Risk-based Life Cycle Assessment Methodology for Green and Safe Product Selection

By

© **Sina Khakzad Rostami**

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Abstract

Life-cycle assessment (LCA) is an effective technique widely used to estimate the emissions produced during the entire life-cycle of a fuel or a product. However, most of the conventional LCA methods consider the risk of voluntary releases such as emissions, discharges or energy use. In other words, involuntary risks such as accident risks associated with exploration, production, storage, process and transportation have been overlooked. For hazardous materials involuntary risks could be significant; thus, ignoring this may result in imprecise LCA. The present study aims to develop a methodology for risk-based life-cycle assessment (RBLCA) of fossil fuels by integrating both the voluntary and involuntary risks (risk associated with potential accidents) of hazardous materials. The risk associated with potential accidents is estimated using Bayesian network approach. This provides a robust probabilistic platform of LCA. The application of the developed methodology is demonstrated for liquefied natural gas (LNG) and heavy fuel oil (HFO) as fuels of a hypothetical power plant. The comparative analysis of two fuels based on RBLCA helps an analyst not only overcome data uncertainty but also identify holistically green and safer fuel option.

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List of Abbreviations and Symbols

Abbreviations

AGR: Acid Gas Removal

API: American Petroleum Institute

BOG: Boil Off Gas

CNG: Compressed Natural Gas

CPT: Conditional Probability Table

EF: Emission Factor

EPA: Environmental Protection Agency

ET: Event Tree

ETA: Event Tree Analysis

FT: Fault Tree

FTA: Fault Tree Analysis

GHG: Green-House Gas

GW: Global Warming

GWP: Global Warming Potential

HFO: Heavy Fuel Oil

IE: Initiating Event

IE: Intermediate Event

IPCC: Intergovernmental Panel on Climate Change

LCA: Life Cycle Assessment

LCRA: Life Cycle Risk Analysis

LNG: Liquefied Natural Gas

LPG: Liquid Petroleum Gas

LSHH: Level Switch High-High

MCR: Maximum Continuous Rating

MRC: Mixed Refrigerant Cycle

NETL: National Energy Technology Laboratory

NG: Natural Gas

OREDA: Offshore Reliability Data Handbook

PE: Primary Event

PSV: Pressure Safety Valve

QRA: Quantitative Risk Assessment

RBLCA: Risk-based Life Cycle Assessment

SB: Safety Barrier

SETAC: Society of Environmental Toxicology and Chemistry

TDS: Total Dissolved Solids

TE: Top Event

TE: Top Event

UNEP: United Nations Environment Programme

USD: United State Dollar

Symbols

Btu: British thermal unit

Psig: Pounds per square inch gage

MJ: Mega Joule

KW: Kilo Watt

KWh: Kilo Watthour

cf: Cubic feet

lb: Pounds

MMcf: Million Cubic Feet

g: Gram

P: Power

LF: Load factor

E: Emission

A: Activity rate

EF: Emission factor

ER: Emission reduction efficiency

TC: Tanker capacity

Dx: Distance

TS: Tanker speed

FC: Fuel consumption

m^3: cubic meter

e: Equivalent

AS: Actual speed

SS: Service Speed

Pr (.): Probability

t: time

∪: Union

∩: Intersection

Chapter 1

Introduction

1.1 Overview

In recent decades, rapid industrial development has led to steady growth in energy consumption all around the world. Meanwhile, the availability and well-controlled nature of fossil fuels have considerably made them popular among energy consumers. Nevertheless, the combustion of fossil fuels results in greenhouse gas (GHG) emission to the atmosphere, which consequently poses the greatest environmental threat in our time; that is, global warming. There is a scientific consensus on climate change that the average temperature of the earth has raised between 0.4 and 0.8 °C over the past 100 years. Furthermore, scientists from the Intergovernmental Panel on Climate carrying out global warming research have recently predicted that average global temperatures could increase between 1.4 and 5.8 °C by the year 2100 [1]. This important issue and the all-around energy supply domination by fossil fuels have raised questions about which fossil fuel is cleaner, and has the least impact on the environment.

Among fossil fuels, natural gas (NG) is believed to be a cleaner fuel since its combustion emits much lower GHGs than those of oil and coal. Having the lowest carbon content of any fossil fuels, NG releases up to 50% less CO2 than coal and about 20-30% less CO2 than oil, when burned [2]. The combustion of natural gas also produces less Nitrogen oxide (NOx), Sulfur dioxide (SO2), mercury (Hg), and particulate matters (PM) compared to oil and coal.

Less emission from combustion, however, does not tell the full story. Natural gas primarily consists of methane (CH4), accounting for 70-90% of the total volume [3], which is a potent GHG and far more powerful than CO2. Inevitable leakage of NG occurring in different stages through its life-cycle results in significant air emissions. To discover the fuel with the lowest GHG emission, a thorough comparison needed to be done considering all potential emission sources of heat-trapping gases during every single stage of the fuel life cycle.

Life Cycle Assessment (LCA) is a “cradle to grave” technique to assess the environmental impacts of a product or process through its life-cycle [4]. However, conventional LCA methods consider the environmental impacts of voluntary releases such as emissions, discharges or energy use. Thus, dealing with the amount of GHG emissions, in LCA, even minor accidents due to the emissions they can pose are of paramount importance. For instance, in April 2004, a routine maintenance operation went wrong in the Sonatrach Skikda LNG plant in Nigeria, and led to a boiler explosion. The explosion destroyed three out of six trains in the plant completely, which caused tones of air emissions in addition to many injuries and fatalities [5]. Although such accidents are rare, the dramatic consequence they cause cannot be ignored.

1.2 Current Research Gaps

Recently, LCA has been widely employed by researchers to assess and compare the GHG emissions associated with different fuels such as LNG, Coal, and Fuel Oil. However, these studies and most of conventional LCA methods developed by Society of Environmental Toxicology and Chemistry (SETAC) or Environmental Protection Agency (EPA) consider the issue of LCA from a pure chemical engineering perspective. In other words, merely the risks of discharged toxic substances are taken into account while other important risks such as those associated with the storage, production, process and transportation of hazardous materials (e.g., fires, explosions, and toxic gases) have been overlooked. This, in turn, can result in non-holistic and in some cases wrong decisions as an alternative with less environmental emissions may seem less hazardous and thus preferable. Although there recently have been attempts to couple risk analysis and LCA to develop Life Cycle Risk Analysis (LCRA) methodologies [6-8], in none of them the risks of abovementioned accidents have been taken into account.

