucks purchased before the implementation of the new regulations are still allowed to drive in their home country (The European Parliament and The Council of The European Union, 2014). Therefore, with limited border monitoring resources, preventing non-compliant tanker trucks on the roadway is not effective practically (Beemt, 2015; Gravendijk, 2015). As a result, the claim of safety for the LNG road transportation chain is both concerning as well as doubtful.

From above points, while regulations are important to ensure safety; raising safety awareness for all stakeholders (e.g. tanker truck drivers, traffic controlling/service agencies, firefighters, police, regulators and other road users) in the entire LNG transportation chain, is equally important. With increased awareness, the stakeholders will have a consistent understanding and implementation of the regulations. This can be achieved by focus groups, training sessions, feedback sessions and iterations in the regulations among all the stakeholders. Furthermore, if an LNG accident occurs, stakeholders must be trained to deal with the accident.

#### **4.3.4 ESD system plays an important role**

Because the ESD system is capable of stopping an operation (e.g. LNG loading or unloading) within one minute in case of leakage, the ESD system is a very important measure to prevent an LNG accident.

The ESD is a sophisticated system including liquid and gas pressure monitoring; heat and fire detectors; and shutdown devices. The ESD equipment is located at critical points of the LNG operational equipment and has high designed reliability (Nasr & Connor, 2014). However, due to their critical location, testing the ESD equipment means interrupting an LNG operation. Therefore, testing of ESD equipment is not always feasible (George, 2015). Hence, it is possible that the ESD system does not function when required.

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<sup>9</sup> Regulation 110, Annex 3B paragraph 2.5. “LNG tanks are double wall stainless steel. To destroy a steel LNG tank, a corrosive liquid would have to be in prolonged contact with the tank. Even if the outer skin of the LNG tank were compromised, the inner steel tank also would have to be substantially exposed....”(UNECE, 2015).



## **4.4 Conclusion**

From the research questions [1.6], and the discussions [4.3], in this section it is attempted to answer the following research questions:

### **4.4.1 How does a major LNG accident occur?**

According to Ale et al. (2009), a major accident cannot be attributed to the occurrence of a single factor. This is especially true for major accidents in the LNG transportation chain. Although the LNG transportation chain is safe, a major accident can still occur due to the combination of the following four factors:

1. Operational failure
2. Enough amount of LNG release
3. Failure of instrumentation system (including ESD system)
4. The presence of an ignition source

These factors are inter-related with each other and for a major LNG accident to occur these four factors must occur together.

### **4.4.2 Can a safe design ensure operational safety?**

The operations throughout the entire LNG transportation chain are robust and the LNG equipment is designed with high safety standards. However, LNG road transportation has the greatest amount of uncontrolled factors in the LNG transportation chain, which can lead to an unexpected accident in reality. Therefore, due to this unpredictability, only a safe design cannot ensure the safety of the LNG operations.

### **4.4.3 Can the regulations be improved to ensure operational safety?**

While, regulations for the LNG transportation chain are stringent and comprehensive, because of loopholes, the regulations alone will not ensure operational safety. To ensure safety, safety awareness must be increased among all the stakeholders in the LNG transportation chain.

### **4.4.4 Which equipment is the most important to ensure safety?**

The ESD system is the most important safety equipment among the various LNG equipment throughout the LNG transportation chain. A properly functioning and reliable ESD system can ensure safety despite the failure of all other operational equipment. Therefore, ESD system is the most important equipment to ensure safety in the LNG transportation chain.

# Chapter 5 : CAUSE- CONSEQUENCE ANALYSIS

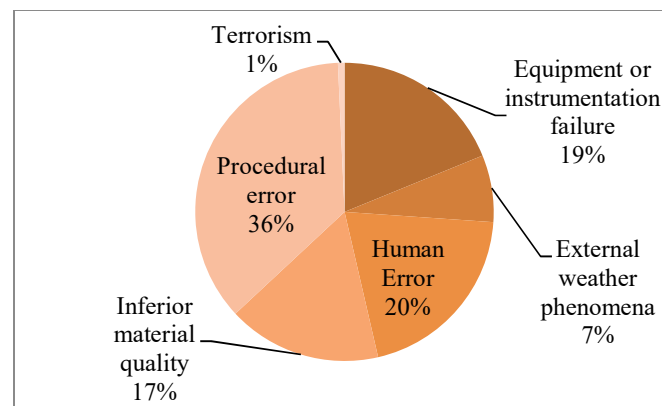
## 5.1 Introduction

In this chapter, causes and consequences of the possible 61 accident scenarios [See Appendix B]<sup>10</sup> throughout the LNG transportation chain are analyzed and identified. In order to communicate effectively, pie charts are used to summarize the categorical results of this CCA. In the discussion section, the CCA of the 61 accident scenarios are validated with the LNG historical accident data [see Appendix E and Appendix F].

For more details, the explanations of CCA and the validity using in this chapter are previous mentioned in 3.1.4 and 3.2. Also the descriptions of CCA in each phase of the LNG chain is present in more detail in Appendix G.

## 5.2 CCA for the overall accidents in the LNG transportation chain

In this section, analysis of causes and consequences of the 61 accident scenarios throughout the LNG transportation chain is performed. The final results are present as follows:



**Figure 4: Causes of overall accidents**

From Figure 4, the majority of the accident scenarios throughout the LNG transportation chain are caused in descending order as:

1. Procedural error

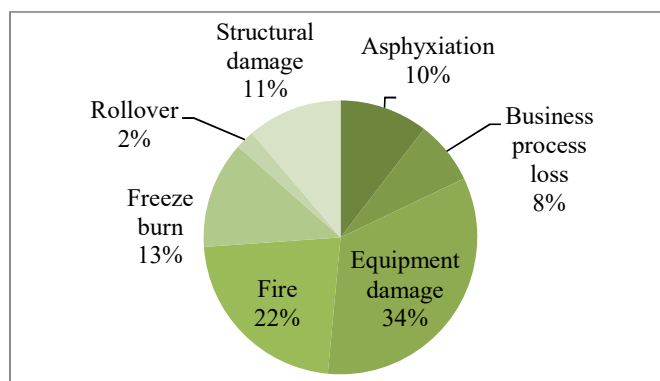
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<sup>10</sup> As aforementioned, these possible 61 scenarios are firstly derived from the literature study and secondly supported by the LNG experts.

2. Human error
3. Equipment or instrumentation failure

The procedural errors form the largest proportion of causes of the accidents throughout the LNG transportation chain. The second largest proportion is human errors. These two factors, procedural and human errors, have a major proportion of causes of the LNG accidents (56%). These two factors are expected since the same trend was observed in each phase of the transportation chain [see Appendix G]. Although, these two factors are analyzed separately, these are in fact are considered together as human errors [see 3.1.4].

However, the third largest proportion of causes of the accidents throughout the LNG transportation chain has been different in the different phases. In the entire LNG transportation chain, it was found equipment or instrumentation<sup>11</sup> failure to be the third major cause of accidents. This equipment or instrumentation failure ranks as the highest cause in the import terminal accident scenarios, its ranking decreases in the tanker truck/train phase and filling station phase. Moreover, in the general accident scenarios, equipment or instrumentation failure does not figure at all as a cause of an accident. Due to this variation in its ranking, equipment or instrumentation failure ranks overall as the third major cause of accidents. Nevertheless, equipment functionality is highly essential for mitigating risks.



**Figure 5: Consequences of overall accidents**

The consequences of the accident scenario phases overall can be seen from Figure 5 to be in descending order as:

1. Equipment damage
2. Fire
3. Freeze burn

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<sup>11</sup> Failure of equipment and instrumentation refers to the failure of operational equipment like pipeline, valves and gas & liquid monitoring/detection systems.

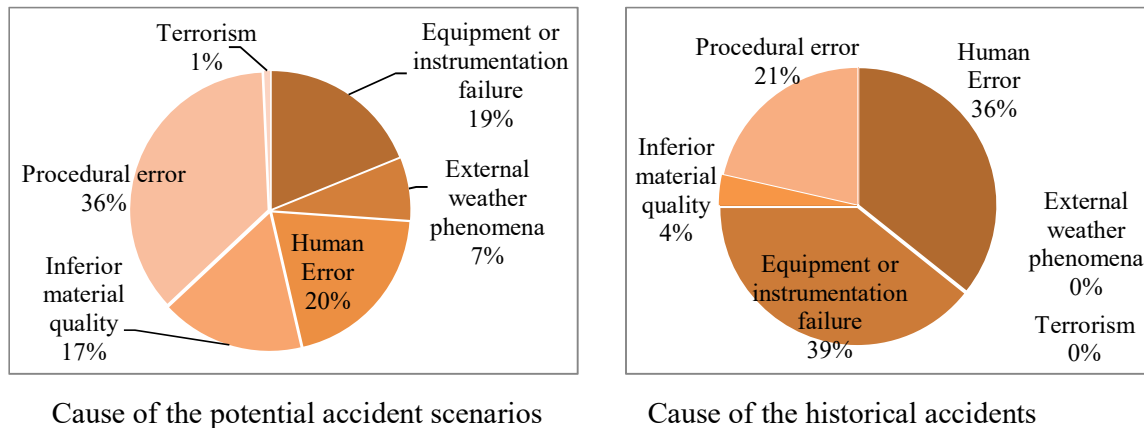
Equipment damage is the major consequence emerging from the accident scenarios. This consequence is expected since the equipment is the actual LNG carrying component and even if the carrying equipment does not damage, the daily use of the LNG equipment throughout the transportation chain means equipment damage will be the highest consequence.

The second and third consequences are related to each other since they are likely to occur when the accidents related with LNG leaks/spills. However, the third major consequence of freeze burns is one of the major consequences in all the phases except the import terminal phase<sup>12</sup>.

Hence, the proportion and presence of causes and consequences are in order of expectation.

### 5.3 CCA validity and discussion

In this section, the causes and consequences from the potential accident scenarios [from the 61 accident scenarios in Appendix B] are compared with the historical accident data [from the 27 historical accident scenarios in Appendix E].



**Figure 6: Comparison of causes of the LNG accidents from two sources**

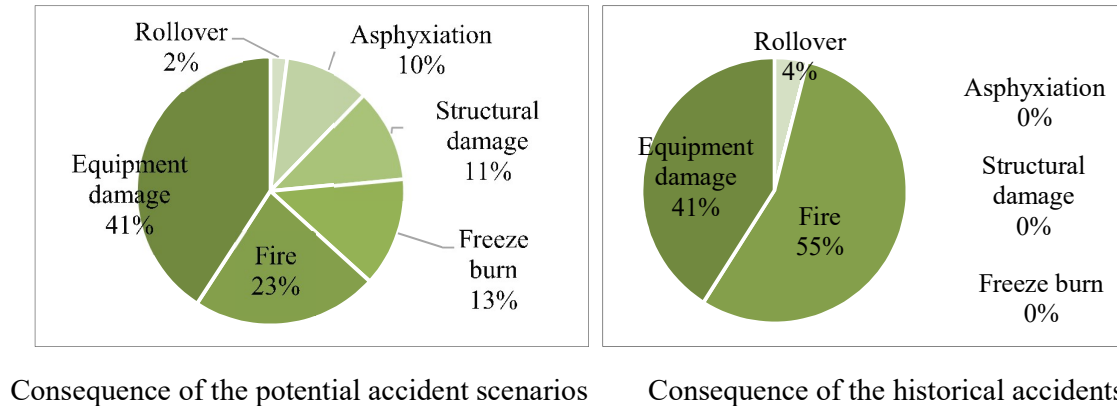
From Figure 6, the two factors of human error and procedural error have a major proportion of cause of the LNG accidents from both sources. As aforementioned, these two factors of human error and procedural error can be considered as human factors. Therefore, human factors were 56% and come to a close 57% in this section.

The same can be said for equipment or instrumentation failure which is the second major cause of accidents from both sources. However, their proportions are not of the same order. From the historical accidents, their proportion 39% of the accidents; while from the accident scenarios, their proportion is only 19%. This difference can be explained with two reasons. First, the greater spread of causes across various categories from the potential accident scenarios compared to the

<sup>12</sup> This is because of higher safety training/ procedures and the use of PPE.

historical data is higher. Second, the historical accidents have been reported mainly from the import terminals (24 reported accidents out of 27). The two reasons also explain the lesser proportion of the accidents due to equipment or instrumentation failure.

As previously discussed, the first line of defense is the continuous operation of reliable operational equipment and instrumentation. In case, of their proper functioning, many accidents can be prevented. Finally, due to the implementation of stringent regulations, better quality of equipment and instrumentation are being used, which explains their reduced failure rate in the literature.



**Figure 7: Comparison of consequences of the LNG accidents from two sources**

It can be seen from Figure 7 that equipment damage from the both sources has the same proportion of consequences of the accident scenarios (40%). This equipment damage is the largest proportion for the potential accident scenarios but it is the second largest proportion for the historical accident. The second largest proportion of consequences in the accident scenarios obtained from literature is fire. While in the historical data, the fire has the largest proportion of consequences. The proportions here are not similar, it is 22% from accident scenarios and 55% from the historical data. Finally, freeze burns are the third largest proportion of consequences in the accident scenarios obtained from the literature. However, in the historical data, it has no proportion in the consequences.

The differing proportions from the two sources can be explained due to the fact that the historical accident only focuses on major consequences such as fire, without considering the many other possible consequences that occur during an accident. Secondly, many historical accidents are a decade old and it is not possible to retrieve precise information on all the consequences of accidents. Finally, many minor accidents go unreported and the proportion of many consequences such as rollover, asphyxiation etc. are not adequately represented.

## 5.4 Conclusion

In this section the following research questions are answered:

#### **5.4.1 How do accidents mainly occur in the LNG transportation chain?**

The most accidents in the LNG transportation chain occurs due to the leakage of LNG from its containment or the failure LNG loading system.

Each phase of the LNG transportation chain has its own characteristics. For example, the road transportation has more open and dynamic environment compared with the terminal or the filling station. These environmental characteristics are mainly led to the accident.

Many causes usually involve in an accident and a single cause cannot lead to a major accident of LNG. However, if a major cause of accidents has to be specified; it is would be human factors, followed by equipment or instrumentation failure.

#### **5.4.2 What are the major causes of accidents in the LNG transportation chain?**

If procedural and human errors are regarded as human factors, then throughout the LNG transportation chain, the trend of human factors being a major cause of accidents is observed in the different phases of the LNG transportation chain. If considered separately, procedural errors have a greater proportion than human errors and except for the import terminal phase; these procedural errors have the greatest proportion in the cause for accidents.

#### **5.4.3 What are the major consequences of accidents in the LNG transportation chain?**

Throughout the LNG transportation chain, it can be said the major consequences of LNG accidents are the damage to the operational and instrumentation equipment, followed by the creation of fire/ fire-like conditions. In the category of fire, the occurrence of fire itself is the most severe consequence. Lastly, the third major consequence of accidents was found to be human injury (asphyxiation, bruises, cuts, fractures, freeze burns).

#### **5.4.4 How can accidents be mitigated in the LNG transportation chain?**

Since procedural errors are a major cause of accidents, improving procedures is the way forward. Improving regulations [4.4.3] has already been discussed earlier. However, from an operational point of view, procedures must be improved; this could mean better training, safety awareness, hiring experienced workers, regular testing, maintenance etc. Better procedures can help to mitigate accidents due to human errors (which is the second major cause of accidents). Secondly, usage of gas/heat/ice/liquid monitoring systems can aid the operators to pre-empt accidents from occurring.

The second major cause besides human factors is equipment or instrumentation failure. This can be mitigated using good quality equipment, which happens to be also a major cause of accidents. Regular inspection of equipment (which is a procedural factor) can also help mitigate these accidents.

Like accidents are not caused by a single factor, in the same manner, accidents cannot be prevented by a single measure. In other words, to prevent an accident a number of measures must be used together.

#### **5.4.5 How valid are the results?**

Compared to the historical LNG accident data, the results from the accident scenarios were found to be valid, especially for the human factors. Human factors are the major cause of accidents in the LNG transportation chain. This factor has a high proportion of both the historical accidents and in the potential accident scenarios.

However, the differing proportions from the two sources can be explained due to the fact that the historical accident only focuses on the major consequences such as fire, without considering other possible consequences that occur during an accident. Secondly, many historical accidents are a decade old and it is not possible to retrieve precise information on all the consequences of accidents. Finally, many minor accidents go unreported and the proportion of many consequences such as rollover, asphyxiation etc. are not adequately represented.

# Chapter 6 : RISK ASSESSMENT AND INTERPRETATION

In this chapter, two RAMs are made and compared. The first RAM is derived from the LNG expert interviews while the second RAM is derived from the literature<sup>13</sup>. The purpose of the second RAM is to validate the RAM from the LNG experts. More details regarding the RAM from literature can be found in Appendix B and details regarding the RAM from the LNG expert interviews can be found in Appendix I.

In the discussion part, the matching and non-matching of the two RAMs are observed and analyzed. This aims to understand how the interviewees perceived the risks in the LNG transportation chain.

## 6.1 RAM from the LNG expert interviews

Two rounds of interviews were held with LNG experts who are specialized in different phases throughout the LNG transportation chain. The experts were asked to rate probability level and severity level for each of the 61 accident scenarios on the scale of 1 to 5 (low to high) [see Appendix C]. This step aims to assess risks in the LNG chain [see 2.1.3]. The rating results are decimal numbers which were rounded off to the nearest 1 to 5 and plotted in a RAM.

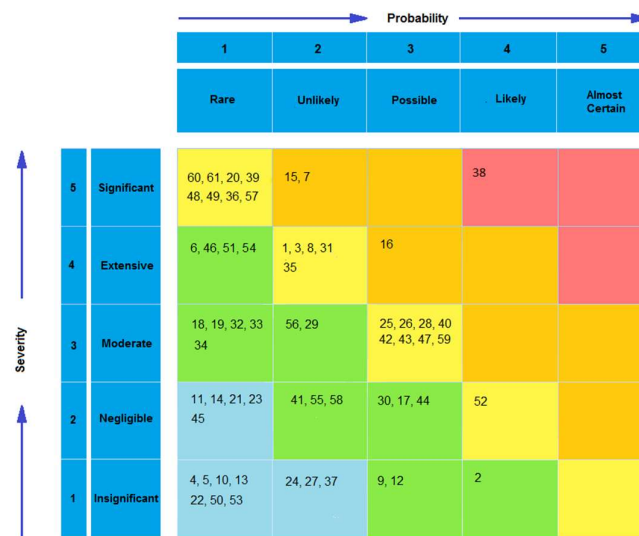
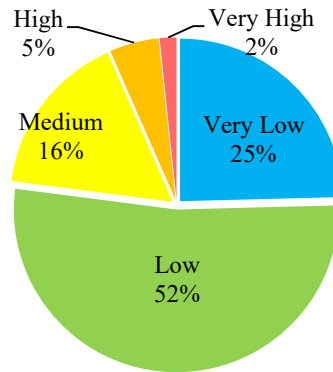


Figure 8: RAM from the LNG expert interviews

<sup>13</sup> Data from literature include both historical data and experimental data [See Appendix B].





**Figure 9: Proportion of risk levels throughout the LNG transportation chain**

It can be seen from the RAM in Figure 8 and the pie chart in Figure 9 that majority of the risks (77%) lie in the low-risk regions. Moreover, in the middle regions (medium to high risk), there are only 21% of risks. Finally, it is also noteworthy that the risk in the very high region is a mere 2% of the total. In fact, the 2% corresponds to only one risk: risk number.38.

Due to high safety control mechanisms and stringent regulations, most of the risks have been contained to safer regions (blue/green/yellow zone). Moreover, redundant instrumentation systems (e.g. monitoring/ detecting system and ESD system) can help the risk levels maintain in the low-risk regions. However, negligence of one regulation or even a small loss of control could cause these risks to migrate to unsafe regions very easily.

Among the interviewees, there is a general consensus that risks no. 38, risk due to the collision of LNG tanker truck/train with the other vehicles while riding is the critical risk.

#### **6.1.1 Concerns of RAM from the LNG expert interviews**

There are two concerns regarding the RAM from the interviews: bias from LNG experts and the less amount of interviewees.

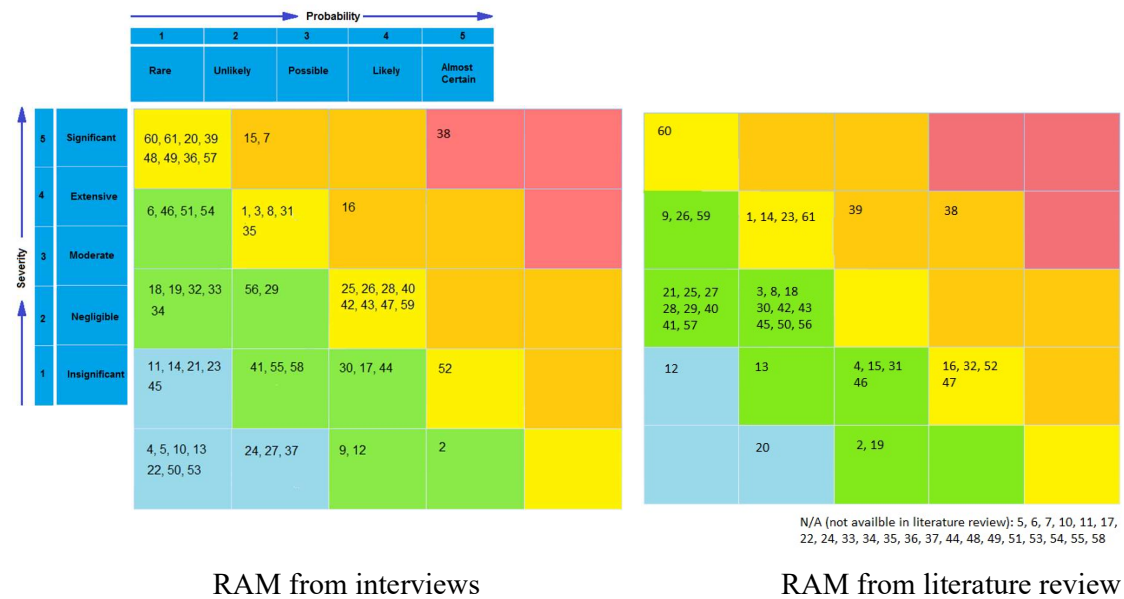
The first concern is that since all of the experts are involved in LNG transportation business, they have a benefit to show a good safety perspective in the LNG field to the public. Therefore, the risk level results may be lower than reality. This bias was prevented by averaging risks across different phases of the LNG chain. This concern is further discussed in 6.3.1.

The second concern is the less amount of interviewees which does not reach the optimal quantitative sample size of 30 interviewees. Although this chapter aims to understand the experts' perception of risks, which is qualitative study; the less amount of interviewees can mean that some information (e.g. perception and opinion) might be missed out. However, it does not mean that the discovered results are invalid (DePaulo, 2000).

## 6.2 Validity of the RAMs

In this section, the validity was conducted between the two RAMs (one from the LNG expert interviews and the other from the literature) using graphical comparison. Here, the RAM obtained from the literature review [see Appendix B] is used as a reference.

However, this validity does not refer to determining the certainty of the risks but the validity here refers to ascertaining if the model RAM (RAM from interview) corresponds to the real system data (RAM from literature). See more details of validity in section 3.2.



**Figure 10: Comparison of RAMs<sup>14</sup>**

From Figure 10, the probability and severity levels of each risk are compared cell by cell. Three issues are observed from this comparison: the critical risk, matching risks and non-matching risks.

The critical risk Figure 10As we can see from Figure 10, the risk number 38 is in the top-right most cell where a high-risk region is. Therefore, the critical risk throughout the LNG transportation chain is the risk number 38: Collision of LNG tanker truck while riding.

### 6.2.1 Matching risks

Some risk numbers present in Figure 10 are plotted in the same cell or slightly different from each other. Therefore, they can be considered as matching risks such as:

<sup>14</sup> 21 risks are absent regarding probabilities and severities from the literature study. Although, these risks, whose probabilities and severities are absent, are still taken into account in the other section but they are not compared in this section of 6.2.

1. Risk number 52: End-user drive away while hose is connected
2. Risk number 60: Earthquake/ Tsunami
3. Risk number 61: Terrorist attack
4. Risk number 47: Normal instrumentation failure (e.g. Pressure indicator)
5. Risk number 16: Normal instrumentation failure

The risk number 52 and 60 are in risk zone 3 (yellow – moderate to high) from both the interviewees and the literature. While the risk number 61 and 47 have one level of severity and probability differ but still lie in the same zone (zone 3). For the risk number 16, even it has two levels of severity and one level of probability differ, it was plotted in the risk zone 4 according to the LNG experts which are only one level different than the risk zone 3 according to the literature.