1.3 Research Objectives

The present study aims to develop a Risk-based Life Cycle Assessment (RBLCA) methodology not only to consider the risks of toxic environmental discharges which are assessed in conventional LCA, but also to quantify the risks of potential fires and explosions resulted from the leakage of hazardous materials. Therefore, the proposed technique takes both voluntary and involuntary risks into the account in order for a holistic risk assessment. This method integrates two widely known techniques in design and operation decision-making; Life-Cycle Assessment and Quantitative Risk Assessment, providing a broader perspective for making conscious decisions. The proposed method includes four major phases; forming a sensible boundary for each product of interest, performing LCA, hazard identification, and risk analysis.

1.4 Thesis Organization

The thesis is written in a traditional format. Outline of each chapter is described below:

Chapter 2 presents the literature review pertinent to this thesis, including current relevant accidents, conventional and advanced risk analysis approaches, conventional life cycle assessment, and current related studies.

Chapter 3 describes the developed methodology, and mainly discuss conventional risk analysis methods such as fault tree and event tree, as well as Bayesian networks, an advanced approach. This chapter further discusses mapping fault tree into Bayesian network, and conventional life cycle assessment in detail.

Chapter 4 presents a comparative RBLCA of liquefied natural gas (LNG) and heavy fuel oil (HFO) as fuels of a power plant is performed to identify the safest fuel with respect to a holistic risk assessment approach.

Chapter 5 presents the results of LCA and QRA performed for each fuel, LNG and HFO, and compare the results for each part. Further, discusses the main causes of the differences in such results. Subsequently, in this chapter, all results are converted to dollar value, and are compared to figure out the safer fuel.

Chapter 6 reports the summary of the thesis and the main conclusions obtained through this research. Also, recommendations for future work are presented.

Chapter 2

Literature Review

2.1 Risk Analysis

2.1.1 Overview

Risk analysis is very important in processing facilities as they deal with a large amount of hazardous chemicals; also, process areas are congested with complex piping, high-pressure compressors, and separators of which malfunctions and mishaps may lead to catastrophic accidents [9,10].

There have been many fatal explosions and fires imposing major capital loss and considerable death toll in the past two decades. On 23 March 2005, the BP refinery explosion in Texas City caused 15 deaths and more than 170 injuries [11]. According to the final report issued by BP (2005) [12], a lack of process safety measures and insufficient risk reduction measures were entirely to blame for the accident. On 7 February 2010, the Kleen Energy power plant exploded in Middletown, Connecticut, U.S., killing 6 and injuring at least 12. The explosion was one of the worst industrial disasters in the U.S. in recent years [13]. Most recently, on 20 April 2010, explosion and fire on Transocean Ltd's drilling rig killed 11 and injured 17 in the Gulf of Mexico. The failure of a blowout preventer (BOP) has been determined as the primary cause of the accident [14]. It is important to broaden the risk analysis scope by considering accident scenario and real-time safety analysis in order to predict and continuously update the likelihood of catastrophic accidents and to take actions to prevent them.

Forecasting likely accident scenarios is the most important step in safety analysis. Khan (2001) [15] proposed a maximum credible accident scenario approach that short-lists the important scenarios based on both their consequences and the likelihood of accident occurrence. Delvosalle et al. [16] used two methodologies: MIMAH for the identification of major accident hazards, in which no safety system was considered, and MIRAS for the identification of reference accident scenarios, in which all the actual safety functions and barriers were included in the analysis.

2.1.2 Risk Assessment Methods

The next step in risk analysis is to quantify the occurrence probability of the selected accident scenarios. For this, there are many techniques available, among which fault tree (FT), event tree (ET), safety barrier diagram, and Bayesian network (BN) are very popular. Although conventional risk assessment methods have played an important role in identifying major risks and maintaining safety in process facilities, they suffer limitations which restrict their application in the risk analysis of complex and interlinked systems.

For example, conventional FTs, as one of the most popular techniques used in quantitative risk analysis, are not suitable for analyzing large systems, particularly if the system presents redundant failures, common cause failures, or mutually exclusive primary events. More importantly, events in a conventional FT are assumed independent, which is not usually a valid assumption [10,17,18].

Likewise, most of the limitations of conventional techniques such as FT and ET arise due to the static nature of these methods that fails to catch up with the dynamic operation environment of process systems. This dynamic nature can be either due to any change in the process environment or operational situation such as variations in temperature, pressure, humidity and geometry or due to change in analyst's initial beliefs as new data in form of near-misses, mishaps, incidents, and accidents become available over time.

2.1.3 Dynamic Risk Analysis

There have been efforts to make risk assessment methods dynamically adapted as real-time changes occur in a process. Shalev and Tiran [19] introduced condition-based fault tree (CBFT) in which failure rates of components are periodically updated using information obtained through predictive maintenance. Consequently, the failure probability of the top event is updated by recalculating the FT for new failure rates. However, their method has to be implemented in specific conditions where, for example, gradual deterioration process of a component can be discretized into several stages at each of which there should be a correlation between residual time of the component and its total failure time.

The issue of deficiency of conventional methods in dynamic risk analysis has remarkably been addressed by introducing the application of Bayesian techniques in the field of risk assessment and safety analysis in the late 1970s (see Apostolakis, 1978 [20]; Parry and Winter, 1981 [21]). Bayesian methods have proven to be an effective technique in handling sparse data as well as different sources of information, and also a well suited framework for subjective probability domains such as decision making under uncertainty [22]. Accordingly, several forms of Bayesian analysis such as two-stage Bayesian methods [23] and empirical Bayes methods (e.g., Carlin and Lous [24]; Martiz and Lwin, [25]) have been applied in the context of probabilistic risk analysis. Consequently, there have been many works to equip conventional risk analysis methods such as FT and ET with Bayesian techniques for dynamic risk analysis. For example, Ching and Leu [26] also used Bayesian theory to update FT while Kalantarnia et al. [27], Meel and Seider [28], and Rathnayaka et al. [29] used Bayesian theory to update the failure probability of the safety functions of an ET.

Apart from the aforementioned efforts, other researchers have attempted to substitute Bayesian network (BN) for reliability block diagrams [10], static FTs [17], Dynamic FTs [30,31] and ETs [32].

BNs have provided a promising framework for system safety analysis and risk management [33]. A comprehensive and state of the art application of Bayesian inference and Bayesian network in risk analysis can be found in Kelly and Smith [34], Siu and Kelly [22], and Weber et al. [35]. Further, there are attempts to substitute Markov models for FT [36] or to construct dynamic FT and ET from corresponding Markov models such that time-dependent failures can be taken into account [37]. However, the application of Markov models in complex systems has been limited due to the well-known problem of state-space explosion and also the error-prone mapping procedure [30].

2.2 Life Cycle Assessment

2.2.1 History of LCA

The first studies that looked at life cycle aspects of products and materials, focusing on issues such as energy efficiency, the consumption of raw materials, and to some extent, waste disposal, date from the late sixties and early seventies. For instance, the Coca Cola Company in 1969 conducted a study to compare resource consumption and environmental releases associated with beverage containers. Meanwhile, a similar inventory approach was being developed in Europe, later known as the 'Eco balance' [38].

Later, in 1979, the Society of Environmental Toxicology and Chemistry (SETAC) was stablished to work as a non-profit professional society in order to promote multi-disciplinary approaches to investigate environmental issues. In the late 1980s, life-cycle assessment appeared to be an approach to better understand the risks, opportunities and trade-offs of product systems in addition to the environmental impacts. The term "life cycle assessment" was coined at the first SETAC-sponsored international workshop in 1990 [39].

In early 1993, a group of SETAC experts were tasked with making a recommendation regarding standardization of LCA, by the International Organization for Standardization (ISO). As a result, the ISO14040 standard for Life cycle assessment – Principles and framework was completed by 1997. Then, a few additional standards were set and reviewed, and finally compiled in 2006 in the form of ISO 14044 Life cycle assessment – Requirements and guidelines [39].

More LCA guidelines and standards have subsequently been developed including the World Resource Institute and World Business Council for Sustainable Development's PAS 2050:2011 Specification in order to assess the greenhouse gas emissions associated with products and services life cycles. In 2012, the European Commission Joint Research Centre's Institute for Environment and Sustainability published the International Reference Life Cycle Data System Handbook as part of the European life cycle push and to further specify the broader provisions of the ISO 14040 and 14044 standards [39].

2.2.2 Life Cycle Assessment Definition and Procedure

Life-Cycle Assessment (LCA) is a technique for systematic evaluation of the environmental impacts of a product or process throughout its entire life, from raw material extraction to the final disposal or recycling (cradle to grave) [40].

According to ISO 14044, the framework of LCA consists of four phases; goal and scope definition, inventory analysis, impact assessment, and interpretation.

The first step in LCA, goal definition, as its name suggests includes determining the desired goal for performing the LCA study, the intended audience, and the intended application, while the scope of a LCA is the planning stages and areas of determination such as system boundaries, functional unit/allocation, data requirements/quality, and report format/need for critical review [41].

The life cycle inventory analysis, as second phase of LCA, deals with collection of the necessary data to meet the objectives of the LCA study. Implementation of a life cycle inventory begins the process of assigning emission values to operations within the defined boundary of the system of interest. Further, the corresponding calculations may differ depending on the data source, whether actual monitored data or an existing inventory database is utilized [41].

The next step in LCA is life cycle impact assessment (LCIA) trying to convert the life cycle inventory results into the related environmental impacts – effects on natural resource use, natural environment and human health. A LCIA consists of two mandatory steps: classification and characterisation. Classification involves dividing the life cycle impact results into impact categories – e.g. global warming, acidification, and human toxicity. In characterisation, the potential impact of each emission or resource use is estimated, using certain scientific factors [41].

The last step in a LCA, life cycle interpretation, according to ISO 14044 a number checks to ensure that the conclusions are sufficiently supported by the data and procedures utilized in the study. These checks may include uncertainty, sensitivity, and contribution analysis. The results, then, are reported, and the need and opportunities to reduce the impact of the products or services on the environment are systematically evaluated [102].

2.2.3 Related Studies

Recently, LCA has been widely employed by researchers to assess and compare the GHG emissions associated with different fuels.

Howarth et al. [42] studies the life-cycle emissions from shale gas production. The study indicated that conventional gas has almost no advantage over coal whereas shale gas has higher life-cycle GHG emissions than coal, due largely to methane emissions during the extraction process. Using new data and comparing the warming potential of methane and carbon dioxide during a 20-year time period, Howarth [43] later declared that both shale gas and conventional natural gas have a larger GHG than coal or oil, particularly for the primary uses of residential and commercial heating. Hultman et al. [44] compared the life-cycle GHG footprints of conventional gas, shale gas and coal, primarily focusing on the electricity generation sector. The authors showed that the GHG impacts of shale gas are slightly higher than those of conventional gas, while those of both conventional and shale gases remain considerably lower than those of coal, under standard assumptions. They reported air emission impacts of shale gas 11% higher than those of conventional gas, and 44% lower than those of coal. In a similar effort, Skone et al. [45] performed a very detailed study of life-cycle emissions from electricity generated from several sources of natural gas, including conventional and unconventional natural gas, and two types of coal. The analysis found that the natural gas-based electricity production has life cycle GHG emissions 35% to 66% lower than those of coal-based. Rose et al. [46] conducted a comparative LCA of diesel and compressed natural gas (CNG) used as fuel in heavy duty vehicles. The analysis utilized real-time operational data obtained from the city of Surrey in British Columbia, Canada. The authors reported that CNG powered vehicles result in a considerably less GHG emissions, about 24% compared to diesel powered vehicles.