### **6.2.2 Non-matching risks**

Some risk numbers present in Figure 10 are plotted in the far different cell. They are considered as non-matching risks such as:

1. Risk number 20: Loss of emergency power supply
2. Risk number 15: ESD (Emergency Shut Down) System Failure
3. Risk number 57: Lack of proper training
4. Risk number 26: Overpressure in tanker truck/train
5. Risk number 59: Lightning strike

The risk number 20 is the most deviated risk (3 different regions). While it is in the high-risk region (4 – orange) according to the interviewees, it is considered as low-risk region according to the literature (1 – blue).

Most of the risk levels from the interviews were ranked higher than those from the literature in term of severity levels but not in term of probability levels since the probability levels are quite similar in each risk in both RAMs. Therefore, it can be concluded that the LNG expert interviewees perceived the severity levels of LNG accidents higher than they are stated in the literature.

However, the risk is directly related to uncertainty: it is unknown exactly whether risk may occur and the severity of the outcome can be. Therefore, the risk results which have been studied and presented in literature cannot be correctly assured, but it can be considered rather the guidelines to assess the risks in the LNG transportation chain.

## **6.3 Discussion: risk perception and the influencing factors**

Between these two RAMs, not all probability and severity levels are matched. Such non-matchings have been found in previous research papers also (such as papers from Tversky & Kahneman, in 1974 and in 1981). Risk perception theory can explain these differences.

According to risk perception theory [see 2.2], the RAM from the LNG expert interviewees can be considered as results from (subjective) cognition and (individual) risk perception which can

be influenced by many factors (e.g. bias and norms). The potential factors which influence the risk perceptions of the interviewees are observed and discussed as follows:

### **6.3.1 Preference: low-risk answers were predicted**

From previous mentioned about bias [see 6.1], since all of the interviewees are involved in LNG transportation business, they have a benefit to show a good safety perspective in the LNG field to the public. The assumption before interviewing is these LNG experts might prefer to rank the levels of probability and severity of these 61 accident scenarios as low as possible. However, from the previous section, the risk results from the interviews show higher risk level than the literature review. Therefore, the first assumption that interviewees' preferences to lower the level of LNG risks is not true.

### **6.3.2 Shared safety knowledge in the professional culture**

Since the LNG-community is considered as small and tight with regular interactions, the workers require a high safety knowledge of expertise in LNG. Therefore, we can say that the interviewees have some common professional culture such as LNG working experiences<sup>15</sup> or education and knowledge<sup>16</sup>. Hence, their perceptions regarding safety knowledge are considered as common too.

In order to be more concrete, safety knowledge which all interviewees have in common are LNG general safety knowledge (e.g. LNG historical accidents, LNG properties and its hazards, and LNG accidents, causes and consequences, and mitigation measures) and LNG-related technical knowledge (e.g. international standards and regulations, technology related to LNG operations/equipment in the current days)

This safety knowledge of LNG can be seen as an important factor which influences the LNG risk perceptions of the interviewees. Hence, safety knowledge can be seen as a dominant factor which influences the risk perceptions of the interviewees.

### **6.3.3 Controllability and Availability Heuristic**

From the RAMs comparison section [6.2.2], the probability levels from the interviewees were found to be similar as those from the literature. However, the severity levels from the interviewees were found to be higher than those from the literature. Two following factors can be used to explain these differences:

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<sup>15</sup> Working experience refers to similar field experience. The interviewees have significant direct field experience and understand the characteristics of LNG.

<sup>16</sup> Education and knowledge refers to not only their university education but professional education regarding LNG. This has been gained via organizational and international trainings. Review of same LNG safety literature and standards.

Firstly, from the common safety knowledge mentioned above [see 6.3.1], the interviewees shared some sense of ‘controllability’. The controllability is present when the interviewees mentioned the assurance of the LNG safety systems. LNG equipment with high endurance and tolerance (such as tanker trucks, pipelines and valves), efficient guarding systems (such as control systems and ESD systems), procedural control measures (such as standards and regulations), which the interviewees mostly mentioned during the interviews, give a sense that the risks are in proper control (Sjöberg et al., 2004). As a result, risk perceptions of the interviewees regarding probability levels are shown as matchings with those from the literature. In other words, the interviewees’ knowledge about LNG safety has influenced their risk perception in terms of the probability levels.

Secondly, the higher severity levels from the interviews compared to those from the literature can be explained by the influences of historical data. When the interviewees explained their answers about their ratings on the severity levels, they referred their ratings to the historical reports regarding that accident scenario. For example, for the scenario of ‘Collision of LNG tanker truck while riding’, they thought about the two LNG tanker truck accidents in Spain in 2002 and 2011 [see 4.2]. The two accidents had fatalities and explosions reports. According to Sjöberg et al. (2004), the approach in which people use available information that they can recall and use to estimate the risk is called availability heuristic. Since the interviewees referred to their memories on the historical LNG accident reports, the ‘availability heuristic’ is considered as the influencing factor for their risk perception.

## **6.4 Recommendations: dealing with the critical risk**

The worst-case scenario of the LNG tanker truck collision is an explosion. This explosion likely occurs as a result of (at least) two events: presence of fierce fire and a pressure relief devices & ESD system of the tanker fails to function.

A fire source could be due to the impact of collision and it can burn faster and more fiercely if engine fuel (e.g. diesel from the accident vehicle or LNG itself) leaks to the fire. If fire cannot be extinguished and it is raging around the tanker, the LNG tanker can explode. This is due the radiant heat from the flames, which speedily stimulates the vapor generation inside the tanker. This vapor increase results in higher pressure in the tanker. Normally, pressure relief devices and ESD system will release the excess pressure. However, if these devices are damaged from the accident and do not functioning properly, this LNG vapor under immense pressure can lead to an explosion. The heat released from this LNG explosive fire will be much greater than that of a regular petroleum fire of equivalent size (DG MOVE, 2013).

### **6.4.1 Strategy to prevent the worst-case scenario**

The first basic strategy to prevent the adverse outcome from this LNG tanker truck collision is to ensure that the containment systems are well functioned and the equipment is matched with the current safety standards. From EU and US regulations, the LNG-truck containment system must consist of a double-walled tank with a combined vacuum and insulation system ((UNECE, 2015). Double walled tanks are very useful to maintain the LNG at cryogenic temperatures, to

provide additional protection to the tanker against mechanical punctures and to reduce the effects of external fire exposure. Isolation and secondary shut-off valves are also very important to reduce/prevent the spillage of LNG. The secondary shut-off valves are an additional source of protection; in case, the isolation valves fail to work. However, this method can be considered as reactive, reacting to the accidents after it has occurred.

The effective strategy to deal with this LNG truck collision accident is to maintain a balance between the reactive and proactive methods. In contrast to the reactive method, proactive method means preparing for possible the future occurrence. Hence, the proactive methods (e.g. extensive safety training, inspection, maintenance, and operation procedures) should also be regularly implemented. Regular inspection and maintenance for both the tanker trucks and the associated (safety) equipment can be a good proactive strategy. However, the safety researchers agree that a more reliable strategy to prevent the LNG truck accident is a well-trained driver (Feijter & Mierlo, 2015; Sivak & Brandon, 2015).

#### **6.4.2 Applicability of intervention technologies**

Since LNG transportation via trucks is the most economical and efficient way to transport LNG from the terminal to the filling station. From this critical risk, the truck drivers are most likely to get injured. Regarding safety of the driver, three currently intervention methods are introduced: (1) PPE, (2) fire-retardant truck cabins, and (3) self-driving truck.

Firstly, PPE can be useful for preventing injury from accident, wearing it has been found to be uncomfortable during driving. Training and better operating procedures have been found to be much more useful in preventing worker injuries than PPE.

Secondly, the fire-retardant truck cabins are useful in separating the consequences of LNG spillage from the driver. However, the associated cost is still very high. Moreover, the characteristics of an accident cannot be simply predicted, this fire-retardant cabins are still not guarantee safety of the drivers.

Thirdly, the intervention technology of using self-driven trucks is very interesting, but its availability is non-existent in the industry since it is yet in initial stages of development. However, it is remarkable to mention that, in a recent pilot project, a platoon of trucks travelled more than 1000 kilometers in EU (Zetlin, 2016). However, even with self-driving trucks, it is impossible to guarantee zero fatalities. Although by 2025, it is hoped to have more such self-driving trucks, thus, for now, the availability and reliability of this technology are very low (Sivak & Brandon, 2015).

However, three of them cannot guarantee zero accidents of LNG tanker truck. They only enhance safety of the truck driver but the risk level remains. Therefore, these intervention technologies are not the exact methods to deal with the root cause of this critical risk. According to Sivak & Brandon (2015), a well-trained driver is currently considered to be more reliable in preventing the truck collision accidents and enhancing road safety than any intervention technologies.

## 6.5 Conclusion

In this chapter, the two RAMs are present and compared. By this comparison, the critical risk, matching risks, and non-matching risks are observed. The result indicates the number of non-matching risks is greater than the number of matching risks. But the critical risk (number 38: the Collision of LNG tanker truck while riding) is well matched. However, if we observe the severity levels and probability levels in each risk, the probability levels from interviewees' ratings are quite similar to those from the literature's ratings. While the severity levels from the interviewees' ratings are higher than those from the literature's ratings.

In discussion part, the risk perception theory was used to explain these differences. This explanation is also attempted to answer the research questions [1.6]:

### 6.5.1 How can the individual risk perceptions be explained?

According to Boholm (1998), the concept of risk can be implied to individual psychological constructs (human mind and value) which are influenced by many factors such as psychological and institutional factors. Therefore, to understand how people understand risk is to understand risk perception (Sjöberg et al., 2004). And to understand the risk perception is to find out what factors influence people's perception. The three potential influencing factors were applied in this thesis in terms of the shared safety knowledge, controllability and availability heuristic.

Firstly, the shared knowledge of LNG safety (e.g. education, training) among the LNG experts are considered. Since the LNG-community is considered as small and tight with regular interactions, the LNG workers require a high safety knowledge of expertise in LNG. This LNG safety knowledge is in common among the interviewees' organizations. Therefore, the shared safety knowledge is the factor that influences risk perceptions of the interviewees.

Secondly, the interviewees also shared the same sense of controllability regarding the LNG safety systems and other safety assurances. During the interviews, they mentioned that they are *in control*. This sense of controllability is considered as the influencing factor since the interviewees' ratings of the probability levels is smaller than the severity level and these ratings are matched with those from the literature.

Lastly, the higher severity levels from the interviews compared to those from the literature can be explained by the influence of historical data. According to Sjöberg et al. (2004), the approach in which people use available information that they can recall and use to estimate the risk is called availability heuristic. Therefore, the availability heuristic is considered as the influencing factor for their risk perceptions.

### 6.5.2 How to deal with the critical risk in the LNG transportation chain?

The critical risk in the LNG transportation chain is a Collision of LNG tanker truck while riding. From the historical accident, the root-causes of the LNG tanker truck collision are mainly from human negligence. However, if no fire is present, the pressure relief devices & ESD system functions properly, and LNG is not leaked from its containment tank; there will be no damage

caused from an LNG. In contrast, if a fire source is present, LNG is released and fuels the fire, and the pressure relief devices & ESD system fails to function; the worst-case scenario is an explosion of the LNG tanker.

Therefore, the first basic strategy to prevent the adverse outcome from this LNG tanker truck collision is to ensure that the whole systems, including the associated equipment are well functioned and matched with the current LNG safety standards (e.g. containment system consists of a double-walled tank with a combined vacuum and insulation system). This method can be considered as reactive methods.

The effective strategy is to maintain a balance between the reactive and proactive methods. For example, regular inspection and maintenance. However, the safety researchers agree that a reliable strategy to prevent the LNG truck accident is a well-trained driver. Hence, the extensive safety education should be regularly provided to both experienced and novice drivers to reduce the LNG truck accident and increase their awareness of the risk.

From this critical risk, the truck drivers are most likely to get injured. In order to protect them, two intervention technologies are proposed: fire-retardant truck cabins and self-driving truck. However, both of them cannot guarantee zero accidents of LNG tanker truck: only enhance the safety of the truck driver but the risk remains. Therefore, this suggestion is not right methods to deal with the critical risk.



# Chapter 7 : VALUES

## 7.1 Introduction

According to Willoughby (1990), different values lead to different outcomes, the most dominant values amongst various values which influence the decision making of people will also influence the future of LNG transportation chain.

In order to discuss the possible future directions of LNG transportation chain, the most dominant values from RAMSHEEP (Wagner & Van Gelder, 2013), will be assessed. In order to assess these values, ‘reasoned and weighted average on the basis of stakeholder and expert judgement’ will be considered. Based on this judgement, finally, the most efficient and effective value choices which lead LNG transport chain to safety and sustainable future will be recommended.

## 7.2 Value assessment of LNG transportation chain

There are five steps to assess the dominant value(s) of the LNG transportation chain: (1) stakeholder analysis; (2) individual stakeholder’s values assessment; (3) values combination result; (4) conclusions; and (5) bridging between values and the critical risk.

### 7.2.1 Stakeholder Analysis

In this section, stakeholder analysis is conducted. The stakeholders’ characteristics, goals, interests and values on the LNG transportation chain are studied. After that, the RAMSHEEP value comparison between each group of stakeholders is analysed and discussed.

#### 7.2.1.1 Identification of the relevant stakeholders

According to the interviews, all stakeholders agreed that participation of the relevant stakeholders plays very important role in the development of LNG transportation business. In the following table, in-depth study is taken on how each stakeholder has goals, interests, and values on the LNG transportation.

In this thesis, the internal stakeholders are identified as LNG private company (i.e. import terminal, truck transportation, filling station, LNG equipment supplier, and consultants), while the external stakeholders are the government and academic institutions, and the citizens. The internal stakeholders can be considered as the major influencing stakeholders of this LNG chain; they directly invest their resources (e.g. experience, finance, labor, knowledge) to operate the LNG transportation operations and facilities. In return, they get direct benefits from this business. These internal stakeholders usually cooperate with each other. While external stakeholders are affected by the LNG operations, but they can influence the LNG in term of its operation performance

(Albrecht, 2015). The success of LNG transportation business and LNG as a fuel use also depends on the external stakeholders.

#### 7.2.1.2 Identification of the stakeholder's goals, interests, and values

In this section, interests, and goals for each stakeholder of the LNG chain from the list of interviews [see Appendix D] is examined and explained in the following table:

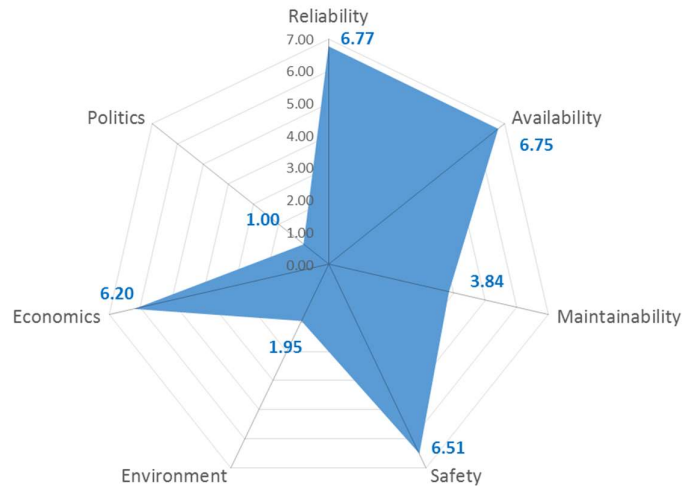
**Table 4: Interests and goals of stakeholders**

Stakeholder group	Organization	Interest	Goal
Private company	LNG import terminal	<ul style="list-style-type: none"> <li>Ensuring the safe operations</li> <li>Providing the reliable and available service to customers</li> </ul>	Increase the user base of LNG products and the reputation of the organization
	LNG tanker truck	Ensuring the high degree of safety of the LNG truck transportation while providing a competitive and reliable service	Increase the user base of LNG as fuel and the reputation of their company
	LNG filling station	Ensuring the high degree of safety and availability of LNG fuel at a competitive price	Increase the user base of LNG as fuel and the reputation of their filling station
	LNG equipment supplier	Supplying products that have a high degree of safety and reliability, that can enhance their reputation in the market	Increase their international reputation among their customers
	LNG consultancy	Providing a high reliable consultancy service	Increase their international reputation among their clients
Government and academic institution	Academic institution	Enhancing the knowledge to maintain sustainability concept which is a balance between people, planet, and profit	<ul style="list-style-type: none"> <li>Strong partnership with the industry</li> <li>Exchange of knowledge</li> </ul>
	Government organization	Ensuring that LNG operations are environmentally friendly and safe for its citizens while ensuring the well-being of all people	<ul style="list-style-type: none"> <li>More employment opportunities</li> <li>Ensure that LNG companies respect the safety regulations and standards</li> </ul>
Citizen		A reliable source of energy that is highly safe, affordable and available at all times.	Ensure that the government provides the cheap energy source

## 7.2.2 Individual stakeholders' values assessment

From the value interviews, the stakeholders were asked to score each value of RAMSHEEP from the most important to the least important [see C.3]. The results from each stakeholder were calculated and were grouped in average regarding their own value perspectives. The three radar charts which resulted from the three groups of LNG stakeholders are shown below:

### 7.2.2.1 Values of private company stakeholders

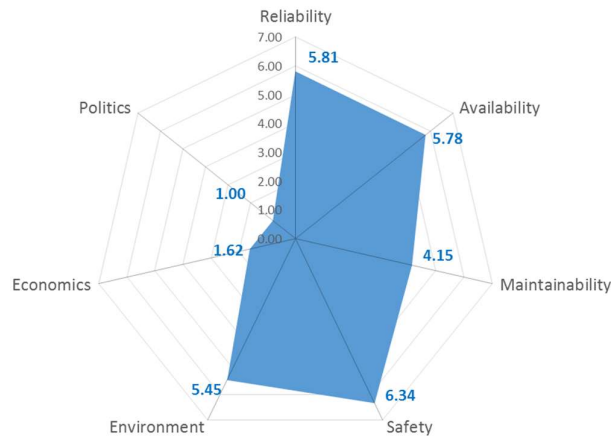


**Figure 11: Value ranking of private company stakeholders**

From Figure 11, the value perception of the private organization group was analysed. In this group, the value perception in descending order was found to be reliability, availability, safety, economics, maintainability, environment, and politics.

The score of reliability which ranks as the first most important value is very close to the second rank of availability value. Therefore, they both can be considered as the first rank. Also, from the result, it was observed that the economics value was ranked as the fourth. This was surprising because the general notion is that for a private company profit should be the most important value. However, most of the private company stakeholders clarified during the interviews that the LNG transportation has unique hazard characteristics and the LNG market scale worldwide is still small in these current days. High degree of safety, reliability and availability would assure good reputation for their organizations and also increase the competitive capacity at the regional level and international level. In contrast, if a company in this LNG business cannot maintain the levels of safety, reliability, and availability; it could be devastated by the loss of reputation.

### 7.2.2.2 Values of government and academic institution stakeholders

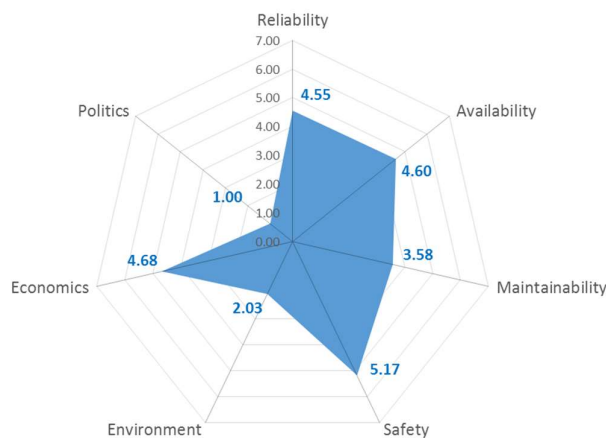


**Figure 12: Value ranking of government and academic institution stakeholders**

From Figure 12, the value perception of the government and academic institution stakeholders were analysed. In this group, the value perception in descending order was found to be safety, reliability, availability, environment, maintainability, economics, and politics.

For the government and academic institution stakeholders, the degree of importance can separate into two groups. The first group includes the five values of safety, reliability, availability, environment, maintainability, and the second group includes economics and politics. In this sense, the government and academic institution stakeholders primarily considered the impact of LNG operations towards the society (well-being of human and environment) and after they considered the prosperity which is a consequence of the LNG business operations.

### 7.2.2.3 Values of citizen stakeholders



**Figure 13: Value ranking of citizen stakeholders**

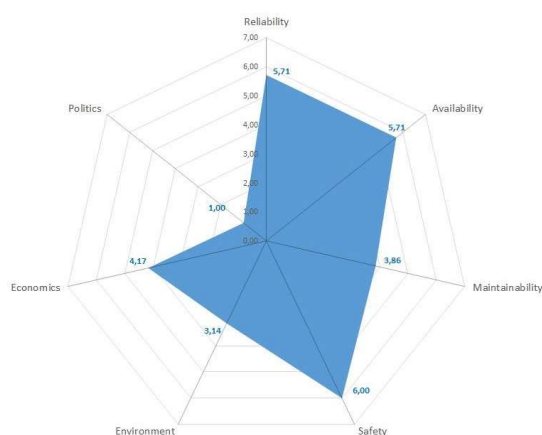
From Figure 13, the value perception of the citizen group was analysed. In this group, the value perception in descending order was found to be safety, economics, availability, reliability, maintainability, environment, and politics.

For the citizen stakeholders' views, the safety of LNG comes first then the economics value. They clarified these results that although, affordable price of fuel is important for them, but safety has to come first. After that, they would consider the reliable and available of this fuel.

### 7.2.3 Values combination result

From the above three value radar charts, it can be observed that the value perception of the private group and the citizen group have the similar shape, although the value ratings and the area occupied by the private group in the value radar chart are much higher. Secondly, the right-most sector of the value radar chart occupied most of the area. Finally, the value perception ratings of the government and academic institution stakeholders were in the similar order as the private company stakeholders, but their ratings for economics value was comparatively very low.

However, the average results from every stakeholder are shown in the radar chart below:



**Figure 14: Average value results from all stakeholders**

From Figure 14: Average value results from all stakeholder, we can see that for the overall safety, whose score is 6 out of 7, is the most important value, in other words, the stakeholders considered the safety of LNG as the most important value. The second important value in the LNG transportation chain is reliability and availability<sup>17</sup>. Since these two values have the same score of 5.71, they will be analysed together. The third rank is economics value<sup>18</sup> with a score of 4.17 and

<sup>17</sup> Although reliability and availability share the same ranking of importance, the relation of the reliability of an equipment with its availability (or vice versa) did not affect the ranking

<sup>18</sup> The term of economics value here directly relates not only to the profit of their organizations, but also to the purchasing cost of activity or equipment which involve with LNG.

followed by the maintainability as the fourth with a score of 3.86. The other values like environment and politics, comparatively have as a second grade of importance as per the stakeholders. The individual value is explained below:

Firstly, safety is ranked as the first and foremost important value. Not only private organizations but also both the government and academic institutions, and the citizens believe safety is the key for the LNG operations. Since the loss of safety will damage the current public perception of LNG and the future prospects of LNG use. This result is matched with safety reports from U.S. Department of Energy (2012) and Drube, Haukoos, Thompson, & Williams (2012) which indicates that ensuring high levels of safety value is a very important factor to influence the acceptance of LNG as an alternative transportation fuel for the future.

Secondly, the two values of reliability and availability are of second most importance for the stakeholders. Moreover, these two values of reliability and availability were found to go together. For example, for the private organization group: the capability of ESD system to detect and stop the spillage from LNG carrying pipeline when LNG spills is referred as reliability and the presence of ESD on that particular pipeline when this spill occurs is referred to as availability. For the end-user group, this value meant that the LNG fuel was reliable and available.

Thirdly, the economics value is ranked. Although the definition of ‘economics’ was clearly written and informed before [see C.3]; the different stakeholders tended to interpret the meaning of economics value differently and individually. According to the stakeholders, their own interpretations of the economics value help them form a reasonable and rational choice when ranking. Each stakeholder group interprets the economics value differently as:

1. The private company stakeholders interpreted the economic value as cost of LNG related equipment and operational activities and profit that their organizations would gain the LNG business. Even though economics is cost of equipment, it affects the procurement of better equipment. The procurement of better equipment leads to higher profits in terms of higher uptime, lower losses, lesser litigations etc.
2. The government and academic institution stakeholders mostly considered economic value as social benefits and impact (e.g. well-being, prosperity) from this LNG business unit.
3. The citizen stakeholders are likely to refer the economic value as the price of LNG fuel.