Chapter 3

Methodology

The method proposed in this study for RBLCA integrates two widely known techniques in design and operation decision-making; LCA and QRA, enabling making more exhaustive decisions by considering not only the emissions but also the accident risks. The methodology includes four major phases: 1) forming a sensible boundary for each life-cycle, 2) performing LCA, 3) hazard identification, and 4) risk analysis. In order for comparison of the environmental impacts of different fuels in the present study, the outcomes of both LCA and QRA converted to dollar value. Figures 1 illustrates a schematic diagram of RBLCA methodology.

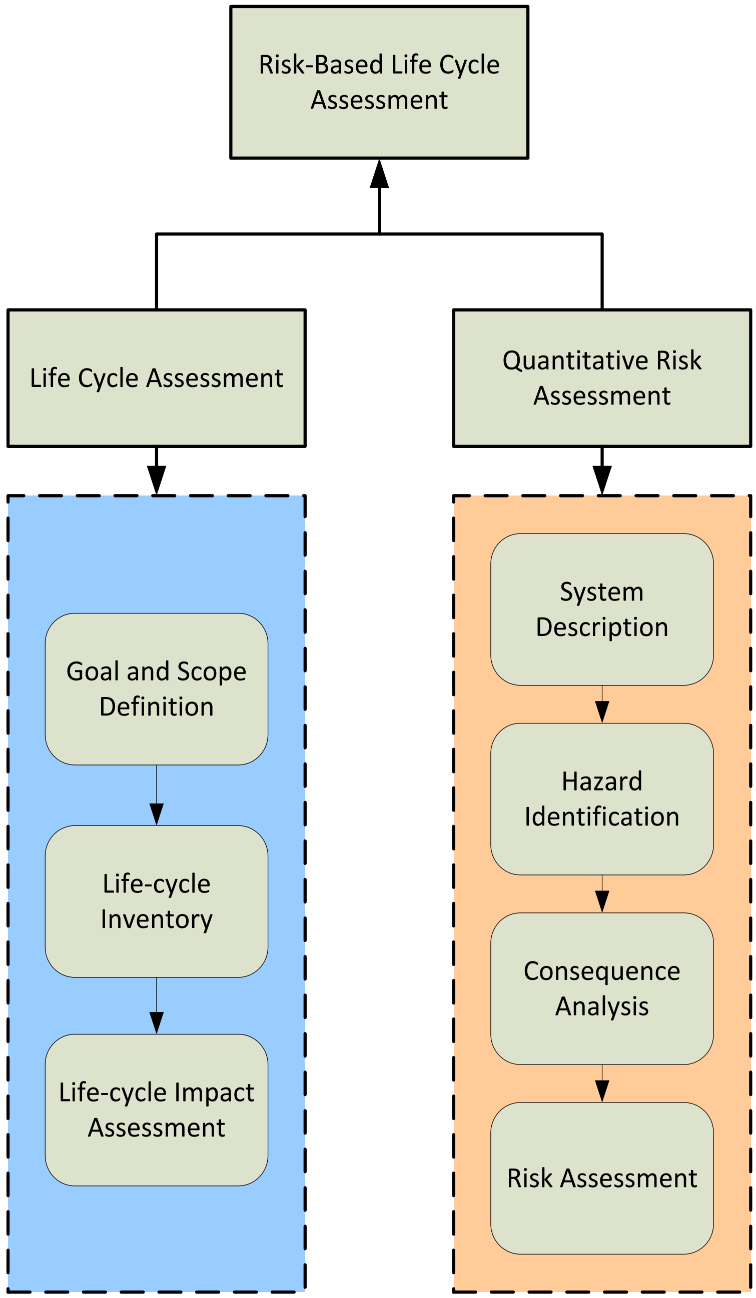

Figure 1. Risk-Based Life Cycle Assessment Diagram

3.1 Life-Cycle Assessment

LCA is a tool employed to estimate the adverse effects the creation of a product or a process has on the environment and human health. To holistically evaluate the environmental effects, LCA should include raw materials extraction, manufacturing, processing, transportation, consumption, maintenance, recycle and waste disposal. Consequently, LCA can be used as an informed decision making tool to choose the alternative, whether products or processes, which is the least harmful to the environment. A typical LCA comprises several steps such as goal determination, boundaries identification, inventory analysis, impact analysis, and improvement analysis [47].

LCA methods are basically data intensive and time consuming. Thus, it is necessary to set the analysis' goals and the boundaries in the first step in order to limit the analysis only to a few important processes during the LCA of a product. To tackle the foregoing issue, several LCA methodologies have been developed such as streamlined LCA [48] and input/output LCA [49, 50] which are less data intensive and do not need to reduce the number of processes to consider. Among the aforementioned steps, inventory analysis is of great importance as the quantities of both the required materials/energy and the environmental discharges (into air, water, and soil) are estimated. In the next step, the impact analysis, the effects of toxic discharges and emissions on the environment and the human are assessed using exposure pathway modeling and dose-effect relationships. The aim of improving analysis is to reduce the harmful effects by either reducing the amount of toxic discharges or devising appropriate safety measures [47]. It is worth noting that the application of risk analysis to LCA has been through the impact analysis or improving analysis.

In life-cycle assessment with regard to GHG emission, direct measurements at an emission source seem to provide the most reliable information. Due to lack of such data, however, emission factors, in spite of their limitations, have been widely employed for emissions estimation [51].

Emission factors are representative values relating the quantity of an emission (atmospheric emission) with the activity generating the emission. To estimate these emission factors, the weight of emission is usually divided by a unit weight, volume, distance, or duration of the activity of concern (i.e., the emitting activity); for example, kilograms of CO_2 emitted per ton of coal burned. Facilitating the estimation of emissions, such factors can be considered as the long-term average of available data yet with an acceptable level of quality, obtained from all facilities in the emission source [51]. The general equation for emission estimation is:

$$E = A.EF.(1 - \frac{ER}{100}) \tag{3.1}$$

Where E is the emission; A is the activity rate; EF is the emission factor, and ER is the overall emission reduction efficiency.

3.2 Risk Assessment

In the recent decades, risk analysis has become an integral part to informed decision making and design of processing facilities due to large inventories of toxic, flammable, and explosive materials which could pose serious harms to human health, the environment, and the assets. Process plants are also attributed with large number of equipment and complex pipeline networks. As a result, any normal accident which could easily have been controlled or tolerated in other infrastructures has the potential to turn into a catastrophe via domino effects [52].