Moreover, it is important to note that the ranking of this economics value is significantly traded off with the other values. For example, the private company stakeholders consider that if safety, availability, and reliability are leading to higher cost, the overall cost of the operation would increase and lead to losing to competitors. Thus, decision making with economics value as the central theme leads to losing on safety, availability, and reliability of the LNG transportation chain according to all stakeholders.

Fourthly, the maintainability is ranked. This means that the interviewees prefer an LNG activity or LNG fuel that it safe, reliable& available, economical, and then easily maintainable.

The fifth important value is environment. The most of the stakeholders realized that the damage that LNG can do to the environment is primarily due to its cryogenic property. For example, when LNG spills, it can freeze the nearby flora and fauna. The relatively lower rating of the environmental damage is not because the stakeholders are insensitive towards the environment but because they understood that a high safety system of LNG operations will automatically ensure safety to the environment.

Finally, the interviewees were found to be politically rational. For the private company stakeholders, they considered their LNG operations as highly professional. Political irrationality, that could occur referred to corruption, for example, the payment of bribe or the usage of personal influence to procure equipment or activity was found to be unlikely. This is because of transparent procurement processes with clear specifications. This has ensured that only reputed suppliers can fulfil these orders. Moreover, transparency has also ensured competition which helps to buy the best product for the best price. The government and academic institution stakeholders, and the citizen stakeholders also mentioned that the political sanction of LNG business has not yet occurred for both regional and international levels, the normal market force is in play.

However, although the average ranking result shows that the safety value is the most important value, selecting only the top important values cannot guarantee sustainable future of the LNG transportation chain. Moreover, it can lead to the situation of values conflict [see 3.3.3]. In order to deal with this conflicting values, the ethical principles of the ‘reasoning about values’ approach should be considered.

Besides the reasoning approach, the ‘value sensitive design’ approach can also be applied in this section. According to van de Poel & Royakkers (2011), the value sensitive design approach can lead to new technical innovations. This approach integrates both the important values of stakeholders and the ethical principles. Therefore, the new innovation derived from the value sensitive design approach together with the reason about values approach will lead to the sustainable LNG transportation chain in the future

#### **7.2.4 Conclusions: reasoned and weighted average judgement**

From the previous section, we can clearly separate these seven values into two groups. The first group consists of safety, reliability, availability, economics, and maintainability which stakeholders considered as more important than the second group which consists of environment and politics. The first important value group (safety, reliability& availability, economics, and maintainability) is considered to be the influencing factors for the future of LNG. This shows that going forward research and development would be oriented towards the development of equipment or operation which are very safe, reliable, and available but less costly making it more economically viable. Therefore, the trend in the future of the LNG transportation chain would be to make highly safe and less costly equipment, activity, and LNG price.

However, the ‘weighted average judgement’ is not only applying method, but also the ‘reasoned on the basis of stakeholder and expert judgement’ is considered in this thesis. According to the three ethical principles, the environmental-friendly LNG equipment/operations, as well as

the reliable operation and available of the LNG fuel which are the important values of the citizens, should be also added.

## **7.3 Discussion and recommendations**

### **7.3.1 Bridging between values and the critical risk**

Since different stakeholders weight values differently, the stakeholders also determine the importance of a particular risk unequally. This is due to the subjective assessment of a risk based on a stakeholder's values (Slovic, 1992). In other words, a particular risk is important or not depending on the values which are the most influencing value in stakeholders' minds.

The important values of each group of stakeholders [see Table 4] are consist of (1) safety value and economics value for the private companies; (2) safety value and environment value for the government and academic institutions; and (3) reliability value and availability for citizens.

As aforementioned, the critical risk in the LNG transportation chain is the Collision of LNG tanker truck while riding. Due to the different values, the three group of stakeholders are likely to see the important of this critical risk differently. The important of the critical risk base of the values of each stakeholder are explained below:

First, the private companies are likely to pay attention to the critical risk. Since the safety value is directly impacted to the economics (profit) value; the private companies will attempt to prevent the occurrence and mitigate the severity of the critical risk (also other risks). If the LNG transportation chain can ensure the high level of safety, the use of LNG will be more attractive and less public resistant and eventually lead to an increase in profits of the LNG-related companies (Woodward & Pitbaldo, 2010). Therefore, they are likely to have a high concern regarding the occurrence of the critical risk.

Second, the government and academic institutions are also likely to pay attention to the critical risk. Since safety and environment are their core values, the occurrence of risks will not only lessen the safety values but also lower the environment values. For example, the consequences of the collision of the LNG tanker truck (also other risks) will directly damage the environment and indirectly reduce credit of LNG safety performance. This can turn the people to use other fuels like petrol or diesel which has more harmful pollution to the environment than the LNG. Therefore, the risk has a negative affect to the government and academic institutions' goals.

Finally, the citizens are unlikely to pay attention to the critical risk. Since their value is the reliability value. They are more likely to see that LNG is a fuel which needs a reliable transportation (predictable and stable) and available when they want to use it (not prone to outages). The risk of LNG transportation chain is probably not an urgent concern for the citizens.

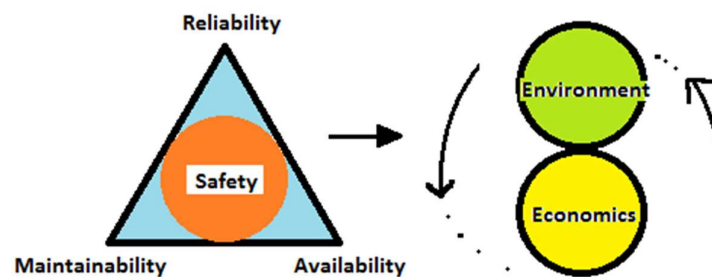
To summarize, the critical risks are important for the private companies and the government and academic institutions since one of their core values is safety. However, the critical risks are less important for the citizens since their core values are reliability and availability.



### 7.3.2 Value integrity: proposition for the future sustainable LNG

In the future, it is important that LNG transportation operation should be sustainable. A sustainable operation is not limited to a value like safety but also considers multiple values. According to Zongwei (2013), there are four values which we cannot only separate and consider them one by one. They are reliability, availability, maintainability, and safety. In fact, they should be considered as a whole because the absence of one value will lead to abnormalities, especially in the operational system, and their related equipment. These four values correlate to each other and supported each other to ensure quality and performance in the efficiently and safety way. Stapelberg (2009), also point that the relation of reliability, availability, maintainability, and safety is important because “these variables are concerned with equipment *usage* or *application* over a period of *time*, the *accessibility*, and *reparability* of the system’s related equipment in the event of *failure*, and the system *load* and *strength* distribution. As a consequence, neither design nor performance should be considered in isolation” (Stapelberg, 2009).

Therefore, their collective enhancement will help to prevent any undesired events in the LNG transportation chain. This collective enhancement is referred as value integrity. Value integrity is proposed to help make the future of the LNG transportation chain sustainable.



**Figure 15: Proposition of value integrity for sustainable LNG transportation chain**

From Figure 15, we can see that three values of reliability, availability, and maintainability are present as a triangle because they always complement each other. The focus of this triangle is safety value. The balance of these four values will positively affect the environment as well as the economics. Although the stakeholders ranked the environment value less important than the above mentioned five values, for sustainable future we cannot compromise the environment with economics (or any values). Therefore, both the environment and economics values are represented as two equal circles that always support one another.

This proposed values can responsibility support the sustainable of LNG transportation chain.

## **7.4 Conclusion**

In this section, it is attempted to answer the research questions relating to this chapter

### **7.4.1 What is the dominant values aspect in the LNG transportation chain?**

According to the LNG stakeholders' rankings, the most dominant value are listed in descending order of safety, reliability & availability, economics, maintainability, environment, and politics. These values were found to be related to each other and all values are related to the safety values. The reliability and availability values have been found to be tightly correlated with each other. Maintainability helps keep the equipment functional: reliable, available and safe. Therefore, reliability, availability, and maintainability can form a triplet that has a central focus on the safety value.

### **7.4.2 How can these dominant values influence the future of the LNG?**

From 7.2.4, the entire order of values can also be separated into two groups. The first group consists of safety, reliability, availability, maintainability, and economics. The stakeholders considered the five values in the first group important that the second group which consists of environment and politics. The first group is important since it is considered as the influencing values to the future of LNG. For example, future of the LNG transportation chain is likely to be developed an equipment which is safe, reliable, available, and at the same time economically viable.

However, it is important to note that the development of the LNG transportation chain should be sustainable. In order to obtain a sustainable chain, multi-values should be integrated [see Figure 15]. Since this multi-value integrity derived from the important values of every stakeholder, it can help reduce the value conflicts among the different stakeholders in the future of the LNG transportation chain. Therefore, the concept of value integrity is important to ensure a sustainable future for LNG.

### **7.4.3 How important are the critical risks for the stakeholders on the basis of their values**

This importance of different risks is due to the subjective assessment of a risk based on a stakeholder's values (Slovic, 1992). In other words, a particular risk is important or not depending on the values which are the most influencing value in stakeholders' minds.

The important values of each group of stakeholders [see Table 4] are consist of (1) safety value and economics value for the private companies; (2) safety value and environment value for the government and academic institutions; and (3) reliability value and availability for citizens.

To summarize, the critical risks are important for the private companies and the government and academic institutions since one of their core values is safety. However, the critical risks are less important for the citizens since their core values are reliability and availability.

# Chapter 8 : CONCLUSION AND RECOMMENDATION

This chapter consists of three parts: conclusions, reflections, and recommendations. The conclusions are linked below to the research and sub-research questions [see 1.6]. Please note that the research question(s) do not always correspond to a particular chapter but are often derived from multiple chapters. The reflection and recommendations are based on the conclusions of this thesis.

## 8.1 Conclusion

### 8.1.1 Sub-research question 1

How does a major of LNG accident in the LNG transportation chain occur?

According to Ale et al. (2009), a major accident cannot be attributed to a single factor. This is also true for major accidents in the LNG transportation chain. Although the LNG transportation chain is safe, a major accident can still occur due to the combination of the following four factors:

1. Operational failure
2. Amount of LNG release
3. Failure of instrumentation system (including ESD system)
4. The presence of an ignition source

These factors are interrelated and for a major LNG accident to occur these four factors must occur together.

### 8.1.2 Sub-research question 2

- What are the major causes/consequences of LNG accidents?
  - How can those accidents be mitigated?

Most accidents in the LNG transportation chain occur due to leakage of LNG from its containment or due to failure of the LNG loading system. For causes of the LNG accident, if procedural and human errors are both regarded as ‘human factors’, then throughout the LNG transportation chain, ‘human factors’ are a major cause for accidents. If considered separately, procedural errors have a greater proportion than human errors except for the import terminal phase; these procedural errors form the greatest proportion in the cause for accidents. Major consequences of LNG accidents are damage to the operational and instrumentation equipment, the creation of fire, and a human injury respectively.

For mitigating the LNG accident, procedures and regulations should be firstly improved. Improving procedures mean enhancing safety awareness and safety knowledge. Moreover, better

procedures can mitigate an accident due to less procedural error and human error. Secondly, a major cause besides human factors is equipment or instrumentation failure. This can be mitigated using good quality equipment, which happens to be also a major cause of accidents. Regular inspection of equipment (which is a procedural factor) can also help mitigate these accidents.

Like accidents are not caused by a single factor, in the same manner, accidents cannot be prevented by a single measure. In other words, to prevent an accident a number of measures must be taken together.

### **8.1.3 Sub-research question 3**

How can the regulations be improved to ensure LNG operational safety?

The LNG regulations are also very new (as recent as 2015) and comprehensive. However, because of loopholes and variation in interpretation, only regulations will not ensure operational safety. For ensuring safety, a continuous dialogue must be encouraged amongst the various stakeholders, so that they have a consistent understanding and implementation of the regulations. This can be achieved by focus groups, training sessions, feedback sessions and iterations in the regulations among all the stakeholders. Special attention needs to be paid to road transportation since a road accident is the most critical component of the LNG transportation chain.

### **8.1.4 Sub-research question 4**

Which mitigation measure is the most important to prevent LNG hazards?

LNG systems are robust and built globally with high technological standards. In this thesis, over the entire LNG transportation chain, it was found that transportation over the road should receive the highest concern. This concern arises from the presence of many unpredictable and uncontrollable factors leading to the occurrence of a hazard. Amongst all the possible mitigation measures, the ESD system was found to be the most important safety component in the various LNG systems. This mitigation measure system is not critical only at the terminal but also at the filling station and LNG tanker truck transportation. If everything else fails and the ESD system is still working, a major accident can be averted. Thus ensuring the ESD system works using the highest building and functioning standards are paramount.

However, as discussed previously for complete system safety, mitigation measures must be complemented with (multiple) other mitigation measures.

### **8.1.5 Sub-research question 5**

How can the individual risk perceptions be explained?

According to Boholm (1998), the concept of risk can be applied to individual psychological constructs (human mind and human values) which are influenced by various factors, such as psychological factor. Therefore, to understand how people understand risk is to understand risk

perception (Sjöberg et al., 2004). And to understand risk perception is to find out what factors influence people's (risk) perceptions. Three possible influencing factors that were applied in this thesis are shared safety knowledge, and the controllability and availability heuristics.

Firstly, the shared knowledge of LNG safety (e.g. through education or training) in the professional culture of the interviewees' organizations are expected to be comparable. Since the LNG-community is considered both small and tight with regular interactions, their work requires them to have a high safety knowledge of and expertise with LNG. This safety knowledge includes shared values amongst the interviewees' organizations which are influencing factor of the interviewees' risk perceptions.

Secondly, regarding the shared safety knowledge in the assurance of LNG safety systems, the interviewees also shared the same sense of controllability. From the sense that they are in control, their risk perceptions regarding the probability of accident occurrences are considered as small (Sjöberg et al., 2004). This sense of controllability is considered as influencing factor since the interviewees' estimations in the probability levels is smaller than the severity level and these estimations have the conformity as the literature.

Lastly, the higher severity levels from the interviews compared to those from the literature can be explained by the influences of historical data. According to Sjöberg et al. (2004), the approach in which people use available information that they can recall and use to estimate the risk is called availability heuristic. Therefore, the availability heuristic is considered as the influencing factor for their risk perceptions.

#### **8.1.6 Sub-research question 6**

- What is the dominant value aspect in the LNG transportation chain?
  - How can these values influence the future of the LNG?

According to the LNG stakeholders' rankings, the most important values are listed in descending order of safety, reliability & availability, economics, maintainability, environment, and politics. These values were found to be related to each other and all values are related to the safety values. The reliability and availability values have been found to be tightly correlated with each other. Maintainability helps keep the equipment functional: reliable, available and safe. Therefore, reliability, availability, and maintainability can form a triplet that has a central focus on the safety value.

The entire order of value can also be separated into two groups. The first group consists of safety, reliability, availability, maintainability, and economics. The stakeholders considered the five values in the first group important that the second group which consists of environment and politics. The first group is important since it is considered as the influencing values to the future of LNG. For example, future of the LNG transportation chain is likely to be developed an equipment which is safe, reliable, available, and at the same time economically viable.

However, it is important to note that the development of the LNG transportation chain should be sustainable. In order to obtain a sustainable chain, multi-values should be integrated [see Figure 15]. Since this multi-value integrity derived from the important values of every stakeholder, it can help reduce the value conflicts among the different stakeholders in the future of the LNG transportation chain. Therefore, the concept of value integrity is important to ensure a sustainable future for LNG.

#### **8.1.7 Sub-research question 7**

How important are the risk for stakeholders on the basis of their values?

This importance to different risks is due to the subjective assessment of a risk based on a stakeholder's values (Slovic, 1992). In other words, a particular risk is important or not depending on the values which are the most influencing value in stakeholders' minds.

The important values of each group of stakeholders [see Table 4] are consist of (1) safety value and economics value for the private companies; (2) safety value and environment value for the government and academic institutions; and (3) reliability value and availability for citizens.

To summarize, the critical risks are important for the private companies and the government and academic institutions since one of their core values is safety. However, the critical risks are less important for the citizens since their core values are reliability and availability.

#### **8.1.8 Sub-research question 8**

Which is the most critical risks for the whole transportation chain?

Results from both the LNG expert interviews and the literature review agreed that throughout the LNG transportation chain, the critical risk is the collision of LNG tanker truck with the other vehicles while riding.

#### **8.1.9 Main research question**

How to deal with the critical risks in the LNG transportation?

The critical risk in the LNG transportation chain is a Collision of LNG tanker truck while riding. From the historical accident, causes of the LNG tanker truck collision are mainly from human negligence. However, if the LNG is not leaked from its containment tank and no fire present, there will be no damage caused from LNG. In contrast, if a fire source is present, LNG is released, and the control & ESD system fails to function, the worst-case scenario is a fire which can lead to an explosion of the LNG tanker.

Therefore, the first basic strategy to prevent the adverse outcome from this LNG tanker truck collision is to ensure that the whole systems, including the associated equipment are well

functioned and matched with the current LNG safety standards (e.g. containment system consists of a double-walled tank with a combined vacuum and insulation system). This method can be considered as reactive methods.

The effective strategy is to maintain a balance between the reactive and proactive methods. For example, regular inspection and maintenance on the LNG tanker truck and the containment systems. However, the safety researchers agree that a reliable strategy to prevent the LNG truck accident is a well-trained driver. Hence, the extensive safety education should be regularly provided to both experienced and novice drivers to reduce the LNG truck accident and increase their awareness of the risk.

From this critical risk, the truck drivers are most likely to get injured. In order to protect them, two intervention technologies are proposed: fire-retardant truck cabins and self-driving truck. However, both of them cannot guarantee zero accidents of LNG tanker truck: only enhance the safety of the truck driver but the risk remains. Therefore, these intervention technologies are not the exact methods to deal with the root cause of this critical risk.

## **8.2 Reflection**

### **8.2.1 LNG risk study**

#### **8.2.1.1 Risks study from expert judgement: cognitive Bias**

Due to the fact that LNG transportation operation is new, the literature is not extensive. Therefore, interviews from LNG expert had to be relied on to gain relevant information. However, even if these experts, have in-depth knowledge in LNG field, they have a cognitive bias. Since we have already discussed that risk perception is an individual cognitive process which can be influenced by many factors e.g. bias and heuristic.

This cognitive process has already explained the rank of the severity of LNG accidents higher by the interviewees than the literature. This was due to heuristic process, the interviewees recalled their memory of the accidents with catastrophic consequences and rated their severity higher compared to accidents that have not occurred yet. Despite, the fact that if they did occur, they would have the same severity level.

Therefore, experts exhibit the same types of biases as lay people with respect to perception of risk. The experts are vulnerable to many of the same biases as lay people. The contributions from the risk study in this thesis may then be combined with considerations of subjective perceptions of risk and value judgements in the decision making process.

#### **8.2.1.2 Risk Study from Literature: Experimental error**

While the individual risk perception could contain bias error, in the literature, engineering calculation could also contain experimental error. For the severity and probability levels some from literature, strict calculations and measurements have been performed. For example, according to

Woodward & Pitbaldo (2010), the experimental calculation for the probability of LNG spill is divided into 3 scenarios according to the size of hole as:

1. The probability of LNG spillage as  $<10$  mm. diameter hole
2. The probability of LNG spillage as  $\geq 10$  mm. diameter hole
3. The probability of LNG spillage as  $\geq 50$  mm. diameter hole

The probability and severity levels resulted from this strict measurement could be underestimation or overestimation since the real accidents of LNG spills do not always have the same hole diameter hole like in the experiment. Therefore, experimental errors could be present. To have a realistic assessment, a range of tolerance should be included in the experiment.

## **8.2.2 Technical Study**

### **8.2.2.1 Guaranteed Safety System**

To guarantee the safety of LNG means looking into the whole system, not only the particular equipment. The whole system comprising of management, operator, procedure, LNG containment etc. must be included.

### **8.2.2.2 More training to the end-user**

Regarding the critical risk (regarding accidents on the road) one main cause of the accident is human error. Although the LNG tanker truck drivers were found to be well-trained professionals, accidents can still occur. This same concern was shared by the interviewees. However, the interviewees were more concerned on the LNG end-users i.e. the LNG-fuel vehicle drivers (i.e. truck, bus). Although the riding accidents of the LNG end-users are out of scope, it is worth to note here that these LNG end-users are less trained, despite requiring same competence as the LNG tanker truck drivers to guarantee the safety. One way of solving this problem would be to change the criteria for acquiring the LNG-fuel vehicle driving license. The criteria should include propagating LNG safety knowledge and passing mandatory training sessions. This can help increase their competence to deal and prevent a possible accident. With the growth of a number of LNG fuel-vehicles in the near future, increasing their competence is urgent.

Regarding the critical risk, human error is a major cause of accidents too. Despite, the LNG tanker truck drivers working in a controlled phase (they are well-trained professional tanker truck drivers), accidents can still occur.

## **8.2.3 Value and the future of LNG transportation**

### **8.2.3.1 Value Study from LNG Expert: Safety is dominant value**

The interviewees were all LNG safety experts, hence, a bias towards the value of safety is expected. If the interviews are conducted on the various field of expertise, for example, procurement engineering, quality engineering, and LNG drivers/operators; the results could be different.



### **8.2.3.2 Culture Difference: Interviewees were mainly Dutch**

The LNG experts were mainly Dutch nationals, except three Thai nationals. Hence, the value views were mostly EU-centric. Moreover, the Netherlands is becoming a technology and safety pioneer in the LNG sector. This technological and national culture could influence the result of interviewees' value aspects in which safety is the first important value and politics is the least important value. However, when interviewing a Thai, the interviewee mentioned about the possible ranking of political value higher than one compared to the definitive low ranking by the Dutch. The observation here is that deep down people in different cultures have different values. Therefore, the absence of other global players prevents a holistic and a deep understanding of value perspectives in this thesis.

### **8.2.4 Difficulty**

#### **8.2.4.1 Thesis scope and 61 accident scenarios**

The scope of this thesis was very large. The entire LNG transportation chain is not only very extensive but also very difficult to assess and evaluate. These difficulties are partially caused due to the lack of scientific literature in this field. Moreover, the breadth of this LNG chain led to a high number of accident scenarios which were complicated and difficult to analyse. Furthermore, to have the proper risk study of the whole LNG transportation chain, all possible accident scenarios had to be considered. If all of these potential accident scenarios would not have been considered, the report would have been incomplete. An incomplete analysis would have led to the wrong comprehension of the reality of risk and safety in the entire LNG transportation chain.

In reflection, if I would have limited my scope in just one phase of the LNG chain, I could have finished this thesis earlier with the less anxiety. The same reflection is true regarding the value aspect of the entire chain. A smaller scope would have led to a lesser amount of interviewees and quicker completion of this thesis.

#### **8.2.4.2 Adequate time is required for safety analysis**

To perform an adequate safety analysis throughout LNG transportation chain, finding the probability and severity levels of 61 accident scenarios should include all external and internal experts (e.g. lay people, a private organization, government and academic institutions). Moreover, this requires adequate time to communicate the result with the stakeholders such as general public, the neighbors of a particular LNG establishment and the authorities concerned. Therefore, for an efficient LNG safety study, a long time period is required.

#### **8.2.4.3 LNG tanker truck/train and LNG filling station are new developments**

Due to the recent implementation of LNG tanker truck/train and LNG filling station, finding the literature related to these phases is difficult. Another difficulty encountered was securing field visits and interviews with LNG experts.

#### **8.2.4.4 No study of the internal value in LNG**

It is considered very important that the involved operators, both onboard vessels and in terminals, are trained to a sufficient level in order to maintain the safety record for LNG handling. It is recommended that the training requirements for all actors in the LNG chain (crews on both LNG bunker vessels and on gas fueled vessels, bunker operators, port authority etc.) be reviewed and if needed, changed in order to meet the different levels of requirements that may arise from the different types of handling of LNG that is anticipated as a result of per the different usage of LNG in the different phases of the LNG transportation chain. The review could also include an estimation of the possibilities to achieve a certain level of training among a sufficient amount of personnel within a reasonable timeframe.

### **8.3 Recommendation for the future study**

In this section, recommendations for future study are presented:

#### **8.3.1 More interviewees**

Although there is no evidence about a culture of information opacity or hiding in LNG transportation field which will make the information erroneous, the small sample size interviews may have the problem of information error too. Therefore, the future research is recommended with a large sample size for both risk and internal value assessments.