Quantitative risk analysis (QRA) focuses on quantifying the occurrence probability of envisaged accident scenarios. There are many techniques available, among which fault tree (FT), event tree (ET), and Bayesian network (BN) are very popular. Although conventional risk assessment methods have played an important role in identifying major risks and maintaining safety in process facilities, they suffer limitations which restrict their application in the risk analysis of complex and dependent systems. For example, conventional FT, which is one of the most popular QRA techniques, are not suitable for analyzing large systems, particularly if the system presents sequential failures, common cause failures, or dependent primary events. More importantly, events in a conventional FT are assumed independent, which is not usually a valid assumption [17,18,53]. Likewise, most of the limitations of conventional techniques such as FT and ET arise due to the static nature of these methods that fails to capture the dynamic nature of process systems. This dynamicity can be either due to changes in the process environment or operational situation such as variations in temperature, pressure, humidity and geometry or due to changes in analyst's initial beliefs based on observed near accident or accident data. As a result, dynamic QRA methods mostly based on Bayesian network (BN) have begun to become popular among risk society and safety experts.

3.2.1 Fault Tree

Fault Tree is a deductive, structured methodology to determine the potential causes of an undesired event, referred to as the top event. The top event usually represents a major accident causing safety hazards or economic loss [54]. While the top event is placed at the top of the tree, the tree is constructed downwards, dissecting the system for further detail until the primary event leading to the top event are known. Primary events are considered binary (with two states) and statistically independent. In an FT, the relationships between events are represented by means of gates, of which AND-gates and OR-gates are the most widely used.

Once completed, the FT can be analyzed both qualitatively and quantitatively. In the qualitative evaluation, using Boolean algebra, an expression is derived for the top event in terms of combinations of primary events. In the quantitative part, the probability of the top event is expressed in terms of the occurrence probability of the primary events or in terms of the minimal cut-sets. Small FTs can be evaluated manually; however, large and complex FTs require the aid of computerized methods for evaluation. Methods for FT analysis include the analytical method, Monte Carlo simulation, and binary decision diagram. Due to limitations in using the Monte Carlo simulation, an analytical approach (e.g., minimal cut-sets determination) is more frequently used for evaluation of a FT. To reduce the margin of error due to inaccuracy and incompleteness of the data of the primary events, some authors have recently used fuzzy set theory and evidence theory in FT analysis [55-58].

Fault trees are built using gates and events. The two most commonly used gates in a fault tree are the AND and OR gates. As an example, consider two events comprising a top event (or a system). If occurrence of either event causes the top event to occur, then these events are connected using an OR gate. As a result, the probability of the top event would be equal to the union of the events' probabilities. On the other hand, if both events need to occur to cause the top event to occur, they are connected by an AND gate. Accordingly, the probability of the top event would be equal to the intersection of the events' probabilities. As a visualization example, Figure 2 shows the two typical AND (left) and OR (right) gates and their corresponding Boolean algebra.

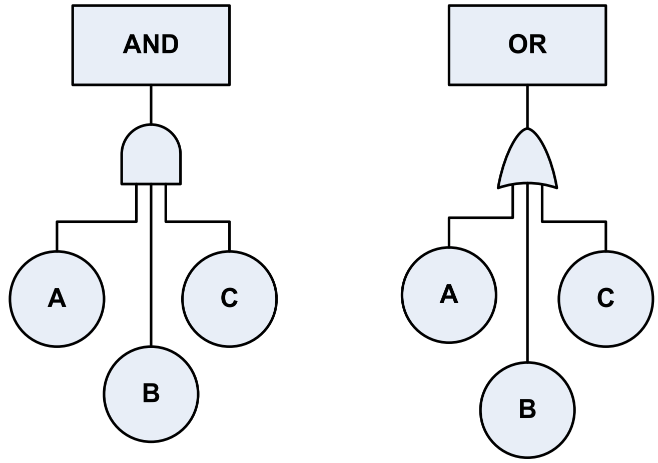

Figure 2. AND gate (left) and OR gate (right) in fault trees

Since conventional fault trees are unable to consider conditional dependencies, the events in such fault trees are presumably considered as independent. As a result, the corresponding Boolean algebra for AND gate and OR gate will be:

$$P(AND) = P(A \cap B \cap C) = P(A)P(B)P(C) \tag{3.2}$$

$$P(OR) = P(A \cup B \cup C) = 1 - \big(1 - P(A)\big)\big(1 - P(B)\big)\big(1 - P(C)\big) \tag{3.3}$$

It is worth noting that in the case of having more than three events, the respective relationship for an OR gate could be written as:

$$P(A_1 \cup A_2 \cup \ldots \cup A_n) = 1 - \prod_{i=1}^{n}\big(1 - P(A_i)\big) \tag{3.4}$$

It should be noted that conventional fault trees usually underestimate or overestimate the probability of top events due to their inability in considering conditional dependencies.

For example, consider the fault tree in Figure 3, in which the intermediate events X1 and X2 share the root event A. A is usually considered as a common-cause failure.

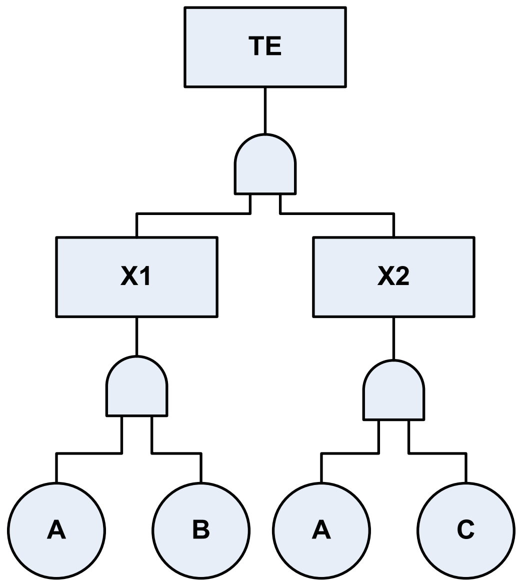

Figure 3. A fault tree with common-cause failure A.