Moreover, interviewing the LNG experts in different knowledge branches, which consists of employees from various expertise (e.g. procurement, management, operations, government and academic institutions), is also recommended. A larger sample can help to obtain a holistic understanding of risks and values in the LNG transportation chain.

#### **8.3.2 Unknown risk for LNG tanker truck/train and filling station**

Among the three phases of the LNG transportation chain, the second phase of LNG transportation by tanker truck/train and the third phase of LNG filling station have just started operations<sup>19</sup>. Therefore, they can possibly cause an unexpected accident scenario or unknown adverse outcomes which may badly harm the public more than the currently defined scenarios. Therefore, further future research in these two phases will greatly contribute to increasing the safety of the LNG transportation chain.

#### **8.3.3 Increasing efficiency of regulations in practice**

Currently, the rules and regulations for assuring safe LNG transportation are not consistent internationally. For example, safety regulations about the type of wall of LNG tanker truck are still different in EU countries. Some countries allow the single-walled tank to use for LNG tanker

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<sup>19</sup> The literature related to these LNG tanker truck/train and LNG filling station have just published in this recent five years, especially during 2013-2015. Therefore, it can be implied that these two phases implementations are new.

trucks. However, regarding recently EU regulations, this single-walled can only drive in their countries, crossing the international borders is not allowed. But nothing can guarantee this in practice. Such concerning issues regarding the efficiency of safety standards implementation in LNG tanker truck transportation and filling station phases have been mentioned during the interviews. For example, some LNG filling stations have not yet followed the safety standards and requirements for LNG equipment. Thus, stringent controlling and monitoring methods need to be implemented. Therefore, to increase the efficiency of regulations in practice, stringent controlling and monitoring methods need to be implemented.

#### **8.3.4 Study on the traffic regulations to prevent the critical risk**

Further research is needed into the difference in regulations across EU especially regarding speed limits, training of drivers, communication means, and signal. The impact of these different international regulations on the safety of LNG road-transportation must be analyzed. Furthermore, strategies must be proposed to increase harmonize and increase the efficacy of these regulations.

#### **8.3.5 Culture**

In this thesis most of the interviewees were either Dutch or Thai. Although this gave some insight into their different cultural attitude towards risk and safety in the LNG transportation chain, it was not enough. To obtain a greater holistic understanding of the attitudes of different cultures, it recommended to study more cultures in detail. It is also recommended to involve affected stakeholders across the LNG transportation chain.

#### **8.3.6 Values**

The primary focus of this research was on risk and safety. It is recommended to further research on the values. This is important because unlike risk which can be (often) objectively measured, values are very difficult to measure objectively. If the values influencing the LNG transportation chain can be determined and predicted, it can also determine the trends of LNG safety. For instance, if economics is the influencing value and it correlates with compromising safety (due to substandard products), then we can determine that in the future safety will be compromised and accidents will occur.

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## **APPENDICES**



## Appendix A. Gate Terminal Field Report

### A.1 Introduction

On 3<sup>rd</sup> June 2015, I got a chance to visit Gate terminal, the first LNG import terminal in the Netherlands. Gate terminal is located on Maasvlakte in Rotterdam. The main functions of the terminal are receive, store, re-gasify, and transfer LNG.

My visiting objective was mainly to interview Linard Velgersdijk, SHEQ Advisor of the terminal. I consider this visit as an important step in taking my thesis forward as it helped me to see the real operations happening on a daily basis at the LNG terminal. This enabled me to think beyond the boundaries of literature and visualize the operations more clearly and get an understanding on how it would work in reality. This helped me create a new path for taking my research forward.

The main purpose of this report is to present my observations and analysis for visiting Gate terminal. These observations are generalized to be applicable for risk analysis for LNG import terminals.

In this field report, the following elements will be included:

- Gate Terminal Region
- Facility Description
- Process Description
- Potential Risk Identification

## A.2 Gate Terminal Region



**Figure 16: Gate Terminal area from top view**

Gate terminal is located near the entrance of the Port of Rotterdam. Industrial sites and waterways are within area of 3 km whereas the nearest residential area are around 3.5 km away which is Hoek van Holland. From Figure 16, we can see that LNG unloading area of Gate Terminal consisting of 2 jetties and one island, Zeehonden Beereiland. The island is made to break the waves for the LNG ships when berthing at the terminal. This area is located on a final stretch of land. The storage tanks and regasification plant are located next to oil storage tanks of the Maasvlakte Olie Terminal. Main LNG transportation lines are between jetty and the LNG storage tank.

The terminal starts its role since LNG ship is berthing at jetty. After LNG unloading via unloading arms, it will be transferred through pipeline and be stored in storage tank. Then it will be either sent to regasification process or sent to tanker truck. However, LNG is gas state is not included in thesis scope. Therefore, only operation related with liquid LNG will be considered.

Next section, the main facility (equipment), and process related with liquid LNG transfer process in Gate terminal will be described. This information is the basic knowledge which will help understanding the risk in this LNG import terminal. Also it can help identifying the risk in case of process/equipment failure. However, the facility description here will be limited as per the scope of this thesis (refer chapter 1).

## A.3 Facility Description

Main facility used for transfer LNG from ship to import terminal comprises:

- Jetty
- Unloading Arms (Liquid arm and vapor return arm)
- Storage tanks

### A.3.1 Jetty

The starting place used for unloading LNG in the terminal is jetty. It functions as LNG unloading platform with a concrete deck providing support for piping and equipment. The jetty consists of breasting aid system, mooring load monitoring system to assist in berthing of LNG ship, and an environmental monitoring system. The jetty accommodates with piping, cables and a roadway for personnel access and small vehicles.



**Figure 17: Jetty of Gate terminal<sup>20</sup>**

From Figure 17, it can be seen that the main piping are fireproofed and cover is provided with cold splash protection to concrete and steel structures. This is done because these structures are in the immediate exposure to spills and are critical for the stability of the jetty.

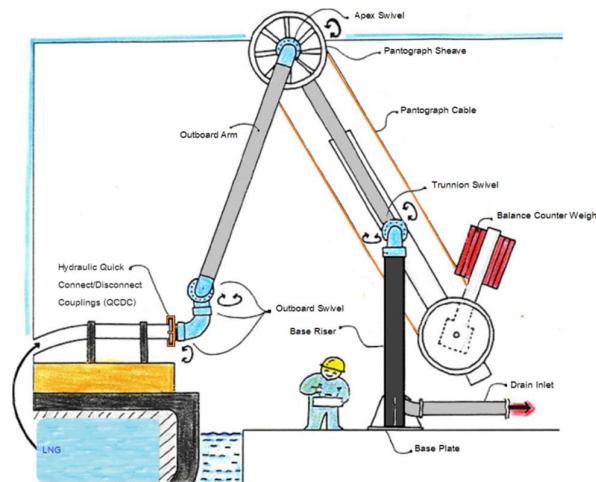
Expected risk scenario at LNG jetty is LNG spill and fire consequence. Thus the structure of jetty is designed to protect pipelines, concrete deck, etc. from failure of LNG spill.

### A.3.2 Unloading Arms

After the ship is moored, LNG will be carried out via the hydraulically operated arms which are installed on the jetty. These fixed arms are an articulated pipe system consisting of rigid piping and swivel joints and can be installed with add-ons such as hydraulic quick connect couplers, position monitoring systems, emergency release systems, and vapor return lines (Balasubramanian, 2011).

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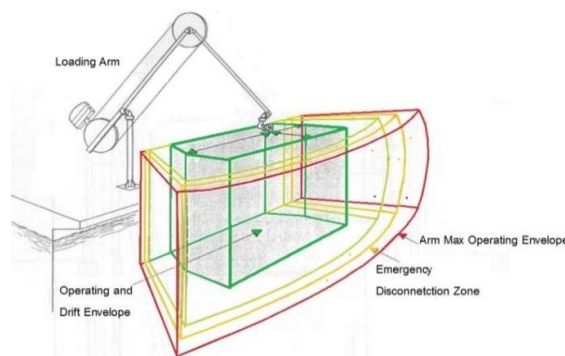
<sup>20</sup> Gate Terminal has 2 jetties with LNG discharge rate of 12,500 m<sup>3</sup>/hour per jetty



**Figure 18: Fixed unloading arm schematic at LNG import terminal**  
(modified from NIIGATA Loading Systems Ltd, 2009).

Usually, a jetty is equipped with two to four liquid arms and one vapor return arm. As in Figure 18, we can see to balance the weight of the piping, a counterweight is needed to reduce the dead weight of the arm on the ships' manifold connection and to reduce the power required to maneuver the arm. Modern LNG arms nowadays use Double Counterweight Marine Arms (DCMA) which are safer than conventional arms, these have an extra safety functionality which prevents the risk of the outer arm to hit ship manifold while disconnection (Lanquetin, 2000).

Due to the dynamics of factors during unloading such as draft, wind, tide, etc; the fixed arm due to its strong structure and flexibility allows it to follow any movement of vessel safely. Compared to flexible hoses, the arms are better suited for large LNG carrier since their symmetric design offers low maintenance service requirement, higher loading rate, and longer service life (Wassink, 2009).



**Figure 19: Working envelopes of a fixed unloading arms operating**  
(modified from Balasubramanian, 2011)

Figure 19 shows three safety levels of working envelopes of a fixed arm which is operated on variations of large tidal and huge vessels. One loading arm employs swivel joints so it is capable to follow the movement of a moored vessel.

The green line represents safe area which the arm can safely operate. The yellow line represents the arm mechanical limit which beyond the safe area due to excessive movement of the ship. The arms need to be disconnected to prevent further damage of the arms and also prevent spillage of LNG during unloading process (Lanquetin, 2000).

Therefore, most of the LNG terminals have quick connect and disconnect system (QCDC) in order to fasten movement and safety in the event of hydraulic failure. The ship and shore flanges are locked mechanically independent of hydraulic power supply. This is done because in case of emergency, the Emergency Shutdown (ESD) can immediately and independently. Moreover, in case of emergency the flanges can break away to prevent further damage of the arms and also prevent spillage of LNG during unloading process.

### **A.3.3 LNG Storage Tank**

The import terminal receives LNG from ship, transfers, and stores it in the LNG storage tank. Here LNG is stored at  $-162\text{ }^{\circ}\text{C}$  to minimize the amount of evaporation with pressure slightly above 1 bar. With evaporation of LNG, the vapor (boil-off gas) will increase the pressure within the storage tank and the temperature will increase too. Therefore, all LNG storage tanks are constructed with thermal insulation to prevent heat transfer, reduce evaporation, and protect the structure from cryogenic temperatures (California Energy Commission, 2013).

Typically, a LNG tank is constructed with double containers, with the inner containing LNG and the outer integrity layer which is for secondary containment in case of inner tank failure. Design decisions are governed by available space and local requirements of terminal port. While, majority of storage tanks are above-ground, in countries like Japan where land is scarce, LNG tanks are below ground (Yang et al, 2006).

LNG on ground tanks are classified as: single containment tank, double containment tank, and full containment tank. Of these, the most advanced is the full containment tank. Besides storing LNG, the inner tank and outer tank are capable of resisting all external loads for instance seismic loads. Moreover, the design of the full containment tank is such that it can even prevent hazardous situations such as LNG leakage by venting off excess vapor. It has additional detection measures namely: temperature leakage, overpressure, liquid tightness, thermal radiation and cold spot (CLP Power, 2006; Nasr & Connor, 2014).

## **A.4 Process Description**

After the carrier docks at a jetty, it takes around 24 hours (including preparation) for the LNG to be unloaded into the onshore tanks. There are three phases to the transfer of LNG: preparation, operation, and post-operation (Sacchi, 2010; DEFSA S.A., 2003):

#### **A.4.1 Preparation phase**

During preparation phase, no unloading activities will take place. The main purpose of the preparation phase is to prepare the system and maintain the cryogenic condition. There are three activities need to be done before unloading process starts, which are purging, leaking test, and cooling down.

First necessary exercise for LNG unloading system is air purging. Although the air purging is not unnecessary for lines that always contain oxygen, mixing between methane<sup>21</sup> and oxygen may cause risk of oxidation, ignition, and explosive. This purging process ensures that the flammable concentration will remain below the explosive range after methane is introduced.

Preferred substance to remove oxygen from the system is nitrogen gas since it does not freeze under cryogenic temperatures. The purging is performed till oxygen content is less than 1% by volume. Later, nitrogen and oxygen are both drained out through drain valves. This process is repeated twice or thrice. After that, a leak test is performed by apply a soapy water to the principal joints in order to ensure that the system is leak-free. After the lines are purged, leak tested, dried, and free from dirt. The terminal is now ready to be cooled down.

Secondly, unloading systems and storage tank are cooled down. When the temperatures reach -140°C, LNG will be gradually introduced. LNG is gradually sprayed into the tank to help the inner container gently cool down. This cooling down is a crucial step since improper operation can lead to severe damage to the facility. Therefore, the cool-down rate and other factors need to be carefully controlled by cooperation between terminal, jetty, and ship (Mokhatab et al, 2013).

When the tank and other LNG lines temperature is low enough, LNG from the ship to the LNG storage tank can then be gradually flowed.

#### **A.4.2 Operation phase: LNG Unloading**

During this process, the vapor pressure in the ship tanks will be maintained by returning vapor from the shore. In this process both unloading and recirculation lines are used in parallel. The recirculation line is used for maintaining cryogenic conditions and the unloading line used in parallel with LNG unloading. In this mode, the jetty recirculation line, which used to circulate LNG from the storage tank to the jetty to maintain cryogenic conditions when the ship is not at port, will be used as unloading line Unloading rates are between 12,000 and 15,000 m<sup>3</sup> per hour depending on the size of the carrier.

As the tank fills, heat also enters; hence some LNG in tank will evaporate. This LNG vapor is called boil-off gas (BOG). The increase of BOG in turn increases pressure inside the

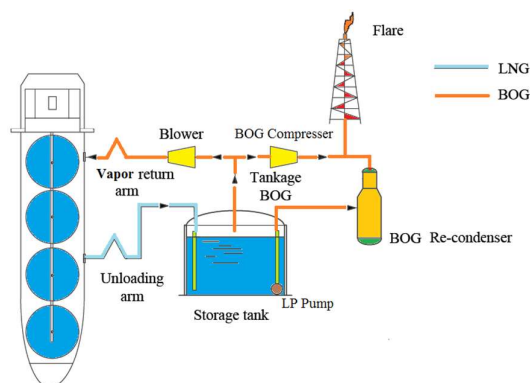
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<sup>21</sup> Methane is the main component of LNG. It is lighter and has lower boiling point than other components e.g. ethane, propane, butane. When LNG is unloaded, methane is firstly introduced to the lines. It will gasify violently and rapidly increases the internal pressure of the lines. Therefore easily makes the atmosphere into a flammable condition (American Gas Association, 2011).

storage tank. Moreover, due to different compositions of LNG, volatile components such as methane will boil off first. Therefore, to maintain pressure within the safe working range, using the BOG compressors, the BOG must be constantly removed (Dobrota, Lalić, & Komar, 2013).

This BOG must be returned back to the ship to replenish the unloaded volume from the ship. Otherwise, this will cause vacuum in the ship tanker. This is achieved by the vapor return arm. Re-liquefaction is performed by the re-condenser and compressors. The liquefied BOG is combined with the main flow and returned to the tank.

Prior to disconnecting the unloading arms, any remaining liquid will be drained and purged with nitrogen. To avoid thermal cycling of the piping, the onshore liquid lines will be left full and a minor circulation maintained, to hold the temperature at approximately  $-162^{\circ}\text{C}$ .



**Figure 20:** Process Diagram of LNG Unloading  
(modified from Dobrota, Lalić, & Komar, 2013)

From Figure 20, during ship unloading, BOG must be returned to the ship to replenish the unloaded volume from the ship, in order to avoid vacuum conditions. To supply the deficit of BOG to the ship, the vapor return arm will be used. While BOG re-condenser will be compressed and re-liquefied the surplus of BOG. The liquefied BOG is combined with the main flow and returned to the tank. When tanks reach 98.5% of the total capacity, the operation is finished.

#### A.4.3 Post-operation mode

During this mode, neither is LNG unloaded nor is it sent to the pipeline system. After LNG unloading finishes, the systems must be again purged with nitrogen. All remaining LNG in the unloading arms will be recovered. The cryogenic conditions are maintained by circulating LNG to the jetty heads, recirculation lines and unloading lines. Lastly, the remaining BOG in the storage tank will be routed to flare (Gate Terminal, 2011).

## **A.5 Personal interview: Linard Velgerdijk (4<sup>th</sup> June 2015)**

### **A.5.1 LNG Storage Tank**

There are several kinds of LNG storage tank (e.g. full containment tank, in-ground tank). Currently, Gate terminal has three full containment tanks with a net capacity of 180,000m<sup>3</sup> each. Choice is made on best available atmospheric design.

### **A.5.2 Loading arms and other connection equipment**

What connection equipment which Gate Terminal uses on truck loading is loading facility with pipes and valves, metal corrugated hoses size 2.5" for liquid, and metal corrugated hoses size 1.5" for vapor. For ship to shore and shore to ship, Gate terminal has fixed loading arms size 20" with swiffles and a 16" flange connection.

For transfer process from ship to shore (storage tank), Gate terminal has 4 loading arms (3 liquid and 1 vapor return). While LNG transfer process for truck loading (from storage tank to LNG tanker trucks) is done by hoses metal corrugated, with the size of 2.5" for liquid transfer and 1.5" for vapor return (see more information about LNG unloading arm in A.3.2).

### **A.5.3 Possible hazard scenario of concern**

Regarding to the scenario which the Gate Terminal has to make according to Seveso II legislation<sup>22</sup>, during processing LNG transfer from ship to the onshore storage tanks we consider a 0.1 diameter leak of an unloading arm as the most credible scenario. A full rupture of an arm is described as well but is not likely to occur. Whereas, in the scenario for LNG transfer from tank to truck, LNG leakage on flange connection is considered as important.

However, according to (Det Norske Veritas, 2011), since the installation is designed for cryogenic conditions, hazard scenarios from low temperature are not possible. However, during the installation, there are five scenarios which selected to demonstrate control over failure mechanisms. The following six scenarios are selected due to a mix of high frequency of occurring and high severity (Det Norske Veritas, 2011):

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<sup>22</sup> Seveso II Directive aims at preventing major-accident hazards involving dangerous substances as well as limit the consequences of such accidents for human (safety and health aspects) and environment (environmental aspect) (European Commission, 2015).



### Possible accident scenarios in Gate Terminal during installation

No	Location	Scenario	Description	Direct Cause	Mitigation	Risk level
1	LNG Unloading at jetty	Leakage of unloading arm	<ul style="list-style-type: none"> <li>• A valve flange connection was not properly mounted due to negligence of a maintenance operator.</li> <li>• Ignition of the LNG vapor could cause by a mobile phone, resulting in a flash and pool fire</li> <li>• The operators get burns and the jetty is damaged</li> </ul>	Human error	<ul style="list-style-type: none"> <li>• Ignition source control</li> <li>• Fully welded piping system without flanges</li> <li>• Dedicated hydraulic QCDC system and ESD</li> </ul>	<ul style="list-style-type: none"> <li>• Probability is 1</li> <li>• Severity is 4</li> <li>• Risk level is 2</li> </ul>
2	LNG Unloading at jetty	Full rupture of unloading arm	<ul style="list-style-type: none"> <li>• Excessive LNG ship movement due to storm &amp; high waves lead to over-extension of the unloading arms</li> <li>• Pool fire</li> <li>• Low Oxygen concentrations lead to asphyxiation</li> </ul>	External load	<ul style="list-style-type: none"> <li>• Mooring system with tension detection</li> <li>• QCDC</li> <li>• Alarm</li> <li>• Sensor in arm activates</li> </ul>	<ul style="list-style-type: none"> <li>• Probability is 1</li> <li>• Severity is 4</li> <li>• Risk level is 2</li> </ul>
3	LNG Unloading at jetty	Leakage of unloading line	<ul style="list-style-type: none"> <li>• Due to small fire near LNG pipeline, operator may misjudge and overlook the situation</li> <li>• Due to heating up the LNG pipe, the design temperature of the pipe may be exceeded, resulting in LNG release.</li> </ul>	High temperature	<ul style="list-style-type: none"> <li>• Insulated pipelines to limits direct heat-up from radiation</li> <li>• ESD</li> <li>• Stainless steel plate prevents direct fire radiation</li> </ul>	<ul style="list-style-type: none"> <li>• Probability is 1</li> <li>• Severity is 4</li> <li>• Risk level is 2</li> </ul>
4	LNG Storage tanks	LNG storage tank rollover	See 2.3.8	External load	Density measurement in tank	<ul style="list-style-type: none"> <li>• Probability is 2</li> <li>• Severity is 3</li> <li>• Risk level is 2</li> </ul>

No	Location	Scenario	Description	Direct Cause	Mitigation	Risk level
5	BOG handling & recovery system	Leakage of BOG compressor	<ul style="list-style-type: none"> <li>• Instead of gas, LNG enters the compressor resulting in vibrate and internal damage occurs</li> <li>• This small leak through the compressor housing may result in a release of natural gas</li> <li>• Asphyxiation</li> </ul>	Vibrations	<ul style="list-style-type: none"> <li>• Vibration detection</li> <li>• Level measurement</li> </ul>	<ul style="list-style-type: none"> <li>• Probability is 1</li> <li>• Severity is 3</li> <li>• Risk level is 2</li> </ul>

## Appendix B. **61 Accident Scenarios from Literature Review**

Accident Scenarios	Cause	Consequence	Mitigation/ Safeguards	Probability/ Severity/ Risk level	References
1. Collision of LNG ship by the other vessels	<ul style="list-style-type: none"> <li>Adverse weather</li> <li>Pilot or navigational officer error</li> <li>Navigator/traffic control system error</li> <li>Ships mechanical failure</li> </ul>	<ul style="list-style-type: none"> <li>It could cause penetrate to the outer/ inner cargo tank which LNG could leak, resulting pool fire, VCE, or RPT.</li> <li>These may deteriorate the strength of the ship, eventually causing the ship to sink.</li> </ul>	<ul style="list-style-type: none"> <li>Use navigation systems with radar that display other vessels and obstacles.</li> <li>Enforce speed limits in harbor areas.</li> </ul>	<ul style="list-style-type: none"> <li>Probability is 2 – unlikely (<math>6.7 \times 10^{-3}</math> per ship per year)<sup>23</sup></li> <li>Severity level is 4–extensive (one fatality)</li> <li>Risk level is 3 – moderate to high</li> </ul>	<ul style="list-style-type: none"> <li>Martorell, Soares, &amp; Barnett, 2014.</li> <li>Woodward &amp; Pitbaldo, 2010.</li> <li>Doorn, 2010</li> </ul>
2. Small leakage of unloading arm during unloading	<ul style="list-style-type: none"> <li>Improper valve flange, seal or the swivel joints connection</li> <li>disconnected arms before the liquid lines have been completely drained</li> </ul>	<ul style="list-style-type: none"> <li>The nearby operator may get freeze burns if LNG directly spills onto them.</li> <li>The jetty will be slightly damaged.</li> </ul>	<ul style="list-style-type: none"> <li>Use monitoring system and alarm system to monitor and indicate the leakage.</li> <li>Install drip tray in the manifold areas. It can collect and drain any spillage.</li> </ul>	<ul style="list-style-type: none"> <li>Probability is 3 – Possible (<math>2.75 \times 10^{-2}</math> per year)</li> <li>Severity level is 1–low</li> <li>Risk level is 2 – low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>SKANGA SS AS, 2013</li> <li>Yun, 2007</li> </ul>

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<sup>23</sup> Collision frequency=  $6.7 \times 10^{-3}$  per ship per year. This number of collision frequency for LNG carriers was derived by historical accident data from several sources which including both serious and non-serious collisions.

Accident Scenarios	Cause	Consequence	Mitigation/ Safeguards	Probability/ Severity/ Risk level	References
3. Rupture of unloading arm	<ul style="list-style-type: none"> <li>Sea current, waves, or wind speed creates violent ship movements.</li> </ul>	<p>Over extension and rupture of unloading arm could spill LNG into water and surrounding areas, lead to:</p> <ul style="list-style-type: none"> <li>Structural damage</li> <li>Vapor cloud formation.</li> <li>Nearby operators get asphyxia/ freeze burns</li> </ul>	<ul style="list-style-type: none"> <li>Stops unloading process</li> <li>ESD shall be used together with monitoring system and alarm system</li> </ul>	<ul style="list-style-type: none"> <li>Probability is 2 – unlikely (<math>2 \times 10^{-3}</math> per year)</li> <li>Severity level is 3 – moderate</li> <li>Risk level is 2 – low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>Waller, 2013</li> <li>Melani, Silvaa, &amp; Souzaa, 2014</li> </ul>
4. Leakage of LNG line from adjacent fire	<ul style="list-style-type: none"> <li>Overlooking the leak by the operator especially, in case of LNG pipelines cross the other chemical lines.</li> </ul>	<ul style="list-style-type: none"> <li>Leakage of LNG from its pipeline could be a fuel of existing fire, leading to a larger fire.</li> <li>Damage in surrounding facilities' structure.</li> <li>Possibility of vapor cloud formation</li> </ul>	<ul style="list-style-type: none"> <li>Spill containment system with provision for high expansion foam</li> <li>Gas and fire detection</li> <li>Fire protection system</li> </ul>	<ul style="list-style-type: none"> <li>Probability is 3 – Possible (<math>2.5 \times 10^{-3}</math> per year)</li> <li>Severity level is 2 – low</li> <li>Risk level is 2 – low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>SKANGA SS AS, 2013a</li> <li>HSE, 2000s</li> <li>Aven, 2011</li> </ul>
5. Leakage of LNG line from high velocity erosion	<ul style="list-style-type: none"> <li>Pipe material cannot withstand high velocity of LNG</li> <li>LNG velocity is set too high or flow direction is changed</li> </ul>	<ul style="list-style-type: none"> <li>The pipeline, especially elbow part gets corroded and LNG releases from the hole.</li> <li>Same consequences as no.4</li> </ul>	<ul style="list-style-type: none"> <li>Regular maintenance</li> <li>Fire and gas detection</li> <li>Emergency system</li> <li>Active/passive fire protection.</li> </ul>	N/A	<ul style="list-style-type: none"> <li>Awang, n.d.</li> <li>Kaupert, Hays, Gandhi, &amp; Kaehler, 2013</li> </ul>

Accident Scenarios	Cause	Consequence	Mitigation/ Safeguards	Probability/ Severity/ Risk level	References
6. Rupture of BOG line from external impact	<ul style="list-style-type: none"> <li>Vehicle crash</li> <li>Maintenance activities</li> <li>Debris from nearby accidents</li> </ul>	<ul style="list-style-type: none"> <li>Gas/ vapor leak and potential ignition</li> <li>A cold vapor could harm nearby operator and facility</li> </ul>	<ul style="list-style-type: none"> <li>Gas and fire detection</li> <li>Fire protection system</li> </ul>	N/A	<ul style="list-style-type: none"> <li>Flemish Government, 2009</li> <li>Waller &amp; Covello, 2013</li> </ul>
7. Collision with pipe bridge	<ul style="list-style-type: none"> <li>Carelessness operation</li> <li>Operator does not align his gig correctly</li> </ul>	<ul style="list-style-type: none"> <li>Leakage of LNG from its pipeline could be a fuel of existing fire, leading to a larger fire.</li> <li>Damage in surrounding facilities' structure.</li> <li>Vapor cloud formation.</li> </ul>	<ul style="list-style-type: none"> <li>Lifting and maintenance procedures</li> <li>Fenders designed for specified impact load</li> </ul>	N/A	<ul style="list-style-type: none"> <li>HSE, 2000s</li> <li>Aven, 2011</li> </ul>
8. LNG storage tank rollover	Mixing of two or several LNG shipments with different composition and density in a storage system	<ul style="list-style-type: none"> <li>Building up of the in-tank pressure could result in release of LNG vapor.</li> <li>If the vapor is excessive, it would release from the roof relief nozzles and from any weak points on the roof.</li> </ul>	<ul style="list-style-type: none"> <li>Controlling the loading procedure</li> <li>Provide sensors to detect stratification</li> <li>Sample incoming LNG for stratification tendencies test.</li> </ul>	<ul style="list-style-type: none"> <li>Probability is 2 – unlikely (<math>2 \times 10^{-3}</math> per year)</li> <li>Severity level is 3 – moderate</li> <li>Risk level is 2 – low to moderate<sup>24</sup></li> </ul>	<ul style="list-style-type: none"> <li>N. Baker &amp; Creed, 1995</li> <li>Keeney, Kulkarni, &amp; Nair, 1978s</li> <li>Det Norske Veritas, 2011s</li> </ul>

<sup>24</sup> The result of risk level of LNG storage tank rollover conforms with personal interview of Velgersdijk (2015).

Accident Scenarios	Cause	Consequence	Mitigation/ Safeguards	Probability/ Severity/ Risk level	References
9. LNG storage tank overflow	<ul style="list-style-type: none"> <li>Failure of level gage/ safety valve</li> <li>Negligence of operators</li> <li>Wrong calculation of filling process</li> </ul>	<ul style="list-style-type: none"> <li>Leak at the tank surface</li> <li>Overflow into the annular space between the inner tank and the outer tank. It might damage the tank structure.</li> </ul>	<ul style="list-style-type: none"> <li>Leak detection procedure and devices</li> <li>Relief valves</li> <li>Gas and fire detection system</li> </ul>	<ul style="list-style-type: none"> <li>Probability is 1 – rare (<math>1.2 \times 10^{-5}</math> per year)</li> <li>Severity level is 4 – extensive</li> <li>Risk level is 3 – low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>Woodward &amp; Pitbaldo, 2010</li> <li>Waller, 2013</li> <li>Flemish Government, 2009</li> </ul>
10. LNG storage tank foundation frost heave	<ul style="list-style-type: none"> <li>Failure of heating system of the tank</li> <li>Failure of power (electrical) supply</li> </ul>	<ul style="list-style-type: none"> <li>An ice lens formation causes a soil to be frozen which lead to destruction of the tank foundation and the tank itself</li> </ul>	<ul style="list-style-type: none"> <li>Temperature measurement</li> <li>Replacement of heating element</li> </ul>	N/A	<ul style="list-style-type: none"> <li>Fornasiero, 1986</li> </ul>
11. Accidental drop of LNG immersed pump <sup>25</sup>	<ul style="list-style-type: none"> <li>Failure of cable/ hoist</li> <li>Inappropriate lifting procedures (e.g. single-drum hoist)</li> </ul>	<ul style="list-style-type: none"> <li>An impact of the falling pump could cause damage to the inner tank and also concrete base.</li> <li>Potential internal leakage</li> </ul>	<ul style="list-style-type: none"> <li>Apply Gas and fire detection/ fire protection systems</li> <li>Apply strict lifting and maintenance procedures</li> </ul>	N/A	<ul style="list-style-type: none"> <li>Det Norske Veri tas, 2011</li> </ul>

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<sup>25</sup> LNG immersed pumps are low pressure pump (LP pump) is functioned to pump LNG from storage tank to BOG re-condenser or return to recirculation line to the jetty. The immersed pump will lift up for maintenance purpose.

Accident Scenarios	Cause	Consequence	Mitigation/ Safeguards	Probability/ Severity/ Risk level	References
12. Liquid lock in the valve/ Valve failure	<ul style="list-style-type: none"> <li>Liquid LNG can get trapped due to</li> <li>Corrosion from CO<sub>2</sub> of carbon steel</li> <li>Defective welded valves</li> <li>Valve deterioration forms cavities</li> </ul>	<ul style="list-style-type: none"> <li>This trapped LNG can exert sufficient pressure and leads to deformation of components.</li> <li>In welded valves transient leakage from flanges can occur especially when cooling down.</li> </ul>	<ul style="list-style-type: none"> <li>Test liquid lock in the stem when the valve is in the fully open position</li> <li>Select the standard manufactured valves</li> </ul>	<ul style="list-style-type: none"> <li>Probability is 1 – rare (<math>8.76 \times 10^{-5}</math> per year)</li> <li>Severity level is 2 – negligible</li> <li>Risk level is 1 – low</li> </ul>	<ul style="list-style-type: none"> <li>HSE Government of UK, 2012</li> <li>SIGTTO, 2008</li> </ul>
13. Corrosion of metallic component	<ul style="list-style-type: none"> <li>Gradual deterioration of the material caused by water, CO<sub>2</sub>, and acids (scale remover substances)</li> </ul>	<ul style="list-style-type: none"> <li>Failures and leaks in header line/ pipelines</li> <li>Leakage of LNG from its pipeline could damage in surrounding facilities' structure</li> </ul>	<ul style="list-style-type: none"> <li>ESD system</li> <li>Monitor during initial design and re-evaluation of pipeline.</li> <li>Follow strictly corrosion management policy<sup>26</sup></li> </ul>	<ul style="list-style-type: none"> <li>Probability is 2 – unlikely<sup>27</sup></li> <li>Severity level is 2 – negligible</li> <li>Risk level is 2 – low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>Ossai, 2012</li> <li>Hidalgo, Silva, &amp; Souza, 2013</li> <li>Aven, 2011</li> </ul>
14. Boiler Explosion	<ul style="list-style-type: none"> <li>Failure of the safety valve</li> <li>Corrosion of critical parts</li> <li>Low water level</li> </ul>	<ul style="list-style-type: none"> <li>Potential for projectiles causing damage to the facility</li> <li>Massive vapor-cloud explosion and fire</li> </ul>	<ul style="list-style-type: none"> <li>Full containment tank designed to withstand projectile impact</li> <li>Boiler controls/ inspection/maintenance</li> </ul>	<ul style="list-style-type: none"> <li>Probability is 2 – unlikely (<math>2.8 \times 10^{-3}</math>)</li> <li>Severity level is 4 – extensive</li> </ul>	<ul style="list-style-type: none"> <li>California Energy Commission, 2004</li> </ul>

<sup>26</sup> In LNG industries, corrosion management policy includes responsibilities, reporting routes, practices, procedures, and resources.

<sup>27</sup> The probability of corrosion failure for the thickness of 9.53 mm submitted to the normal operation pressure (0.1 MPa) has small probability of occurrence and severe consequences (the failure probability is very small to 0.098 for 60 years)(Hidalgo et al., 2013).



Accident Scenarios	Cause	Consequence	Mitigation/ Safeguards	Probability/ Severity/ Risk level	References
15. ESD (Emergency Shut Down) System Failure	<ul style="list-style-type: none"> <li>• Improper instalment /maintenance</li> <li>• Physical damage (e.g. mechanical overstress)</li> <li>• Manufacturing defect</li> </ul>	<ul style="list-style-type: none"> <li>• No safeguard when emergency situation occur.</li> <li>• Leakage or spillage of LNG may cause LNG related hazards</li> </ul>	<ul style="list-style-type: none"> <li>• Redundant sensors</li> <li>• Apply strict testing procedure such as checking before the LNG transfer for the hidden failures</li> </ul>	<ul style="list-style-type: none"> <li>• Probability is 3 – Possible (<math>3.95 \times 10^{-2}</math>)</li> <li>• Severity level is 2 – negligible</li> <li>• Risk level is 2– low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>• Oktem, Pariyani, Seider, &amp; Soroush, 2013</li> <li>• Hsua, Shub, &amp; Tsaoc, 2010</li> </ul>
16. Normal instrumentation failure	<ul style="list-style-type: none"> <li>• Improper instalment /maintenance</li> <li>• Physical damage (e.g. mechanical overstress)</li> <li>• Manufacturing/ Welding defect</li> </ul>	<ul style="list-style-type: none"> <li>• Misunderstanding cause wrong decision and wrong operation</li> </ul>	<ul style="list-style-type: none"> <li>• Provide ESD system</li> <li>• Applying the proper maintenance, mitigation &amp; control techniques</li> </ul>	<ul style="list-style-type: none"> <li>• Probability is 4 – likely<sup>28</sup> (highly probable)</li> <li>• Severity level is 2 –negligible</li> <li>• Risk level is 3– moderate to high</li> </ul>	<ul style="list-style-type: none"> <li>• Biamonte, 1982</li> <li>• Pelto, Baker, Holter, &amp; Powers, 1982as</li> </ul>
17. Cool-down failure	<ul style="list-style-type: none"> <li>• Wrong technical calculation (time, temperature, pipe)</li> <li>• Instrumentation failure</li> </ul>	<ul style="list-style-type: none"> <li>• Damage of LNG transfer line from pipe stress and pipe bowing</li> </ul>	<ul style="list-style-type: none"> <li>• Review and evaluate procedures for cool-down</li> <li>• Limit cool-down to the predetermined rate within the designed limits</li> </ul>	N/A	<ul style="list-style-type: none"> <li>• Akhuemonkhan &amp; Vara, 2009</li> </ul>

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<sup>28</sup> “Minor malfunctions of instrumentation and controls are highly probable but, because of design considerations, the probability of mal functions resulting in the releases is judged to be medium” (Pelto et al., 1982a).

<b>Accident Scenarios</b>	<b>Cause</b>	<b>Consequence</b>	<b>Mitigation/ Safeguards</b>	<b>Probability/ Severity/ Risk level</b>	<b>References</b>
18. Purging failure	<ul style="list-style-type: none"> <li>• Lack of inert gas/nitrogen/air</li> <li>• Inert gas/nitrogen pumping failure</li> </ul>	<ul style="list-style-type: none"> <li>• Formation of flammable mixtures in pipelines</li> <li>• Damage of flange connection</li> </ul>	<ul style="list-style-type: none"> <li>• Ensure that mixture of LNG and air is not present in the pipelines after purging</li> <li>• Ensure oxygen content in the pipelines matches standard requirements</li> </ul>	<ul style="list-style-type: none"> <li>• Probability is 2 – unlikely</li> <li>• Severity level is 3 – moderate</li> <li>• Risk level is 2– low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>• Akhuemonkhan &amp; Vara, 2009</li> <li>• American Gas Association, 2011</li> </ul>
19. Loss of power supply	<ul style="list-style-type: none"> <li>• Technical failure</li> <li>• Faults at power stations</li> <li>• Damage to electric transmission lines</li> <li>• A short circuit</li> <li>• Overloading of electricity mains.</li> </ul>	<ul style="list-style-type: none"> <li>• LNG re-generator<sup>29</sup> circulation will stop which could lead to:</li> <li>• Increase the pressure in the tanks and the pipelines</li> <li>• Overpressure for the storage tank</li> </ul>	<ul style="list-style-type: none"> <li>• Backup electric power sources (e.g. UPS, diesel electric generators)</li> <li>• Insulation and thermal/pressure relief</li> </ul>	<ul style="list-style-type: none"> <li>• Probability is 3 – possible<sup>30</sup></li> <li>• Severity level is 1–negligible</li> <li>• Risk level is 2– low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>• Oil Industry Safety Directorate, 2000</li> <li>• Woodfibre LNG, 2015</li> </ul>

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<sup>29</sup> Emergency power generator and UPS will be used when the main power supply fails but it will supply for only critical devices (e.g. lighting, controls, and safety critical systems).

<sup>30</sup> According to Woodfibre LNG (2015), unplanned facility shutdown, including emergency flaring, process upset, or power outage has the likelihood of ‘May occur’ and consequence of ‘negligible’.

Accident Scenarios	Cause	Consequence	Mitigation/ Safeguards	Probability/ Severity/ Risk level	References
20. Loss of emergency power supply	<ul style="list-style-type: none"> <li>• Technical failure (e.g. failure of diesel engines)</li> <li>• Lack of diesel supply for emergency</li> </ul>	<ul style="list-style-type: none"> <li>• Heat leaks in equipment, piping and the storage tank leading to overpressure</li> <li>• The overpressure can rupture the pressure relief valve or in the top dome of the tank</li> </ul>	<ul style="list-style-type: none"> <li>• Insulation and thermal/pressure relief</li> <li>• On-site diesel storage</li> <li>• Backup electric power sources (e.g. UPS, diesel electric generators)</li> </ul>	<ul style="list-style-type: none"> <li>• Probability is 2 – unlikely</li> <li>• Severity level is 1–negligible</li> <li>• Risk level is 2– low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>• Mokhatab et al., 2014</li> </ul>
21. Loss of Nitrogen <sup>31</sup>	<ul style="list-style-type: none"> <li>• Damage of vapour header</li> <li>• Wrong calculation</li> <li>• Failure of vent/valve</li> <li>• nitrogen piping network.</li> <li>• Malfunction of pressure control valves.</li> </ul>	<ul style="list-style-type: none"> <li>• Purging/flushing operation failure</li> <li>• Gas ingression could lead to enough O<sub>2</sub> level which support combustion</li> <li>• Moisture or dust ingression leads to premature life failure of bearing part of unloading arm/ valve/ pump</li> </ul>	<ul style="list-style-type: none"> <li>• Redundant Nitrogen source (generation and small liquid storage/vaporizer)</li> </ul>	<ul style="list-style-type: none"> <li>• Probability is 1 – rare (<math>7 \times 10^{-5}</math>)</li> <li>• Severity level is 3–moderate</li> <li>• Risk level is 2– low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>• Yataghène, Tallec, &amp; Roue, 2005</li> </ul>
22. Loss of hydraulic system	<ul style="list-style-type: none"> <li>• Failure of instrument air compressors</li> </ul>	<ul style="list-style-type: none"> <li>• In case of failure of these compressors, the ESD</li> </ul>	<ul style="list-style-type: none"> <li>• Redundant air compressors</li> <li>• Redundant air receiver</li> </ul>	N/A	<ul style="list-style-type: none"> <li>• Peekema, 2013</li> </ul>

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<sup>31</sup> Inert properties of nitrogen can be used to protect against loss of quality by oxidation by expelling any air entrained in the liquid and protecting liquids in storage tanks by filling the vapor space (blanketing). Therefore, Nitrogen is used as the inert gas in the purging process at the import terminal, or flushing process at LNG filling station (American Gas Association, 2011).

Accident Scenarios	Cause	Consequence	Mitigation/ Safeguards	Probability/ Severity/ Risk level	References
compressed air		valves will have sufficient capacity to perform. <ul style="list-style-type: none"> <li>In case of failure of the ESD system, the unloading operation will stop.</li> </ul>	<ul style="list-style-type: none"> <li>Flow control valves</li> </ul>		
23. Rupture of gas transportation line	<ul style="list-style-type: none"> <li>Management miscommunication with excavation contractor</li> <li>Mechanical damage to pipelines due to material defects (e.g. corrosion, weld cracking)</li> <li>Construction errors</li> <li>External forces (e.g. excavation, earthquake)</li> </ul>	<ul style="list-style-type: none"> <li>Improper execution of excavation can rupture the pipeline leading to LNG vapour release which could cause asphyxiation or burns to the excavating crew</li> <li>If the gas leak ignites, it can cause explosions.</li> <li>A confined<sup>32</sup> vapor cloud explosion can produce severe overpressure with the flame.</li> </ul>	<ul style="list-style-type: none"> <li>Provide automatic cutoff valves</li> <li>Select the double wall transfer line</li> <li>Extra depth cover</li> <li>Concrete slabs and warning tapes</li> </ul>	<ul style="list-style-type: none"> <li>Probability is 2 – unlikely<sup>33</sup></li> <li>Severity level is 4 – extensive</li> <li>Risk level is 3 – moderate to high</li> </ul>	<ul style="list-style-type: none"> <li>Peekema, 2013</li> <li>The Institution of Gas Engineers and Managers (IGEM), 2015s</li> </ul>

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<sup>32</sup> Confinement occurs due to presence of objects, such as buildings near the location of the explosion. These buildings also stand a great chance of damage due to the explosion (Peekema, 2013).

<sup>33</sup> The total rupture frequency of natural gas transportation line is  $5.03 \times 10^{-3}$  per 1,000 kilometers per year (The Institution of Gas Engineers and Managers (IGEM), 2015).

Accident Scenarios	Cause	Consequence	Mitigation/ Safeguards	Probability/ Severity/ Risk level	References
24. Sloshing in tanker truck/train cause overturn	<ul style="list-style-type: none"> <li>If the cargo tank is partially full, the LNG cargo will be more susceptible to the effect of pitching and rolling.</li> </ul>	<ul style="list-style-type: none"> <li>If the vehicle turns, LNG will also flow towards the turn direction. This changes the center of gravity can eventually cause rollover.</li> <li>Excessive impact pressure on the tank surface cause damaging to the tank.</li> </ul>	<ul style="list-style-type: none"> <li>Vehicle should run only with LNG levels near empty or full</li> <li>Select the shape optimization of LNG tank to reduce sloshing pressures</li> </ul>	N/A	<ul style="list-style-type: none"> <li>J. L. Woodward &amp; Pitbaldo, 2010</li> <li>Park et al., 2014</li> </ul>
25. Overfilling in tanker truck/train	<ul style="list-style-type: none"> <li>Failure of level gauge/ valve gauge/ scale indicator/ high-level alarm</li> <li>Failure of leak detector</li> <li>Wrong calculation of filling process</li> </ul>	<ul style="list-style-type: none"> <li>Overflow to the annular space leading to overpressure in tank</li> <li>The overpressure can lead to a cracking of cargo tank covers or nearby operator get freeze burns.</li> </ul>	<ul style="list-style-type: none"> <li>Multiple level indication</li> <li>Develop emergency response procedures and provide training</li> </ul>	<ul style="list-style-type: none"> <li>Probability is 1 – rare (<math>1.2 \times 10^{-5}</math>)</li> <li>Severity level is 3–moderate</li> <li>Risk level is 2–low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>J. L. Woodward &amp; Pitbaldo, 2010</li> <li>Skramstad, Musaeus, &amp; Melbo, 2000</li> </ul>
26. Overpressure in tanker truck/train	<ul style="list-style-type: none"> <li>Fire surrounding the tank</li> <li>Failure of tank pressure instrument/ pressure relief valve/ cargo tank insulation system</li> </ul>	<ul style="list-style-type: none"> <li>If there is a fire surrounding LNG cargo tank (from accidental collision), heat can escalate the transition rate of LNG to vapor.</li> <li>If vapor cannot release, explosion could result.</li> </ul>	<ul style="list-style-type: none"> <li>Provide emergency release connection</li> <li>Provide LNG impoundment basins in safe locations.</li> <li>Provide shielding around flanges, valve stems, and pump axles.</li> </ul>	<ul style="list-style-type: none"> <li>Probability is 1–rare (<math>6.5 \times 10^{-7}</math>)</li> <li>Severity level is 4–extensive</li> <li>Risk level is 2–low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>Federal Transit Administration, 1999</li> <li>Woodward &amp; Pitbaldo, 2010</li> </ul>

Accident Scenarios	Cause	Consequence	Mitigation/ Safeguards	Probability/ Severity/ Risk level	References
27. Liquid lock in the valve/ Valve failure	<ul style="list-style-type: none"> <li>Liquid LNG can get trapped due to</li> <li>Corrosion from CO<sub>2</sub> of carbon steel</li> <li>Defective welded valves</li> <li>Valve deterioration forms cavities</li> </ul>	<ul style="list-style-type: none"> <li>This trapped LNG can exert sufficient pressure to cause deformation of components.</li> <li>In welded valves transient leakage from flanges can occur especially when cooling down.</li> </ul>	<ul style="list-style-type: none"> <li>Test liquid lock in the stem when the valve is in the fully open position</li> <li>Select the standard manufactured valves</li> <li>Provide shielding around valve</li> </ul>	<ul style="list-style-type: none"> <li>Probability is 1 – rare (<math>8.76 \times 10^{-5}</math>)</li> <li>Severity level is 3 – moderate</li> <li>Risk level is 2 – low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>HSE Government of UK, 2012</li> <li>SIGTTO, 2008</li> </ul>
28. Flexible hose failure	<ul style="list-style-type: none"> <li>Fatigue due to high pressure or low temperature</li> <li>External impact (i.e. lifting activities)</li> </ul>	<ul style="list-style-type: none"> <li>Leakage or spillage of LNG can cause the related hazards</li> <li>Explosive environment can create by leakage of LNG</li> </ul>	<ul style="list-style-type: none"> <li>Visual inspection before the hose is connected</li> <li>A breakaway coupling can limit the spilled volume</li> </ul>	<ul style="list-style-type: none"> <li>Probability is 1 – rare (<math>1.5 \times 10^{-6}</math>)</li> <li>Severity level is 3 – moderate</li> <li>Risk level is 2 – low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>DNV, 2012</li> </ul>
29. Flange connection on truck/train failure	<ul style="list-style-type: none"> <li>Damage of flange connection</li> <li>Improper maintenance</li> </ul>	<ul style="list-style-type: none"> <li>Leakage or spillage of LNG may cause LNG related hazards</li> </ul>	<ul style="list-style-type: none"> <li>Apply strict flange testing/ maintenance procedure</li> <li>Provide shielding around flanges</li> </ul>	<ul style="list-style-type: none"> <li>Probability is 1 – rare (<math>6.5 \times 10^{-5}</math>)</li> <li>Severity level is 3 – moderate</li> <li>Risk level is 2 – low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>Woodward &amp; Pitbaldo, 2010</li> </ul>
30. Flushing failure	<ul style="list-style-type: none"> <li>Lack of inert gas/nitrogen/air</li> <li>Inert gas/nitrogen pumping failure</li> </ul>	<ul style="list-style-type: none"> <li>Formation of flammable mixtures in pipelines</li> <li>Damage of flange connection</li> </ul>	<ul style="list-style-type: none"> <li>Ensure that mixture of LNG and air is not present in the pipelines</li> <li>Ensure oxygen content in the pipelines matches standard requirements</li> </ul>	<ul style="list-style-type: none"> <li>Probability is 2 – unlikely</li> <li>Severity level is 3 – moderate</li> <li>Risk level is 2 – low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>Akhuemonkhan &amp; Vara, 2009</li> <li>American Gas Association, 2011</li> </ul>