According to the logical relationship embedded in AND gate, the probabilities of X1 and X2 will be

$$P(X1) = P(A)P(B) \tag{3.5}$$

and

$$P(X2) = P(A)P(C) \tag{3.6}$$

Consequently, assuming that X1 and X2 are independent (which is the common assumption in the fault tree) the probability of TE (Top Event) will be calculated as:

$$P(TE) = P(X1 \cap X2) = P(X1)P(X2) = P(A)^2 P(B)P(C) \quad (3.7)$$

However, as we know, X1 and X2 are not independent since they share the common cause A. As a result:

$$P(TE) = P(X1 \cap X2) = P(X1)P(X2|X1) = P(A)P(B)P(C) \quad (3.8)$$

Comparing the probabilities of the top event given by Equations (3.7) and (3.8), it can be seen that the fault tree in Figure 3 underestimates the top event by a factor of P(A). Similarly, if X1 and X2 were connected to TE by means of an OR gate, the respective probability would be overestimated instead. Although such limitation of conventional fault trees can be relaxed by relying on state-dependent methods such as Markov chains and Bayesian network [53], which BN method is discussed in the next section.

3.2.2 Bayesian Network

BNs are increasingly used for the construction of system reliability models, risk management, and safety analysis based on probabilistic and uncertain knowledge. Similar to other graphical probabilistic methods (e.g., fault tree and reliability block diagram), BNs consist of both qualitative and quantitative parts. BNs are directed acyclic graphs, in which the nodes represent variables, arcs signify direct causal relationships between the linked nodes, and the conditional probability tables assigned to the nodes specify how strongly the linked nodes influence each other. In BNs, the nodes without any arc directed into them are called root nodes, possessing marginal prior probabilities. All other nodes are intermediate nodes and each one is assigned a conditional probability table (CPT). Among intermediate nodes, the nodes having arcs directed into them are called child nodes and the nodes that have arcs directed from them are called parent nodes (Figure 4). Each child has an associated CPT, given all combinations of the states of its parent nodes. Nodes without any child are also called leaf nodes.

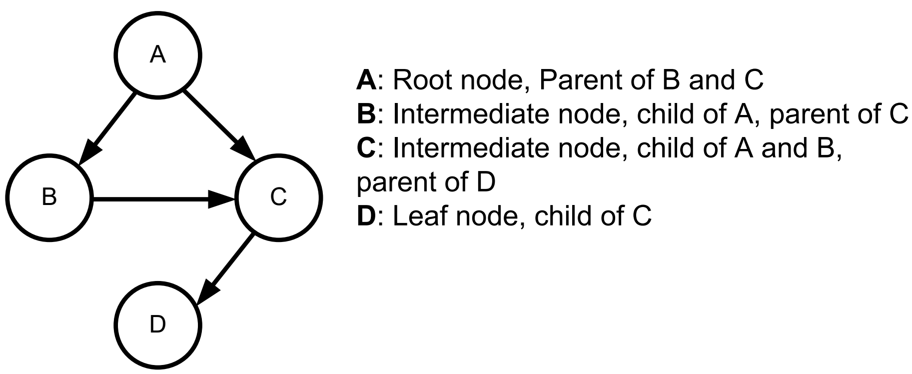

Figure 4. A typical Bayesian network

BN takes advantage of the "d-separation" criterion [59-61] and the chain rule to calculate conditional dependencies. Node A is d-separated from node C if node B blocks the path between A and C. In this case, A is conditionally independent of C given B; i.e., $P(A|B,C) = P(A|B)$. In either a serial path or a diverging path (Figures 5a and 5b), A and C are d-separated from each other if the state of B is known. In a converging path (Figure 5c), A and C are independent if the state of B is unknown. Based on these three conditions, in a BN all root nodes are conditionally independent of each other and the other nodes are conditionally dependent on only their direct parents [17].

According to the conditional independence and the chain rule, BNs represent the joint probability distribution P(U) of variables $U = \{A_1, A_2, \dots, A_n\}$ included in the network as:

$$P(U) = \prod_{i=1}^{n} P(A_i | Pa(A_i)) \tag{3.9}$$

Where $Pa(A_i)$ is the parents of A_i in the BN, and P(U) reflects the properties of the BN [60]. Figure 5 summarizes the three probabilistic relationships commonly used in a BN [62].

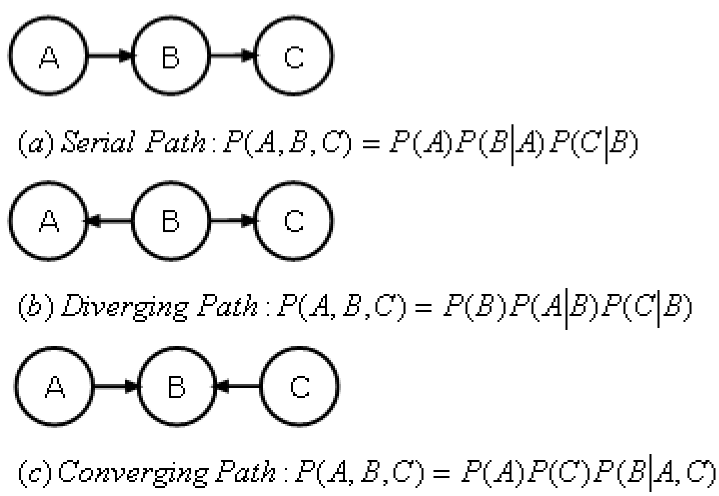

Figure 5. d-separation Criteria (Wilson and Huzurbazar, 2007)

Using Equation (3.9), the joint probability distribution of the variables included in the BN in Figure 4 can be represented as P(U) = P(A,B,C,D) = P(A) P(B | A) P(C | A,B) P(D | C). BN's main application in accident analysis is an inference engine for updating the prior occurrence probability of events given new information, called evidence E. The new information is usually operational data including occurrence or non-occurrence of the accident or primary events:

$$P(U|E) = \frac{P(U,E)}{P(E)} = \frac{P(U,E)}{\sum_U P(U,E)} \quad (3.10)$$

Equation (3.10) can be used for either probability prediction or probability updating. In predictive analysis, conditional probabilities of the form P (Accident | event) are calculated, indicating the occurrence probability of a particular accident given the occurrence or non-occurrence of a certain primary event. On the other hand, in updating analysis, those of the form P(event | Accident) are evaluated, showing the occurrence probability of a particular event given the occurrence of a certain accident [63]. BNs are increasingly used in risk analysis and safety assessment. Khakzad et al. [53] have examined the parallels between BNs and FTs and have shown the obvious superiority of BNs over FTs in terms of modeling and analysis capabilities. Bobbio et al. [17] showed that the limitations of FTs can be relaxed to a great extent by relying on BNs. Other relevant works have been done by mapping dynamic FTs into the dynamic BNs [30,31,64]. A comprehensive review of Bayesian network application in risk analysis, safety assessment, and reliability engineering can be found in Weber et al. [35].

3.2.3 Event Tree

Event tree analysis (ETA) is an analysis technique for identifying and evaluating the sequence of events in a potential accident scenario following the occurrence of an initiating event. ETA utilizes a visual logic tree structure known as an event tree (ET). The objective of ETA is to determine whether the initiating event will develop into a serious mishap or if the event is sufficiently controlled by the safety systems and procedures implemented in the system design. An ETA can result in many different possible outcomes from a single initiating event, and it provides the capability to obtain a probability for each outcome.

ETA is a binary form of a decision tree for evaluating the various multiple decision paths in a given problem. ETA appears to have been developed during the WASH-1400 nuclear power plant safety study (Circa, 1974). The WASH-1400 team realized that a nuclear power plant probabilistic risk analysis could be achieved by FTA; however, the resulting fault trees would be very large and cumbersome, and they therefore established ETA to condense the analysis into a more manageable picture, while still utilizing FTA.

ETA has been successfully applied to a wide range of systems, such as nuclear power plants, spacecraft, and chemical plants. Considering an undesired event as the initiating event (IE) of an event tree, there will be two branches at every top event (TE) or safety measure. These branches usually represent the failure/function or present/absent of safety measures or occurrence/non-occurrence of a sequence of events. Figure 6 illustrates a typical ET with one IE and two TEs. As a result, four outcomes or consequences could have been envisaged, C1, C2, C3, and C4.

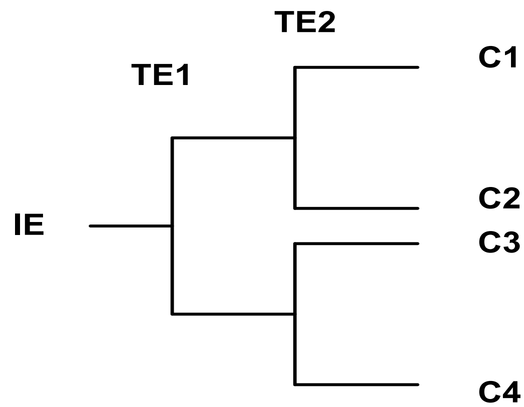

Figure 6. A typical event tree

Having the required probabilities, the probabilities of consequences can readily be calculated. For example, the probabilities of C1-C4 in Figure 6 can be calculated as:

$$P(C1) = P(IE).\left(1 - P(TE1)\right).\left(1 - P(TE2)\right) \tag{3.11}$$

$$P(C2) = P(IE).\left(1 - P(TE1)\right).P(TE2) \tag{3.12}$$

$$P(C3) = P(IE).P(TE1).\left(1 - P(TE2)\right) \tag{3.13}$$

$$P(C1) = P(IE).P(TE1).P(TE2) \tag{3.14}$$

In an ET usually the last consequence (e.g., C4 in Figure 6) has the lowest probability and the highest severity.

3.2.4 Mapping fault tree into Bayesian network

To overcome the limitations of the FT mentioned before (e.g., binary events and independent events) and also taking advantage of probability updating, FT can be mapped to a corresponding BN. In the mapping algorithm, the basic events, intermediate events, and the top event of the FT are represented as root nodes, intermediate nodes, and the leaf node of the BN, respectively. The capability of BN in the incorporation of several leaf nodes, as opposed to only one top event in FT, is another feature making BN a superior technique to FT. Likewise; the probabilities of the basic events in the FT are allocated as the marginal probabilities of the corresponding root nodes in the BN. The Boolean gates (e.g., AND/OR gates) can be converted into appropriate conditional probabilities [17,18,53].

Chapter 4

Application of the methodology

4.1 Case study

To see the influence of the inclusion of accident risk analysis in LCA of different products/processes, we consider a hypothetical power plant in Holyrood in Newfoundland, Canada, which can operate using either LNG or HFO as the power plant fuel. After each fuel supply chain to the power plant was determined, LCA and QRA will be performed for specific stages along the supply chains. It should be noted that the last stage of the fossil fuel life cycles, that is, combustion in power plant, is excluded for either fuel in the present study. Figures 7 and 8 illustrate schematic diagrams of RBLCA of LNG and HFO, respectively.