Accident Scenarios	Cause	Consequence	Mitigation/ Safeguards	Probability/ Severity/ Risk level	References
31. ESD (Emergency Shut Down) System Failure	<ul style="list-style-type: none"> <li>• Improper install /maintenance</li> <li>• Physical damage (e.g. mechanical overstress)</li> <li>• Manufacturing defect</li> </ul>	<ul style="list-style-type: none"> <li>• No safeguard when emergency situation occur</li> <li>• Leakage or spillage of LNG may cause LNG related hazards</li> </ul>	<ul style="list-style-type: none"> <li>• Redundant sensors Apply strict testing procedure such as checking before the LNG transfer for the hidden failures</li> </ul>	<ul style="list-style-type: none"> <li>• Probability is 3 (<math>3.95 \times 10^{-2}</math>)</li> <li>• Severity level is 2 – negligible</li> <li>• Risk level is 2– low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>• Oktem, Seider, &amp; Soroush, 2013</li> <li>• Hsua, Shub, &amp; Tsaoc, 2010</li> </ul>
32. Normal instrumentation failure	Same as no. 31 (above)	<ul style="list-style-type: none"> <li>• Misunderstanding cause wrong decision and wrong operation</li> </ul>	<ul style="list-style-type: none"> <li>• Provide ESD system</li> <li>• Applying the proper maintenance, mitigation &amp; control techniques</li> </ul>	<ul style="list-style-type: none"> <li>• Probability is 4 – likely</li> <li>• Severity level is 2 –negligible</li> <li>• Risk level is 3– moderate to high</li> </ul>	<ul style="list-style-type: none"> <li>• Biamonte, 1982</li> <li>• Pelto, Baker, Holter, &amp; Powers, 1982as</li> </ul>
33. Collision of LNG tanker train while loading at terminal	<ul style="list-style-type: none"> <li>• Negligence of controller/driver</li> <li>• Signal failure</li> <li>• Lack of training</li> </ul>	<ul style="list-style-type: none"> <li>• LNG tank could be damaged causing the leakage</li> <li>• Freeze burns or brittle fractures can be resulted</li> <li>• Fire which could occur from the collision can trigger the fire hazards</li> </ul>	<ul style="list-style-type: none"> <li>• Operator training</li> <li>• Warning signal (e.g. visual light, siren) for the other vehicle which approaching</li> <li>• Limiting access of the loading area</li> <li>• Fire detection and ESD</li> </ul>	N/A	<ul style="list-style-type: none"> <li>• Eurostat, 2016</li> <li>• Anderson &amp; Barkan, 2004</li> </ul>
34. Collision of LNG tanker truck while loading at terminal	Same as no. 33 (above)			N/A	<ul style="list-style-type: none"> <li>• Gottlieb, 2011</li> </ul>

<b>Accident Scenarios</b>	<b>Cause</b>	<b>Consequence</b>	<b>Mitigation/ Safeguards</b>	<b>Probability/ Severity/ Risk level</b>	<b>References</b>
35. Collision of LNG tanker truck while loading at filling station	Same as no. 33: Collision of LNG tanker train while loading at terminal			N/A	<ul style="list-style-type: none"> <li>• Gottlieb, 2011</li> <li>• Planas-Cuchi et al., 2004s</li> </ul>
36. Collision of LNG tanker train while loading at filling station	Same as no. 33: Collision of LNG tanker train while loading at terminal			N/A	<ul style="list-style-type: none"> <li>• Gottlieb, 2011</li> <li>• Planas-Cuchi et al., 2004s</li> </ul>
37. Tanker truck/train ride over hose	<ul style="list-style-type: none"> <li>• Negligence of operator</li> <li>• Operation failure</li> </ul>	<ul style="list-style-type: none"> <li>• Hose damage</li> <li>• Spillage of LNG could harm the nearby objects/ human</li> </ul>	<ul style="list-style-type: none"> <li>• Check the hose fitting/ dispenser before and after filling operation</li> </ul>	N/A	<ul style="list-style-type: none"> <li>• Arnet, 2014</li> </ul>
38. Collision of LNG tanker truck while riding	<ul style="list-style-type: none"> <li>• Negligence of controller/driver</li> <li>• Signal failure</li> <li>• Lack of training</li> </ul>	<ul style="list-style-type: none"> <li>• LNG tank could be damaged causing the leakage</li> <li>• Freeze burns or brittle fractures can be resulted</li> <li>• Fires from collision can also trigger other LNG fire hazards</li> </ul>	<ul style="list-style-type: none"> <li>• Control driving speed</li> <li>• Extensive safety training</li> <li>• Warning signal (e.g. visual light, siren) for the other vehicle</li> <li>• Limit/Specify the transported time</li> </ul>	<ul style="list-style-type: none"> <li>• Probability is 4 – likely</li> <li>• Severity level is 4 – extensive</li> <li>• Risk level is 4– high</li> </ul>	<ul style="list-style-type: none"> <li>• Gottlieb, 2011</li> <li>• Planas-Cuchi et al., 2004s</li> </ul>



Accident Scenarios	Cause	Consequence	Mitigation/ Safeguards	Probability/ Severity/ Risk level	References
39. Collision of LNG tanker train while riding	Same as no.38 (above)			<ul style="list-style-type: none"> <li>• Probability is 3 – possible</li> <li>• Severity level is 4– extensive</li> <li>• Risk level is 4– high</li> </ul>	<ul style="list-style-type: none"> <li>• Eurostat, 2016</li> <li>• Anderson &amp; Barkan, 2004</li> </ul>
40. Leakage of LNG from storage tank from external load	<ul style="list-style-type: none"> <li>• Accidental collision with other vehicles</li> <li>• Failure of ESD valve/transfer valve</li> <li>• Crack of the cargo tank (outer or inner wall) from the impact</li> </ul>	<ul style="list-style-type: none"> <li>• Nearby people get freeze burns</li> <li>• Erosion on cargo tank covers/other equipment makes the tank weak</li> <li>• A vapor cloud occur and ignite in the flammable environment leading to flash fire and pool fire</li> </ul>	<ul style="list-style-type: none"> <li>• Install a flammable gas detection system around the tanksan.</li> <li>• Install remote isolation systems to shut the valves</li> <li>• Install an LNG drain and impoundment basin at a safe location</li> </ul>	<ul style="list-style-type: none"> <li>• Probability is 1 – rare (highly unlikely)</li> <li>• Severity level is 3– moderate</li> <li>• Risk level is 2– low to moderate</li> </ul>	Woodward & Pitbaldo, 2010
41. LNG storage tank overfill	<ul style="list-style-type: none"> <li>• Failure of level gauge/ scale indicator</li> <li>• Failure of leak detector</li> <li>• Negligence of operators</li> <li>• Wrong calculation of filling process</li> </ul>	<ul style="list-style-type: none"> <li>• Overflow to the annular space leading to overpressure in tank</li> <li>• The overpressure can lead to a cracking of cargo tank covers or nearby operator get freeze burns.</li> <li>• Explosive environment can create by leakage of LNG</li> </ul>	<ul style="list-style-type: none"> <li>• Leak detection procedure and devices</li> <li>• Relief valves</li> <li>• Gas and fire detection system</li> <li>• Multiple level indication</li> <li>• Develop emergency response procedures and provide training</li> </ul>	<ul style="list-style-type: none"> <li>• Probability is 1 – rare (<math>1.2 \times 10^{-5}</math>)</li> <li>• Severity level is 3– moderate</li> <li>• Risk level is 2– low to moderate</li> </ul>	Woodward & Pitbaldo, 2010

Accident Scenarios	Cause	Consequence	Mitigation/ Safeguards	Probability/ Severity/ Risk level	References
42. Hose connection failure	<ul style="list-style-type: none"> <li>Hose is damaged from external impacts (e.g. object hits the hose)</li> <li>User abuse (e.g. driving the vehicle over hose/nozzle)</li> </ul>	<ul style="list-style-type: none"> <li>In case of hose or flange connection fails, the</li> <li>The leakage erodes the flange face material.</li> <li>In case of LNG leaks on operator, skin damage as freeze burns can happen.</li> </ul>	<ul style="list-style-type: none"> <li>Provide quick release connector</li> <li>Provide breakaway coupling</li> <li>Inspection of hose for signs of distress or distortion</li> </ul>	<ul style="list-style-type: none"> <li>Probability is 2 – unlikely</li> <li>Severity level is 3 –moderate</li> <li>Risk level is 2– low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>Arnet, 2014s</li> <li>UNECE: Inland Transport Committee, 2015</li> </ul>
43. Hose rupture during transferring	<ul style="list-style-type: none"> <li>Damage/rupture of the hose from external impacts</li> <li>Hose become squeezed between two surfaces</li> </ul>	<ul style="list-style-type: none"> <li>LNG release as a spray or droplets or small leakage:</li> <li>The leakage erodes surrounding materials</li> <li>Nearby operators get injured by freeze burns</li> </ul>	<ul style="list-style-type: none"> <li>Quick release connector</li> <li>Breakaway coupling</li> <li>Automatic shutoff valve (excess flow valve)</li> <li>Equip dispensers with safety valves in their base</li> </ul>	<ul style="list-style-type: none"> <li>Probability is 2 – unlikely</li> <li>Severity level is 3 –moderate</li> <li>Risk level is 2– low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>UNECE: Inland Transport Committee, 2015</li> </ul>
44. Vehicle coupling failure	<ul style="list-style-type: none"> <li>Improper flushing operation</li> <li>Improper selection of fitting equipment</li> <li>Improper lubrication/sludging</li> <li>Poor seal because of freeze/thaw deterioration</li> </ul>	<ul style="list-style-type: none"> <li>Locking device failure</li> <li>External valve failure</li> <li>LNG release as a spray or droplets or small leakage</li> </ul>	<ul style="list-style-type: none"> <li>Perform visual inspections</li> <li>Maintenance and check the coupling frequently</li> <li>ESD System</li> <li>Proper flushing operation</li> </ul>	<ul style="list-style-type: none"> <li>N/A<sup>34</sup></li> </ul>	<ul style="list-style-type: none"> <li>Science Applications International Corporation, 1998</li> <li>Rathi Transpower Private Limited, 2011</li> </ul>

<sup>34</sup> The performance parameters of the LNG vehicle coupling are not known because of limited use (Rathi Transpower Private Limited, 2011)

Accident Scenarios	Cause	Consequence	Mitigation/ Safeguards	Probability/ Severity/ Risk level	References
45. Flushing failure	<ul style="list-style-type: none"> <li>Lack of inert gas/nitrogen/air</li> <li>Inert gas/nitrogen pumping failure</li> </ul>	<ul style="list-style-type: none"> <li>Formation of flammable mixtures in pipelines</li> <li>Damage of flange connection</li> </ul>	<ul style="list-style-type: none"> <li>Ensure that mixture of LNG and air is not present in the pipelines after purging</li> <li>Ensure oxygen content in the pipelines matches standard requirements</li> </ul>	<ul style="list-style-type: none"> <li>Probability is 2 – unlikely</li> <li>Severity level is 3 – moderate</li> <li>Risk level is 2– low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>Hidalgo et al., 2013</li> <li>Pelto, Baker, Holter, &amp; Powers, 1982</li> </ul>
46. ESD System Failure	<ul style="list-style-type: none"> <li>Improper install/maintenance</li> <li>Physical damage (e.g. mechanical overstress)</li> </ul>	<ul style="list-style-type: none"> <li>No safeguard when emergency situation occur.</li> <li>Leakage or spillage of LNG may cause LNG related hazards</li> </ul>	<ul style="list-style-type: none"> <li>Redundant sensors</li> <li>Apply strict testing procedure such as checking before the LNG transfer for the hidden failures</li> </ul>	<ul style="list-style-type: none"> <li>Probability is 3 (<math>3.95 \times 10^{-2}</math>)</li> <li>Severity level is 2 – negligible</li> <li>Risk level is 2– low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>Biamonte, 1982</li> <li>Hsua et al., 2010s</li> </ul>
47. Normal instrumentation failure	Same as no. 46 (above)	<ul style="list-style-type: none"> <li>Misunderstanding cause wrong decision and wrong operation</li> </ul>	<ul style="list-style-type: none"> <li>Provide ESD system</li> <li>Applying the proper maintenance, mitigation &amp; control techniques</li> </ul>	<ul style="list-style-type: none"> <li>Probability is 4 (highly probable)</li> <li>Severity level is 2 –negligible</li> <li>Risk level is 3– moderate to high</li> </ul>	<ul style="list-style-type: none"> <li>Biamonte, 1982</li> <li>Pelto, Baker, Holter, &amp; Powers, 1982as</li> </ul>
48. Collision of LNG filling station by vehicles	<ul style="list-style-type: none"> <li>Accidental collision</li> <li>Lack of attention of driver</li> </ul>	<ul style="list-style-type: none"> <li>The collision could attack filling machine leading to LNG leakage</li> <li>Leakage of LNG erode surrounding materials or harm nearby people</li> </ul>	<ul style="list-style-type: none"> <li>Protect dispensing unit from vehicle collision</li> <li>Use a dry-break system at LNG dispensing points</li> </ul>	N/A	<ul style="list-style-type: none"> <li>Federal Transit Administration, 1999</li> </ul>

<b>Accident Scenarios</b>	<b>Cause</b>	<b>Consequence</b>	<b>Mitigation/ Safeguards</b>	<b>Probability/ Severity/ Risk level</b>	<b>References</b>
49. Presence of ignition source inside LNG filling station	<ul style="list-style-type: none"> <li>• An ignition spark (e.g. electrical switch, cigarette, static electrical discharge, etc.)</li> </ul>	<ul style="list-style-type: none"> <li>• Possible thermal radiation effects on tank</li> <li>• LNG will burn if it leaks and met the ignition source</li> </ul>	<ul style="list-style-type: none"> <li>• Concrete outer shell can withstand radiation effects</li> <li>• Fire detection and emergency shutdown system</li> </ul>	N/A	<ul style="list-style-type: none"> <li>• PGS Publication, 2013</li> </ul>
50. Overfilling of LNG fuel in end-user vehicle	Same as no.41: LNG storage Tank overfill			<ul style="list-style-type: none"> <li>• Probability is 2</li> <li>• Severity level is 3–moderate</li> <li>• Risk level is 2–low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>• PGS Publications, 2013</li> <li>• UNECE, 2015</li> </ul>
51. Collision of the end-user vehicles during LNG loading in the station	<ul style="list-style-type: none"> <li>• Human error</li> <li>• Lack of training</li> </ul>	<ul style="list-style-type: none"> <li>• LNG release as a spray or droplets or small leakage:</li> <li>• The leakage erodes surrounding materials</li> <li>• Nearby operators get injured by freeze burns</li> </ul>	<ul style="list-style-type: none"> <li>• Clear signal for other vehicles during loading operation</li> <li>• Fire detection and emergency shutdown system</li> <li>• Dispensers are equipped with safety valves in their base</li> </ul>	N/A	<ul style="list-style-type: none"> <li>• European Commission's Directorate General for Mobility and Transport, 2013</li> </ul>
52. End-user drive away while hose is connected	<ul style="list-style-type: none"> <li>• Negligence of driver</li> <li>• Lack of training</li> </ul>	<ul style="list-style-type: none"> <li>• LNG which is still remained in hose leaks out</li> <li>• Freeze burns or brittle fractures can be resulted</li> </ul>	<ul style="list-style-type: none"> <li>• End-user Training</li> <li>• Fire detection and emergency shutdown system</li> <li>• Dispensers are equipped with safety valves</li> </ul>	<ul style="list-style-type: none"> <li>• Probability is 4</li> <li>• Severity level is 2–negligible</li> <li>• Risk level is 3–moderate to high</li> </ul>	<ul style="list-style-type: none"> <li>• Science Applications International Corporation, 1998</li> <li>• UNECE, 2015</li> <li>• Bikker, 2015</li> </ul>

<b>Accident Scenarios</b>	<b>Cause</b>	<b>Consequence</b>	<b>Mitigation/ Safeguards</b>	<b>Probability/ Severity/ Risk level</b>	<b>References</b>
53. End-users lack of knowledge and training	<ul style="list-style-type: none"> <li>• Poor information system</li> <li>• Ineffective training</li> </ul>	<ul style="list-style-type: none"> <li>• Risk of accident increases</li> <li>• Operational failures</li> <li>• General personnel hazards</li> </ul>	<ul style="list-style-type: none"> <li>• Develop training plan/ strategy to the end-user</li> </ul>	N/A	<ul style="list-style-type: none"> <li>• RODRIGUE S, 2013</li> </ul>
54. Miscommunication between terminal or filling station and truck/train operators	<ul style="list-style-type: none"> <li>• Poor communication system</li> <li>• Being unaware of the operators</li> </ul>	<ul style="list-style-type: none"> <li>• Risk of accident increases</li> <li>• LNG hazards related with loading operation such as the tanker truck/train drives away while LNG is loading</li> <li>• Operational failures</li> </ul>	<ul style="list-style-type: none"> <li>• Develop communication system</li> <li>• Adopt communication technology</li> </ul>	N/A	<ul style="list-style-type: none"> <li>• PGS Publications, 2013</li> <li>• RODRIGUE S, 2013</li> </ul>
55. Unclear/ outdated writing procedure	<ul style="list-style-type: none"> <li>• Poor information system</li> <li>• Management errors</li> </ul>	<ul style="list-style-type: none"> <li>• General personnel hazards</li> <li>• Risk of accident increases</li> <li>• Operational failures</li> </ul>	<ul style="list-style-type: none"> <li>• Develop information system</li> <li>• Develop document updating procedure</li> </ul>	N/A	<ul style="list-style-type: none"> <li>• Tusiani &amp; Shearer, 2007</li> </ul>
56. Error on maintenance system/ job complexity	<ul style="list-style-type: none"> <li>• Complex maintenance system</li> </ul>	<ul style="list-style-type: none"> <li>• General personnel hazards relate with maintenance activities</li> <li>• Mechanical damages on critical points (such as tees, elbows, supports, flanges, valves, etc.) lead to LNG leakage or spill.</li> </ul>	<ul style="list-style-type: none"> <li>• Operating and safety procedures</li> <li>• Operator training</li> <li>• Improve maintenance system</li> </ul>	<ul style="list-style-type: none"> <li>• Probability is 2 –unlikely</li> <li>• Severity level is 3– moderate</li> <li>• Risk level is 2– low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>• Tusiani &amp; Shearer, 2007</li> </ul>

Accident Scenarios	Cause	Consequence	Mitigation/ Safeguards	Probability/ Severity/ Risk level	References
57. Lack of proper training	<ul style="list-style-type: none"> <li>• Management errors</li> <li>• Planning errors</li> <li>• Underestimation of skills needed</li> </ul>	<ul style="list-style-type: none"> <li>• General personnel hazards</li> <li>• Risk of accident increases</li> <li>• Operational failures</li> </ul>	<ul style="list-style-type: none"> <li>• Thorough operator training should involve instruction or hands-on training</li> </ul>	<ul style="list-style-type: none"> <li>• Probability is 1 (<math>6.1 \times 10^{-6}</math>)</li> <li>• Severity is 3</li> <li>• Risk level is 2</li> </ul>	<ul style="list-style-type: none"> <li>• SKANGASS AS, 2013a</li> <li>•</li> </ul>
58. Inexperienced operators	<ul style="list-style-type: none"> <li>• Underestimation of skills needed</li> <li>• Management errors</li> </ul>	<ul style="list-style-type: none"> <li>• General personnel hazards</li> <li>• Risk of accident increases</li> <li>• Operational failures</li> </ul>	<ul style="list-style-type: none"> <li>• Proper supervision</li> <li>• Intensive training</li> </ul>	<ul style="list-style-type: none"> <li>• N/A</li> </ul>	<ul style="list-style-type: none"> <li>• RODRIGUES, 2013</li> <li>• Yun, 2007</li> </ul>
59. Lightning strike	<ul style="list-style-type: none"> <li>• Lightning during bad weather</li> </ul>	<ul style="list-style-type: none"> <li>• It could strike sharp high points on the terminal</li> <li>• This lightning can travel to other LNG carrying equipment like pipelines.</li> <li>• If LNG leaks, fire hazards could occur and cause damage to infrastructure or human</li> </ul>	<ul style="list-style-type: none"> <li>• Fire snuffing system on tank top and vent stack</li> <li>• Consider radiation effects from ignition in vent stack design</li> <li>• Instrumentation system designed for fail safe condition</li> </ul>	<ul style="list-style-type: none"> <li>• Probability is 1</li> <li>• Severity level is 4– extensive</li> <li>• Risk level is 2– low to moderate</li> </ul>	<ul style="list-style-type: none"> <li>• Carpenter &amp; McIvor, 1996</li> </ul>
60. Earthquake/ Tsunami	<ul style="list-style-type: none"> <li>• Seismic loading agitation to a structure</li> </ul>	<ul style="list-style-type: none"> <li>• LNG release from the pipes</li> <li>• LNG release from the containment tanks</li> <li>• The leak cause release of a flammable vapor cloud which could ignite immediately and lead to a fire/ explosion</li> </ul>	<ul style="list-style-type: none"> <li>• Geotechnical studies</li> <li>• Storm water drainage system</li> <li>• Develop Tsunami warning procedures for</li> </ul>	<ul style="list-style-type: none"> <li>• Probability is 1 (extremely unlikely)</li> <li>• Severity level is 5– significant</li> <li>• Risk level is 3– moderate to high</li> </ul>	<ul style="list-style-type: none"> <li>• Beggs &amp; Warren, 2009</li> <li>• Southwell, 2005S</li> </ul>

<b>Accident Scenarios</b>	<b>Cause</b>	<b>Consequence</b>	<b>Mitigation/ Safeguards</b>	<b>Probability/ Severity/ Risk level</b>	<b>References</b>
61. Terrorist attack <sup>35</sup>	<ul style="list-style-type: none"> <li>Personal intent to cause harm and spread fear to people due to political, ideological, or religious convictions</li> </ul>	<ul style="list-style-type: none"> <li>LNG hazards such as pool fire, drifting vapor cloud, Rapid Phase Transition, etc. are expected.</li> <li>For the worst case is devastating explosion can occur.</li> </ul>	<ul style="list-style-type: none"> <li>Security plan for the LNG facilities, and all LNG carrier/cargo</li> <li>Controlled access of LNG facilities</li> <li>Routine security guard check</li> </ul>	<ul style="list-style-type: none"> <li>Probability is 2 –unlikely</li> <li>Severity level is 4– extensive</li> <li>Risk level is 3– moderate to high</li> </ul>	<ul style="list-style-type: none"> <li>Clarke, 2005</li> <li>Marks, 2003</li> </ul>

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<sup>35</sup> LNG facilities are a possible terrorist target, however they are located at remote areas. Therefore they have low attractiveness compared to other assets (Southwell, 2005).

## Appendix C. Questions for LNG Interviews

### C.1 PART 1: Risk Identification

1. If we talk about LNG transportation from import terminal via tanker truck or tanker train to LNG fueling station (whole chain), which are the top 5 hazard scenarios according to you?

2. There are 4 tables below which separated by each phase of LNG transportation chain. Please rate this following accident scenarios on the scale of 1 to 5 for the column of probability (likelihood of occurrence) and severity which has scale definition below:

		Likelihood of Occurrence	
1	$\geq 10E-4/yr$	Rare	
2	$< 10E-4/yr$	Unlikely	
3	$< 10E-3/yr$	Possible	
4	$< 10E-2/yr$	Likely	
5	$< 10E-1/yr$	Almost certain	

		Likelihood					
Severity		0	1	2	3	4	5
1	Safety						
1	Accident with first aid. No permanent injury		1 - Low	1 - Low	2 - Low to moderate	2 - Low to moderate	3 - Moderate to high
2	Accident with medical treatment and restricted work.		2 - Low to moderate	2 - Low to moderate	2 - Low to moderate	3 - Moderate to high	3 - Moderate to high
3	Accident with lost workday		2 - Low to moderate	2 - Low to moderate	3 - Moderate to high	3 - Moderate to high	4 - High
4	Accident with permanent injury 100 % disabled for work. One fatality		2 - Low to moderate	3 - Moderate to high	4 - High	4 - High	5 - Very high
5	Multiple fatalities		3 - Moderate to high	4 - High	4 - High	5 - Very high	5 - Very high

Phase 1: Import Terminal		Probability	Severity
Jetty	1. Collision of LNG ship by the other vessels		
	2. Small leakage of unloading arm		
	3. Rupture of unloading arm		
Pipeline	4. Leakage of LNG line from adjacent fire		
	5. Leakage of LNG line from high velocity erosion		
	6. Rupture of BOG line from external impact		
	7. Collision with pipe bridge		
Storage tank	8. LNG storage tank rollover		
	9. LNG storage Tank overflow		
	10. LNG storage tank foundation frost heave		



	11. Accidental drop of LNG immersed pump		
Auxiliary	12. Liquid lock in the valve		
	13. Corrosion of metallic components		
	14. Boiler Explosion		
	15. ESD Failure (safety instrumentation such as safety valve)		
	16. Normal instrumentation failure (e.g. pressure indicator)		
	17. Cool-down failure		
	18. Purging failure		
Process	19. Loss of power supply		
	20. Loss of emergency power supply		
	21. Loss of Nitrogen		
	22. Loss of hydraulic system compressed air		
	23. Rupture of gas transportation line		
<b>Phase 2: LNG tanker truck/train</b>		<b>Probability</b>	<b>Severity</b>
Tanker	24. Sloshing in tanker truck/ train cause overturn		
	25. Overfilling in tanker truck/train		
	26. Overpressure in tanker truck/train		
	27. Liquid lock in the valve/ Valve failure		
Auxiliary	28. Flexible hose failure		
	29. Flange connection on truck/train failure		
	30. Flushing failure		
	31. ESD Failure		
	32. Normal instrumentation failure		
Loading area	33. Collision of LNG tanker truck with the other vehicles while loading at terminal		
	34. Collision of LNG tanker train with the other vehicles while loading at terminal		
	35. Collision of LNG tanker truck with the other vehicles while loading at filling station		
	36. Collision of LNG tanker train with the other vehicles while loading at filling station		
	37. Tanker truck/train ride over hose		
Driving	38. Collision of LNG tanker truck with the other vehicles while riding		
	39. Collision of LNG tanker train with the other vehicles while riding		

<b>Phase 3: LNG filling station</b>		<b>Probability</b>	<b>Severity</b>
	40. Leakage of LNG from storage tank from external load		
	41. LNG storage tank overfill		
	42. Hose connection failure		
	43. Hose rupture during transferring		
	44. Vehicle coupling failure		
	45. Flushing failure		
	46. ESD (Emergency Shut Down) System Failure		
	47. Normal instrumentation failure (e.g. Pressure indicator)		
	48. Collision of LNG filling station by vehicles		
	49. Presence of ignition source inside LNG filling station		
	50. Overfilling of LNG fuel in end-user vehicle		
	51. Collision of the end-user vehicles with the other vehicles during LNG loading in the station		
	52. End-user drive away while hose is still connected		
	53. End-users lack of knowledge and training		
	54. Miscommunication between terminal or filling station and truck/train operators		
<b>Phase 4: For General situations</b>		<b>Probability</b>	<b>Severity</b>
	55. Unclear/Outdated writing procedure		
	56. Error on maintenance system/ job complexity		
	57. Lack of proper training		
	58. Inexperienced operators		
	59. Lightning strike		
	60. Earthquake/ Tsunami		
	61. Terrorist attack		

## C.2 Part 2: How to deal with the risks of LNG transportation

3. Which business partner (both government and private) help you to reduce the risks of LNG operation?

4. In the future, what is the most efficient way to deal with accident of LNG transportation and operation?

### C.3 Part 3: Stakeholders Value

5. According to you, what are the values you observe that come first? ( you can imagine if you are a customer who is deciding to purchase LNG equipment or you are provider or consultant when your customer is deciding to buy LNG equipment/support service from you.)

6. From question 5, what are the dominant values which relate to LNG transportation? Please rank them from 1 (which is the most important) to 7 (which is least important).

- ☐ Reliability: the failure probability of a system in which its functions cannot be fulfilled
- ☐ Availability: the time duration in which the system is functional and its functions can be fulfilled
- ☐ Maintainability: the ease in which the system can be maintained over time
- ☐ Safety (and Security): the absence of human injuries during using or maintaining the system
- ☐ Environment: influence of the system on its direct physical environment
- ☐ Economics: a serious reflection in terms of costs versus benefits
- ☐ Politics

7. Do you think in the future; which value will be the most dominant in LNG field?

## Appendix D. Stakeholder's list identification for value

Stakeholder category	Business type	No	Interviewee's Name	Organization	Date of Interview
Private company	Import Terminal	1	Linard Velgerdijk	Gate Terminal, NL	4 <sup>th</sup> June, 15
		2	Yuttasart Promban	PTTLNG, TH	2 <sup>st</sup> Oct, 15
	LNG related equipment supplier	3	Sander Verweij	Gutteling BV: Composite Hoses, NL	2 <sup>nd</sup> Oct, 15
		4	Joe V. George	CB&I, NL	22 <sup>nd</sup> May, 15
		5	Pitiporn Thammongkol		23 <sup>th</sup> Apr, 15
		6	Rene Gravendijk	Thm GAASBEEK B.V., NL	7 <sup>th</sup> , Oct, 15
	LNG tanker truck & LNG filling station	7	Marcel Bikker	Rolande LNG, NL	5 <sup>th</sup> Oct, 15
	Consultant	8	Bas van den Beemt	TNO, NL	8 <sup>th</sup> Oct, 15
		9	Ruijter Bram	Antea Group, NL	29 <sup>th</sup> Apr, 15
Government and academic institution	Academic Institution	10	Jos Theunissen	TPM Faculty, TU Delft, NL	8 <sup>th</sup> Feb, 15
		11	Mirek Kaminski	3ME Faculty, TU Delft, NL	19 <sup>th</sup> May, 15
		12	Udo Pesch	TPM Faculty, TU Delft, NL	23 <sup>rd</sup> June, 15
	Government Body	13	Fitri Yustina	Indonesia Investment Coordinating Board	28 <sup>th</sup> Aug, 15
Citizens		14	Soontree Umbangtalad	Arnhem, NL	1 <sup>st</sup> June, 15
		15	Keshav Bhatt	Rotterdam, NL	24 <sup>th</sup> Apr, 15
		16	Pierluca D'agnese	Delft, NL	13 <sup>rd</sup> May, 15
		17	Amphon Jeamsa-nga	Bangkok, TH	19 <sup>th</sup> Oct, 15
		18	Ariya Phathanachindakit	Bangkok, TH	23 <sup>rd</sup> Oct, 15

## Appendix E. Chronological list of LNG accidents

No	Date	Location	Cause of failure	LNG spilled/ released	Consequence	Description
1	Oct. 1944	Cleveland, Ohio (USA)	failure of a low-nickel LNG storage tank	Yes	124 deaths 200 – 400 Injures  Damages from explosion	During World War II due to rationing, the storage tank was built with a low-nickel content (3.5%) alloy steel and the shell insulation was cork and crushed peanut shell. Exposed to the extremely cold LNG, three tanks failed shortly. This caused the LNG to spill into the city sewer system. The LNG vaporized, ignited, exploded, and burned (Elliott, Seibel, Brown, Artz, & Berger, 1946; National Association of State Fire Marshals (NASFM), 2005).
2	19641965	Arzew (Algeria)	Lightning struck the vent-riser	No	Small equipment damaged	The incidents occurred first during LNG loading and second during the departure of ship. Lightning struck the vent-riser <sup>36</sup> of the LNG ship and ignited vapor that was being vented through the ship venting system. The flame was quickly extinguished by purging with nitrogen through a connection to the riser (CHIV International, 2012; Darwish, 2007).
3	May 1965	Arzew (Algeria)	Overfilling (instrument error)	Yes	Fracture of the cover plating of the tank and deck	While loading of a LNG ship, overflowing caused fracture of the cover plating of the tank and of the adjacent deck plating. The cause has been mainly attributed to failure of liquid level instrumentation and unfamiliarity with equipment by the cargo handling watch officer (CHIV International, 2012; Mannan, 2004).

<sup>36</sup> The vent-riser is the piping for venting the air from a LNG tank, which being submerged was under sea pressure.

No	Date	Location	Cause of failure	LNG spilled/ released	Consequence	Description
4	May 1965	Canvey Island, Essex, UK	Error from maintenance operation	Yes	1 seriously burned	During maintenance, a small amount of LNG spilled from the tank. This spill got ignited and one worker was seriously burned (Chan, Hartline, Hurley, & Struzziery, 2004).
5	May 1965	Vessel named Methane Princes <sup>37</sup>	Improper disconnect caused leak (human error)	Yes	Deck fractures	Before the lines had been completely drained, premature disconnection of LNG discharging arms, caused the LNG liquid to pass through a partially opened valve and leak. To combat the effects of the leak, seawater was used, but still fracture appeared in the deck plating (CHIV International, 2012).
6	Nov, 1969	Kenai, Alaska	Sloshing from partial filling of LNG tank	N/A	Damage of LNG cargo tank	<p>During LNG unloading, gas leakage was detected at a primary barrier of the tank. They found that part of the supports for the cargo pump electric cable tray to break loose, resulting in several small holes (perforations) of the primary barrier (CHIV International, 2012).</p> <p>The investigation showed that this failure was the consequences of partial filling of the tank (sloshing)<sup>38</sup>. For this filling, the liquid motions in some point created the tank overpressures (Gilles, 1972).</p>

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<sup>37</sup> There is no record for the location of the accident cannot be found.

<sup>38</sup> The root cause of sloshing accidents might come from procedural error which lead to operation error, or only operation error which could cause from human error. However, there is no detailed record.

No	Date	Location	Cause of failure	LNG spilled/ released	Consequence	Description
7	Sept, 1970	Negishi, Japan	Sloshing from partial filling of LNG tank	N/A	LNG cargo tank deformations	Due to bad weather and a partially filling of LNG cargo tank, the strong motions of LNG caused the rupture of the electric wires. The fragments of these wire supports made perforations at the tank bottom. Also, tank inspection found deformations of the primary barrier. One of these deformations had produced a leak into the barrier (CHIV International, 2012).
8	1971	La Spezia, Italy	LNG rollover (procedural error)	N/A	The roof of the storage tank damaged	After eighteen hours of filling, the tank in the ship developed a sudden increase in pressure causing LNG vapor to discharge from the tank safety valves. This also damaged the roof of the tanks. Large amount of LNG vapor flowed out of the tank. No ignition took place. This occurred due to the rollover phenomenon (Chan et al., 2004).
9	Jan. 1972	Montreal, Canada	<ul style="list-style-type: none"> <li>Human error</li> <li>Instrumentation failure</li> <li>Flammable area</li> </ul>	Yes as vapor	Damages from explosion	During defrosting operations, the valves on the nitrogen were not closed after completing the operation. This caused over-pressurization of the compressor leading to a back flow of natural gas from the compressor to the nitrogen line. Natural gas entered the control room (where operators were allowed to smoke) and an explosion occurred when an operator tried to light a cigarette. No report about detailed damages (Chan et al., 2004).
10	Jul. 1974	Massachusetts, USA	Loss of power supply	Yes	Deck fractures	While LNG was being loaded on the barge, power failure occurred. This caused the automatic closure of the main liquid line valves. However, a small amount of LNG leaked from a 1-inch nitrogen-purge globe valve. This caused several fractures in the deck plates that were contacted by the LNG spill. Around two meters of area was deluged with 40 gallons of LNG spill (CHIV International, 2012).

No	Date	Location	Cause of failure	LNG spilled/ released	Consequence	Description
11	Sept. 1977	Bontang, Indonesia	Level alarm was set too high caused tank overfilled	Yes	No report	During the filling of a cargo tank, LNG overflowed through the vent mast. Since, the high-level alarms of the liquid level gauge system were set in the override mode to prevent nuisance; the overflow went undetected (CHIV International, 2012).
12	Mar. 1978	Das Island, UAE	Pipe connection of an LNG tank failed	Yes, inside the LNG tank.	N/A	LNG spill inside the LNG tank containment due to a pipe connection of LNG tank failed. Internal valve stopped the liquid flow resulting in a large vapor cloud dissipated without ignition (Rijnmond Public Authority, 1982)
13	Apr. 1979	Cove Point, Maryland, USA	Check valve failed during unloading	Yes	deck fracture	While LNG was unloading, a check valve in the piping system of the vessel failed causing an LNG release. Even the ESD system and water spray systems were activated, fractures of the deck plating occurred (BASHA, 2012).
14	Oct. 1979	Cove Point, Maryland, USA	<ul style="list-style-type: none"> <li>Poorly pump seal caused leak</li> <li>No gas detection</li> </ul>	Yes as vapor	1 death 1 seriously Burned  Damages from explosion	LNG leaked through a loose LNG pump seal. It vaporized and flowed to the substation where no gas detectors had been installed. The flammable vapor was ignited by the arcing contacts of the circuit breaker, resulting in an explosion (CHIV International, 2012; NTSB (National Transportation Safety Board), 1980; Woodward & Pitbaldo, 2010).
15	Apr. 1983	Bontang, Indonesia	<ul style="list-style-type: none"> <li>Flange failure</li> <li>Over-pressure</li> </ul>	Yes as vapor	3 deaths  Damages from fire	During dry-out and purging, the heat exchanger ruptured due to over pressurization caused by a blind flange left in a flare line. The designed pressure of the heat was at 1.76 bar while the gas pressure reached 34.5



No	Date	Location	Cause of failure	LNG spilled/ released	Consequence	Description
						bar. The rupture resulted in projected debris and fire. Three workers were killed (CHIV International, 2012; Darwish, 2007; Harris, 1993).
16	Dec.1983	Sodegaura, Japan	<ul style="list-style-type: none"> <li>LNG ship moved</li> <li>Loading arms failure</li> </ul>	Yes	No report	During cooldown of the cargo transfer arms, prior to LNG unloading, the ship suddenly moved under its own power. The unloading arms sheared and LNG spilled. No ignition occurred (Woodward & Pitbaldo, 2010).
17	1985	Barcelona, Spain	Valve failure	Yes	Deck fractured	Failure of LNG tank in the vessel caused LNG overflow during unloading. LNG release resulted in deck fractured due to low temperature embrittlement (CHIV International, 2012; Harris, 1993)
18	1988	Everett, WA, USA	Improper LNG transfer	Yes	N/A	Operation of LNG transfer was interrupted, resulting spillage of around 30,000 gallons <sup>39</sup> of LNG through a blown flange gasket. The spill was contained in a small area. Also, a stable atmosphere prevented the vapor cloud from propagating (BASHA, 2012; Chan et al., 2004).
19	1989	Thurley, UK	<ul style="list-style-type: none"> <li>Improper operation</li> <li>Human error</li> </ul>	Yes	2 operators burned	While cooling down vaporizers, drain valves were opened. When pumps were started and LNG entered the vaporizers, high pressure LNG was released through the opened drain valves. The vapor cloud ignited, resulting in flash fire which burned the face and hands of two operators (Woodward & Pitbaldo, 2010).

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<sup>39</sup> 1 Gallon (Fluid, US) = 3.7854118 Liters

No	Date	Location	Cause of failure	LNG spilled/ released	Consequence	Description
20	Feb. 1989	Skikda, Algeria	Severe weather condition	Yes	Unloading arms and piping damaged	During LNG unloading, the strong wind blew ship from its berth, resulting in sheared unloading arms sheared and heavy damages of piping on ship. LNG was released from the cargo transfer arms (CHIV International, 2012; Woodward & Pitbaldo, 2010)
21	1992	Balti-more, USA	Relief valve failure	Yes	Tank damaged	A failure of relief valve on LNG piping made it opened for over 10 hours which led to release of LNG around 25,000 gallons. This released into the storage tank containment resulting in brittle fractures on the outer shell of the LNG tank (CHIV International, 2012).
22	1993	Bontang, Indonesia	Pipe rupture during maintenance	Yes	Sewer system damaged	During a pipe modification project, LNG leaked from pipeline into the underground sewer system. LNG underwent rapid vapor expansions that ruptured the sewer pipes (BASHA, 2012).
23	Jan. 2004	Skikda, Algeria	LNG release from a pipeline was ignited upon ingestion into the boiler	Yes	27 deaths 80 injured  Damages from fire and explosion	A refrigerant pipeline leaked and a large amount of vapors escaped from the pipeline. The vapors formed a highly flammable and explosive cloud which hovered over the facility. Then the vapors were pulled into a high pressure steam boiler, resulting in the boiler got fire and exploded. After coming into contact with a flame source, the massive vapor-cloud exploded. An explosive fire and a fireball that damaged surrounding LNG facilities (National Association of State Fire Marshals (NASFM), 2005; Sonatrach, 2004; Woodward & Pitbaldo, 2010).
24	Jul. 2004	Ghislenghi en, Belgium	Rupture of LNG gas pipeline	Yes as vapor	24 deaths 132 injured from fire and explosion	Earthworks which held at the site accidentally damaged the gas pipeline, resulting in a gas leak. The gas cloud ignited, producing a fireball that finally became explosion (French Ministry for Sustainable Development, 2009).

No	Date	Location	Cause of failure	LNG spilled/ released	Consequence	Description
25	June 2002	Tivissa, Spain	Road accidental collision (human error)	Yes	1 death 2 injured  LNG-related BLEVE (BLEVE like)	<p>An LNG tanker truck speeding overturned and caught fire. Due to the accident, few external connections got ruptured which leaked LNG and fed the fire. The flame became very fierce since it fed probably by both the diesel oil from the truck and by LNG leaks from the broken pipe connecting the cargo tank. The cargo tank which was a simply single wall construction insulated externally with unprotected polyurethane<sup>40</sup> insulation could not tolerate the overpressure.</p> <p>After 20 minutes, the tank exploded and a large fireball resulted. The tank structure was broke, distorted, and ejected to several fragments.</p> <p>Further damage was caused by thermal radiation and a pressure wave which flew debris (glass, metal). The mechanical effects were very severe. The truck driver died and two people suffered burn injuries 200 meters away (Planas et al., 2015; Planas-Cuchi et al., 2004; Woodward &amp; Pitbaldo, 2010)</p>
26	Oct. 2011	Murcia, Spain	Road accidental collision (human error)	Yes	1 death LNG-related BLEVE (BLEVE like)	<p>Since the driver was over-speeding, an LNG tanker truck could not be controlled. It ran into the back of the parked lorry and immediately caught fire. It seems more likely that the crash caused rupture on the central loading cabinet of the tank, resulting in LNG leaks. But the subsequent very strong fire was due to both the crash and the vehicle's engine acting as an ignition source.</p>

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<sup>40</sup> Polyurethane is a combustible and self-extinguishing substance (Planas-Cuchi et al., 2004).

No	Date	Location	Cause of failure	LNG spilled/ released	Consequence	Description
						In an LNG tanker truck, the LNG is normally stored at atmospheric pressure. However, due to very high relief valve set point in this case, the LNG heated and built up a high pressure approximately 8 bars. At this high pressure the stored LNG no longer had properties and hazards of an atmospheric pressure fluid. This highly pressurized and heated LNG escaped from the tank and formed a large fireball. After 71 minutes of the collision, the tanker exploded. The impacts were known in terms of thermal radiation, overpressure blast wave and flying shrapnel (Planas et al., 2015; Planas-Cuchi et al., 2004).
27	2015	LNG filling station	End-user drive away while hose is connected (Human error)	Yes	Nozzle damaged Hose rupture	An LNG end-user (LNG-fueled truck driver in this case) drove away from LNG filling station while the nozzle was still connected. This made the hose broken into two pieces due to forcefully pull. LNG, which remained in the hose, leaked out. It had no damage since the small amount of LNG leakage was quickly evaporated (Bikker, 2015; Science Applications International Corporation, 1998)

## Appendix F. Summary of LNG Hazards

No	Causes (LNG Properties)	Hazards	Consequence	Mitigation	Occurred Accident <sup>41</sup>
1	<ul style="list-style-type: none"> <li>LNG is non-toxic but it can replace oxygen in a confined space</li> <li>LNG is colorless and odorless</li> </ul>	Asphyxiation	<ul style="list-style-type: none"> <li>In low oxygen concentrations areas (methane in air concentrations of 50% by volume), humans suffer from suffocation symptoms such as breathing difficulties</li> <li>Consequences of asphyxiation can be from the ability to respond deteriorates, muscle coordination weakens, or even death</li> </ul>	<ul style="list-style-type: none"> <li>Minimize congestion and confined spaces of LNG facilities (e.g. keep transfer lines in open areas)</li> <li>Operators work in low oxygen areas should be completely protected</li> </ul>	No exactly report
2	LNG is a cryogenic liquid (- 161° C)	Brittle fracture	<ul style="list-style-type: none"> <li>When carbon steel and low alloy steel get in contact to LNG, a collapse of their structures is likely to occur</li> <li>The embrittlement combined with the high thermal induced strains can causes damage of normal steel (e.g. ship deck and tank covers) or insulation damage</li> </ul>	<ul style="list-style-type: none"> <li>Select appropriate materials which are not affected by brittle fracture</li> <li>Protect and insulate all grades of standard carbon steel from any possible exposure to LNG spillage</li> <li>Install a leak detection system and automatic cut-off valve</li> </ul>	No exactly report

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<sup>41</sup> See Appendix E

No	Causes (LNG Properties)	Hazards	Consequence	Mitigation	Occurred Accident <sup>41</sup>
		Freeze burns	<ul style="list-style-type: none"> <li>Contact with LNG or LNG vapor can cause severe damage to the skin and eyes</li> </ul>	<ul style="list-style-type: none"> <li>Prepare adequate Personal Protective Equipment (PPE) for operators (e.g. gloves, insulated clothing)</li> <li>Install remotely operated valves</li> </ul>	<ul style="list-style-type: none"> <li>3, 5, 6, 7, 10, 13, 17, 22, 21</li> </ul>
3	<ul style="list-style-type: none"> <li>To be flammable, only the vapor (above an LNG spill) is ignited</li> <li>The LNG vapor will ignite when vapor concentration is in flammable range of between 5-15% and an ignition source is present</li> </ul>	<p>If LNG ignites, different fire risk scenarios can occur :</p> <ul style="list-style-type: none"> <li>Flash fire</li> <li>Jet Fire</li> <li>Pool fire</li> <li>Vapor Cloud Explosion (VCE)</li> </ul>	<ul style="list-style-type: none"> <li>Each fire form has different characteristics leading to different consequences:</li> <li>Flash fire could result in severe consequences to anyone within the flames, but low risk for public exposure outside of the vapor cloud's flammable area</li> <li>Jet fire can occur under pressure. It is unlikely for an LNG storage tank since LNG is not stored under pressure. Severe damage would be confined to a local area.</li> <li>Pool fire generates significant thermal radiation. It can cause extensive damage to life and property</li> <li>When LNG spills, its evaporate can be visibly seen as a vapor cloud. The explosion occurs if a vapor cloud is confined and an</li> </ul>	<ul style="list-style-type: none"> <li>Strictly control potential ignition sources (e.g. electricity sparks, heat sources)</li> <li>Provide adequate separation distances from public areas and LNG facilities</li> <li>Provide protection structures (e.g. firewalls)</li> <li>Provide radiation shields for areas with personnel</li> <li>Apply LNG leak detection systems (e.g. monitoring of vapor pressure, temperature and liquid level, direct sensing of gas)</li> <li>Apply emergency shutdown systems</li> <li>Apply pressure relief devices</li> </ul>	<ul style="list-style-type: none"> <li>2, 4, 15, 20, 25, 26</li> </ul>

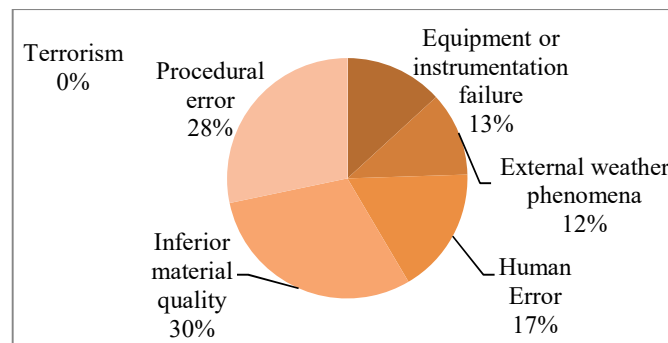
No	Causes (LNG Properties)	Hazards	Consequence	Mitigation	Occurred Accident <sup>41</sup>
			ignition source is encountered within the range of flammability •		
4	LNG in liquid phase is around 600 times in volume less than LNG in gaseous phase	RPT	• An RPT is occurred when a liquid rapidly changes phase to vapor, which means the volume of the LNG instantly expands 600 times due to vapor generation. This huge volume increases may result in an air or waterborne blast wave	• Build strong vessels and transfer equipment capable of withstanding small overpressure	• No exactly report
5	LNG can spontaneous mix up of two different gaseous cargos due to changes in the density of upper and lower layers	Overpressure due to rollover	• When this situation occurs, stratification develops and the unstable condition relieves itself with spontaneous mixing known as rollover • Tank over pressurization and excessive boil-off leading to emergency venting is the likely consequence of such occurrence	• Practice proper transfer procedures • Using jet nozzles, recirculation, distributed fill systems, and alternate top and bottom filling • Measure temperature and density gradient along the tank • Regular sampling and analysis of boil-off gas including monitoring of boil-off gas quantity	• 8

## Appendix G. Detailed of CCA in each phase of the LNG chain

From Chapter 5, we can see that the final results of causes and consequences analysis from the whole LNG transportation chain [see Appendix B] are present. In this appendix, CCA is present in more detail by separating the accident scenarios as per their phase of occurrences, i.e. import terminal phase, truck/train transportation phase, filling station phase, and general accident.

### G.1 Phase 1: import terminal

In this section a synthesis of the 61 accident scenarios [See Appendix B] over the entire LNG transportation is performed. The synthesis involves a proportional and graphical analysis of the 61 accident scenarios. Finally, a comparison of the overall 61 accident scenarios is done with the historical accident data [see Appendix E and Appendix F].



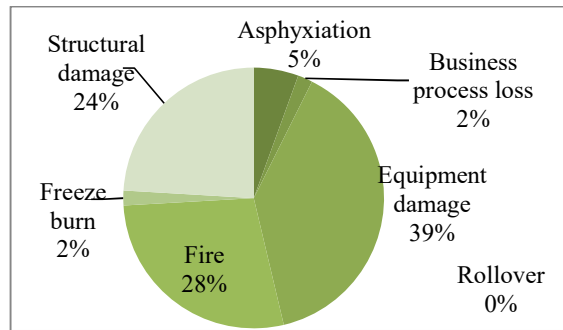
**Figure 21: Causes of accident scenarios in import terminal**

As can be seen from Figure 21, majority of the accident scenarios in this phase are caused in descending order due to:

1. Inferior material quality
2. Procedural error
3. Human error

At the import terminal, the operation is continuous and large quantities of LNG are processed. The operational characteristics are also extreme due to the variation in the operational temperature (cryogenic to normal) leading to material deterioration. In case, material used is inferior, an accident can occur, this can occur despite regular checks. The second major cause is procedural error; correct procedures can immensely help in the continuity of process, while incorrect procedures can lead to risks. Finally, human error accounts for the third major cause of risk scenarios. According to Reason (2000), the occurrence of procedural and human errors as a major chunk of errors can be attributed to them being eventually corresponding facets of human fallibility. Furthermore, human fallibility is the major cause of accidents (Reason, 2000b).





**Figure 22: Consequences of accident scenarios in import terminal**

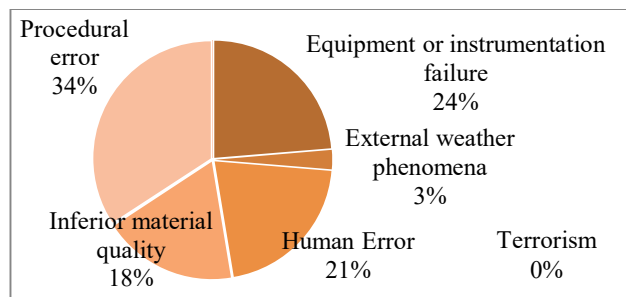
The consequences of these scenarios in this phase can be seen from Figure 23 to be in descending order due to:

1. Equipment damage
2. Fire
3. Structural damage

As in the above figure, the consequences relate to the causes. Since, the import terminal is a phase of continuous operation, in case an accident scenario does occur, it will firstly cause damage to the equipment carrying it. Secondly after it has damaged the equipment, the release of LNG (typically with high pressure) can lead to a fire event. The consequences though do create conditions for a fire, the import terminal being a widely open area, prevents the occurrence of fire. Finally, if the magnitude of the accident is high enough it can cause structural damage to the plant. In this section, the trend of equipment damage and fire being the major consequences is observed.

Hence, the proportion and presence of causes and consequences are in order of expectation.

## G.2 Phase 2: LNG transportation by tanker truck/train

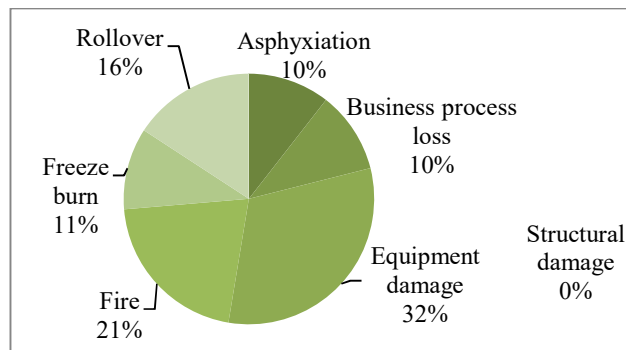


**Figure 24: Causes of accident scenarios in tanker truck/train transportation**

As can be seen from Figure 23, majority of the scenarios in this phase are caused in descending order as:

1. Procedural error
2. Equipment or instrumentation failure
3. Human error

In the tanker truck/train transportation phase, similar to the import terminal phase, the procedural and the human errors form a major chunk of the cause of accident scenarios. As discussed previously, this is because them being corresponding facets of human factors. Moreover, the same trend of procedural errors having a higher share than human errors is observed in this section too. Compared to the import terminal, in the tanker truck/train phase, since the equipment is not in a continuous operation, thus rather than inferior quality, their independent failure is a greater cause of accidents.



**Figure 25: Consequences of accident scenarios in tanker truck/train transportation**

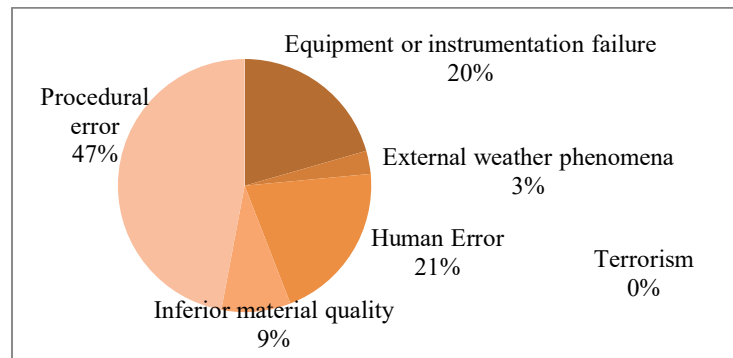
The consequences of these scenarios in this phase can be seen from Figure 24 to be in descending order as:

1. Equipment damage
2. Fire
3. Rollover

As in the previous section, the consequences relate to the causes. Whenever, a transportation accident (on the road or railway) occurs, the first point of damage will be the equipment carrying the LNG, which here refers to the tanker and the instrumentation connected to the tanker. Secondly after the damage of equipment, the release of LNG (typically with high pressure) can lead to a fire event. The equipment that is being damaged here refers mainly to the tanker and the instrumentation attached to the tanker which gets damaged during an accident. In case of tanker truck/train transportation too, the absence of confined space prevents the occurrence of fire. But if it does occur (in an open public space e.g. highways) it can cause a high degree of damage. Finally, rollover is a consequence present only in this phase. It is caused due to the human factor of improper filling of the tanker, causing a shift in the center of gravity leading to rollover of the vehicle. In this section too, the trend of equipment damage and fire being the major consequences is observed.

Hence, the proportion and presence of causes and consequences are in order of expectation.

### G.3 Phase 3: LNG filling station

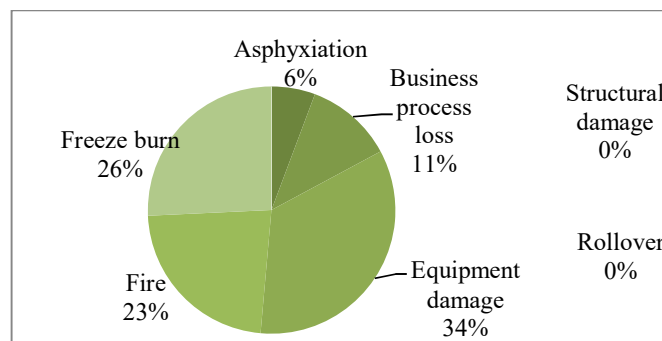


**Figure 26: Causes of accident scenarios in filling stations**

As can be seen from Figure 25, majority of the accident scenarios in this phase are caused in descending order as:

1. Procedural error
2. Human error
3. Equipment or instrumentation failure

In the filling station phase, it can be seen similar to the previous sections, procedural and human errors form a major chunk of the cause of accident scenarios. As discussed previously, this is because they are corresponding facets of human factors. Moreover, the same trend of procedural errors having a higher share than human errors is observed in this section too. Similar to the tanker truck/train phase, since the equipment is not in a continuous operation, thus rather than inferior quality, their independent failure is a greater cause of accidents.



**Figure 27: Consequences of accident scenarios in filling stations**

The consequences of these accident scenarios in this phase can be seen from Figure 26 to be in descending order as:

1. Equipment damage

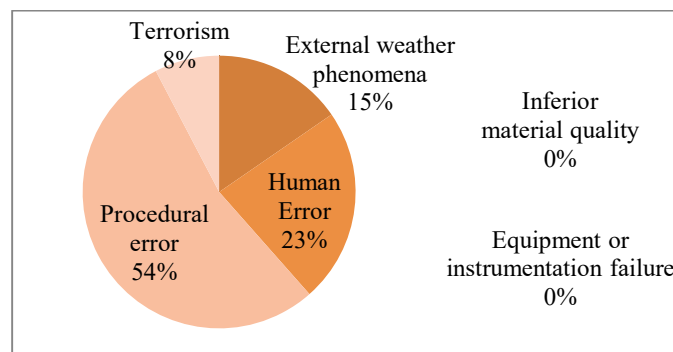
2. Freeze burn
3. Fire

As in the previous section, the consequences relate to the causes. Unlike the equipment damage in tanker truck/train phase, these equipment damages are mainly damage to hose and dispenser of the filling station. These damages occur primarily because human and procedural errors e.g. forgetfulness, lack of training, lack of supervision, lack of responsibility. Compared to the drivers of LNG tanker truck/train, the drivers here are lay-drivers and comparatively less trained. This leads to equipment damage e.g. due to the driver, driving over the hose, handling the hose roughly, driving away when the hose is plugged in, asking their handy-man to complete the filling operation while they attend to other affairs etc. Freeze burns also occur due to a conjunction of human and equipment factors e.g. the driver not paying attention to the remaining LNG in the hose and spilling this LNG on himself. Fire is also caused due to leakage of LNG in conjunction with hose human factors such as smoking or usage of mobile phones in the premises etc. Similar to previous sections, the trend of equipment damage and fire being the major consequences is observed.

Hence, the proportion and presence of causes and consequences are in order of expectation.

#### G.4 General accidents scenarios

Beside the above risk numbers which particularly occur in each phase, there are some risk numbers that share among the whole LNG transportation chain. These risk numbers are termed as general risks in this thesis.

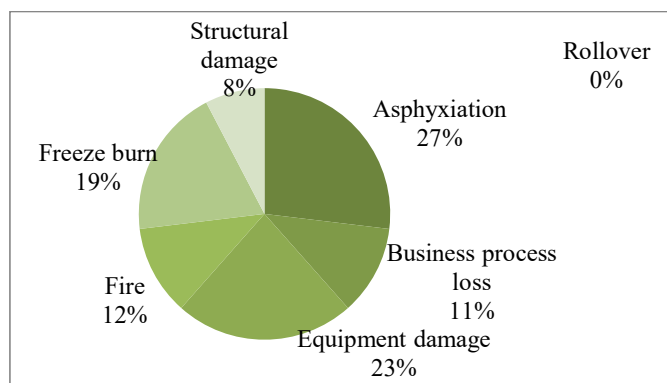


**Figure 28: Causes of general accidents**

As can be seen from Figure 27 majority of the accident scenarios in this phase are caused in descending order as:

1. Procedural error
2. Human error
3. External weather phenomena

Accidents that are in general phase have similar characteristics for human factors as in the previous sections i.e. procedural and human errors form a major chunk of the cause of scenarios. As discussed previously, this is because them being corresponding facets of human factors. A separate trend is observed here is that external weather phenomena are the third major cause of accidents. However, since general accidents are being discussed, equipment errors are not observed here, this explains external weather phenomena being the third major cause of accidents.



**Figure 29: Consequences of general accidents**

The consequences of these accident scenarios in this phase can be seen from Figure 28 to be in descending order as:

1. Asphyxiation
2. Equipment damage
3. Freeze burn

As in the previous section, the consequences relate to the causes. The consequence of asphyxiation or freeze burns is caused due to procedural or human factors e.g. lack of training, inexperience, forgetfulness etc. These consequences of asphyxiation or freeze burns are in fact the greatest that can occur. Human factors can otherwise also cause general physical damages such as bruises, bone fracture, bodily injury etc. These physical damages can be caused to the operator himself or his nearby colleagues. Since, this section refers to general hazards over the entire LNG chain, equipment here refers any equipment in the LNG chain e.g. pipelines, elbows, hose, loading arms, valves, instrumentation etc. These equipment damages are due to human factors or uncontrollable external phenomena e.g. weather. In this section too, the trend of equipment damage and fire being the major consequences is observed.

Hence, the proportion and presence of causes and consequences are in order of expectation.

## Appendix H. LNG expert interviews

After the literature review, the first phase of interviews which was held primarily with open questions regarding risks and accidents in operation of LNG storage, transport, and transfer were asked. These interviewees were selected from their working expertise relating with safety of LNG transportation field. The interviews centered into discussion about LNG related risks, accidents, hazards, equipment, safety mitigation methods, regulations and technology rather than ranking the probability and severity. A list of interviewees interviewed for the first phase is below:

1. Jos Theunissen from Safety and Security Department, TPM Faculty, TU Delft
2. Ruijter Bram from Antea Group
3. Linard Velgerdijk from Gate Terminal
4. Mirek Kaminski from 3ME Faculty, TU Delft
5. Pitiporn Thammongkol from Safety Department, CB&I
6. Joe V. George from Instrumentation and Controls Department, CB&I

After first phase of interviews, the 61 accident scenarios are selected. These scenarios cover all possible LNG accidents throughout the LNG transportation chain in the present days. These accident scenarios were separated into three phases of LNG transportation chain [see Appendix B]

For the 2<sup>nd</sup> phase of interview, the questionnaire consisted of open questions and a ranking table of potential accident scenarios, organized per phase [see Appendix C]. A list of interviewees interviewed related to LNG accident scenarios are below:

1. Sander Verweij from Gutteling BV: Composite Hoses
2. Marcel Bikker from Rolande LNG
3. Rene Gravendijk from thmGAASBEEK B.V.
4. Bas van den Beemt from TNO
5. Yuttasart Promban from PTTLNG

In addition, repeat interviews were held with Joe V. George and Pitiporn Thammongkol to cover some aspects that could not be asked in the first phase.

From the second phase of interview, the interviewees were asked to rate the level of probability and the level of severity in each accident scenario from overall 61 accident scenarios throughout the LNG transportation chain [see Appendix B].

## **Appendix I. Detailed analysis of RAM from LNG expert interviews**

From Chapter 6, this appendix presents in detailed analysis of Figure 8: RAM from the LNG expert interviews. In this appendix, the highlighted risk numbers will be separately presented in each phase (i.e. import terminal phase, truck/train transportation phase, filling station phase, and general phase) in order to get a holistic picture of risk that could occur in the particular phase.

### **I.1 Phase 1: import terminal**

According to the interviews, no critical risk presents in the terminal phase. The highlighted risks are:

- No. 16: Normal instrumentation failure
- No. 15: ESD (Emergency Shut Down) System Failure
- No. 7: Collision with pipe bridge
- No. 20: Loss of emergency power supply
- No. 2: Small leakage of unloading arm

#### **I.1.1 Risk No. 16: Normal instrumentation failure**

The severity of this risk is extensive while its probability is possible. Since normal equipment, have safety redundancy controls such as ESD, an overall failure of the associated equipment is prevented. Its severity can be considered as low. However, normal equipment is also used with higher frequency than redundant safety system. Often normal equipment is not as robust as the redundant system, either due to wear and tear (high usage frequency) or design choice. Furthermore, to maintain the continuity of the process, maintenance is not always possible.

#### **I.1.2 Risk No. 15: ESD (Emergency Shut Down) System Failure**

The severity of this risk is significant while its probability is unlikely. This nature forms a unique characteristic of the risk. ESD system corresponds to a set of equipment provided to protect the system in case of emergency. LNG carrying equipment such as loading arm can be isolated using ESD system. The ESD system consists of a set of valves and actuators that help to isolate the carrying equipment from harm. Typically, harm that can occur originates from a leakage of LNG. This in conjunction with an ignition source could lead to potential fire hazard. Otherwise, also leakage could cause a structural/ human harm. At the very least, it can cause financial loss. The high significance of this risk is due to the criticality of the ESD system towards ensuring continuity of the operation.

However, the unlikely probability of this risk is also related to the criticality of ESD system. The ESD system is built with robust materials and is designed to work under extreme conditions. Moreover, these ESD system undergo regular testing and periodic maintenance. Stringent regulations worldwide for ESD system have ensured that they are reliable and less likely to fail.

### **I.1.3 Risk No. 7: Collision with pipe-bridge**

The severity of this risk is significant while its probability is unlikely. This risk can occur primarily due to human error e.g. accident of a vehicle (truck, internal vehicle) with the pipe bridge or accidentally hitting the pipe bridge from carrying equipment (crane) or accidental strike (hammer, crowbar, etc.) of the LNG pipe by a maintenance worker working on a nearby line (water, air, etc.). The significance of this severity is due to its impact on the working personal nearby and on the nearby structure. Moreover, if the accident is caused with a high force, it carries with itself a greater impact. The impact could be due to the volume of leaked LNG or its force. In presence of an ignition source, it could lead to a jet fire if the LNG leaks rapidly from a small rupture (high pressure and high velocity).

This unlikely probability is due to experienced professionals working in the terminal. Maintenance technician are required to have high degree of training and understanding of the lines running on the pipe bridge. Similarly, operators are required to operate their equipment (vehicles, cranes) carefully and slowly to avoid collision with the pipe bridge.

### **I.1.4 Risk No. 20: Loss of emergency power supply**

The severity of this risk is significant while its probability is rare. Loss of power or emergency power, which possibly leads to failure of the recirculation process, can pose devastating impact to the import terminal

The loss of emergency power supply can cease the working of cryogenic equipment and result in losing cryogenic property of LNG from the outside ambient temperature. This will rapidly increase the vapor generating rate and increase pressure level in the equipment (e.g. storage tank). Under this situation, the vapor can be produced continuously lead to the pressure increases more and more. If the pressure and vapor is too high that the pressure relief valve (PRV) proves to be inadequate. The pressure can easily rupture the PRV or other areas (e.g. top dome of the tank).

However, the probability of occurrence is rare because there are sufficient controls in place to prevent a complete loss of power supply. Even if the main power supply fails, power can restore using emergency (diesel) power generation system. Even in the worst case of failure of diesel generators, power can be supplied for critical process equipment using battery based UPS power system. UPS power system is designed to cater for critical plant system for a maximum of two days. These redundant systems ensure that there is not a complete loss of power.

### **I.1.5 Risk No. 2: Small leakage of unloading arm**

The severity of this risk is insignificant while its probability is likely. Although the small amount of leakage doesn't pose any damages, LNG leakage from seal or swivel joints are likely to occur. LNG frequently leaks in the unloading arm during disconnecting and connecting. During this stage, failures can occur since the connections are very vulnerable but the small leakage of LNG can easily get vaporize into atmosphere.



Another reason of high probability of this risk is that the couplings and joints are not very strong due to their continuous usage and the sealant material to retain its property of flexibility has to compromise on strength. It cannot be expected to perform its duty while retaining the strength (e.g. of steel). Failures are also possible due to human error; the arms could be disconnected before the liquid lines had been completely drained, causing leakage of LNG.

## **I.2 Phase 2: LNG transportation by tanker truck/train**

From Figure 10, there is consensus from both the experts and the literature that risk no. 38 is the critical risk [see 6.2]. Although, risk no. 39 does not lie in the high-risk region, but since both of these risks are similar in nature, both of them should be mentioned in this phase:

- No. 38: Collision of LNG tanker truck with the other vehicles while riding
- No. 39: Collision of LNG tanker train with the other vehicles while riding

Despite numerous controls and precautions involved in the transportation of LNG via LNG truck or train, accidents can easily cause a fire hazard. Moreover, their leakage in public area (roads/railroads) can cause greater harm to humans than a similar accident occurring in the terminal area. In countries like the Netherlands, where highways and railroads are in close proximity of human residences, LNG leakage can cause immense damage to human life. This damage could be due to resulting fire, freeze burns, and inconvenience to traffic. Moreover, a spill causes high financial loss to the operating company, not only due to loss of cargo but also due to litigations and damage control.

The probability of these risks are however different. Risk no. 38 is much higher than no. 39 because road are much closer to human habitation. Moreover, a high amount of traffic and a large number of vehicles on the road can lead to an unexpected accident characteristics. In contrast, railroads are neither very close to human habitation nor interact with many moving objects. Furthermore, due to centralized and robust control system, it is much easier to mitigate the risk of an accident due to LNG tanker train.

## **I.3 Phase 3: LNG filling station**

In this phase, three risks numbers are highlighted.

- No. 48: Collision of LNG filling station by vehicles
- No. 49: Presence of ignition source inside LNG filling station
- No. 52: End-user drive away while hose is still connected

### **I.3.1 Risk No. 48: Collision of LNG filling station by vehicles**

The severity of this risk is significant while its probability is rare. Since the dispenser is a stand-alone system, it can easily get damaged. The severity of the impact can easily cause ignited the spill LNG leading to a fire. If not, the spill can cause freeze burns/ asphyxiation to humans or structural damage. The probability is rare because only professional and trained drivers are allowed

to enter the LNG filling stations. Moreover, in some stations, fence is provided around critical structures like storage tanks.

### **I.3.2 Risk No. 49: Presence of ignition source inside LNG filling station**

Similar to risk no. 48, the severity of this risk is significant while its probability is rare. The severity is significant since even a small leakage in presence of this ignition source can cause a devastating fire. However, the probability is rare because stringent control and regulations in LNG station ensure that no ignition source is present. Furthermore, LNG filling stations are built in considerable an open area which minimizes the chance of inflammability.

### **I.3.3 Risk No. 52: End-user driving away while hose is still connected**

The severity of this risk is negligible while its probability is likely. The selection of this risk as critical is due to its high probability. This risk occurs due to human errors, especially due to lack of attention (e.g. absent-mindedness, rushing to do multiple tasks, lack of concentration etc.). In case if the driver indeed drives away, the coupling at dispenser end will get disconnected and the hose will remain attached only to the truck. This safety mechanism prevents major leakage from the dispenser. However, the loss of hose still remains. The probability compared to its severity is considerably high, which denotes that basic human errors are possible even with high technology and high training procedures.

## **I.4 General risks**

Beside the above risk numbers which particularly occur in each phase, there are some risk numbers that share among the whole LNG transportation chain. These risk numbers are termed as general risks in this thesis. Two risks numbers in general risk are highlighted.

- No. 60: Earthquake/ Tsunami
- No. 61: Terrorist attack

These two risk numbers are rarely to occur but they are significantly severe. Occurrence of both risks will definitely cause widespread devastating damage to any LNG facility. However, earthquakes/tsunamis are natural events with very low probability of occurrence worldwide. In regions (e.g. filling station in Groningen or import terminal in Japan) that are susceptible to such natural phenomena, flexible and robust foundation is designed to counter the effects of these natural disasters. Although, terrorist attacks have been rising in the recent past but LNG facility are not the typical targets of terrorist. Moreover, multiple safety controls and their remote location prevent large scale damage to human life.