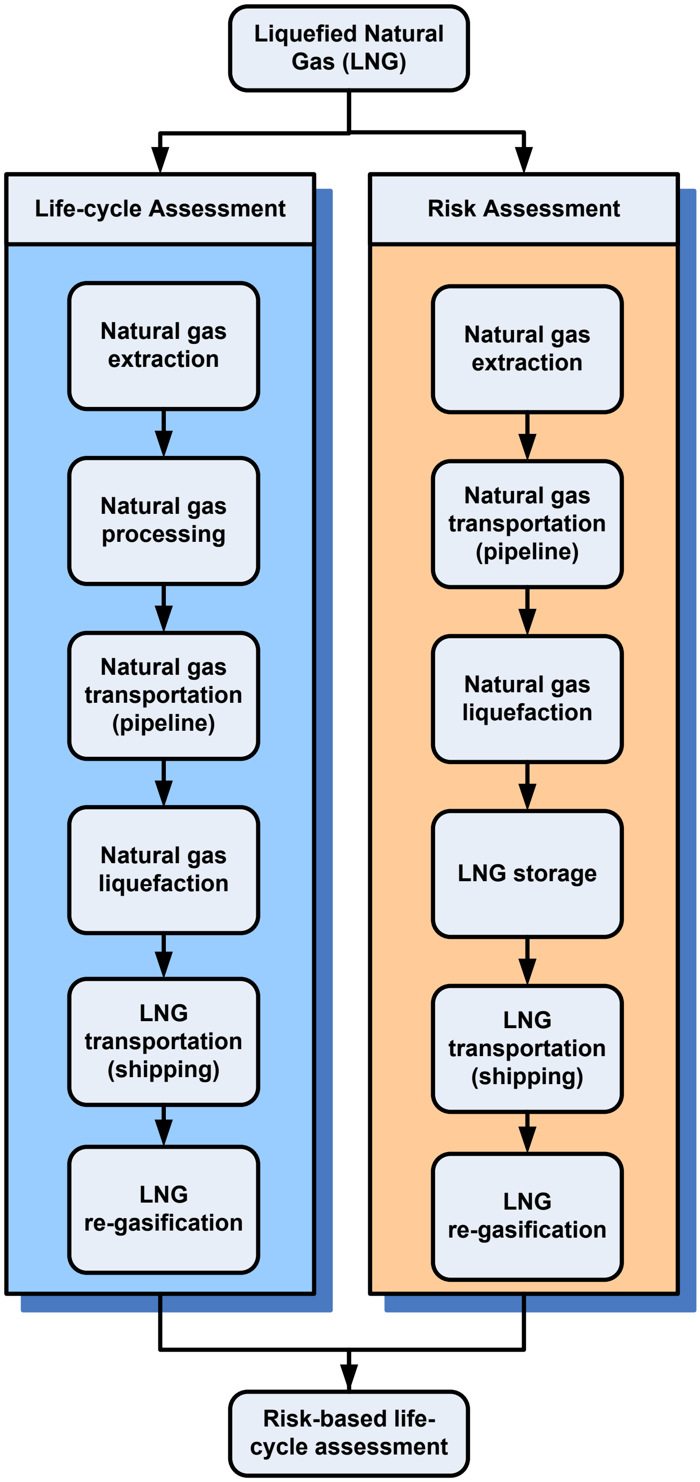

Figure 7. Risk-based life-cycle assessment of liquefied natural gas (LNG)

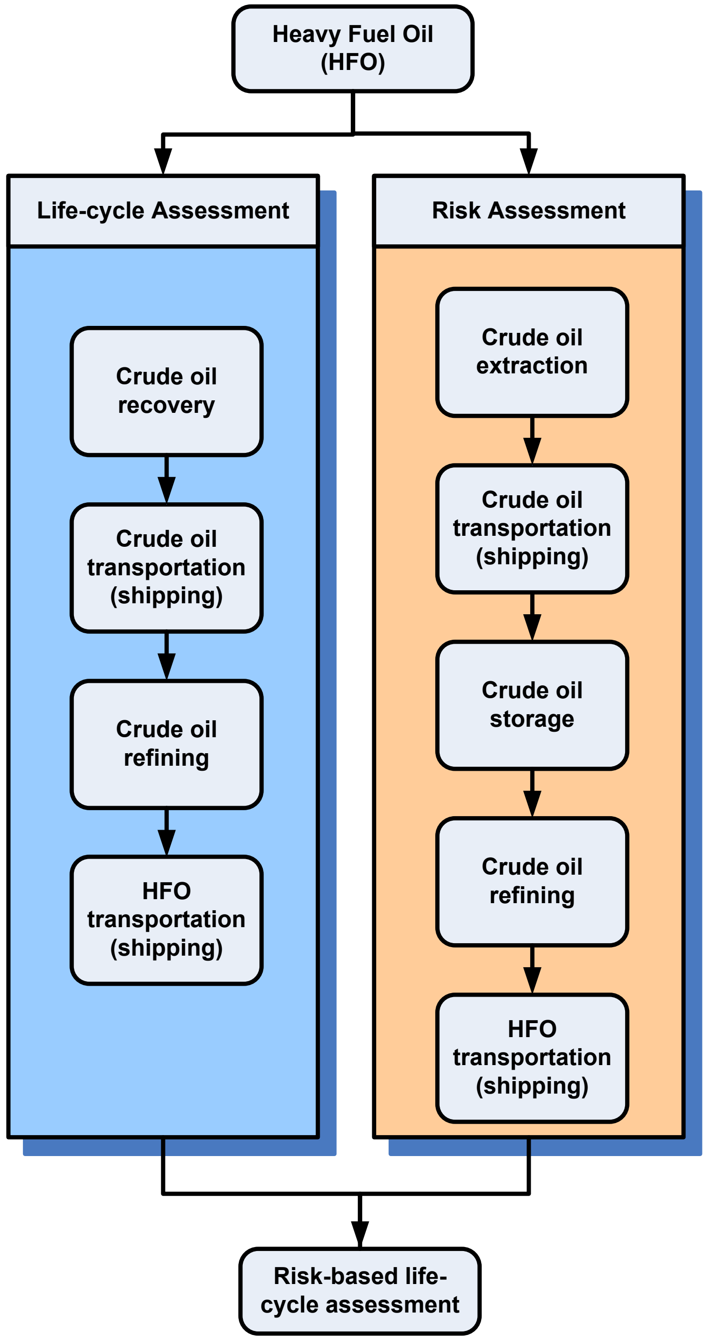

Figure 8. Risk-based life-cycle assessment of heavy fuel oil (HFO)

4.2 Life-Cycle Analysis

Holyrood thermal station at pick is able to produce three billion kilowatt-hours of electricity per year [65]. This electricity amount is used as a basis for required calculations in the GHG emission LCA of LNG and HFO. For further calculations in LCA, heat rates of 10,354 Btu/kWh and 10,334 Btu/kWh are assumed to be the power plant heat rates when it is fueled with natural gas and HFO, respectively [66].

In the present study, GHG emissions are reported on a common mass basis of carbon dioxide equivalents (CO2e) using the global warming potential (GWP) of each gas from the Fifth Assessment Report (AR5) of Intergovernmental Panel on Climate Change (IPCC) in 2013 [67]. Table 1 shows the GWPs used for the GHGs inventories in the current study. All GHG results in this report are expressed as 100-year GWPs unless specified otherwise.

Table1. IPCC Global Warming Potentials

GHG	AR5 (IPCC 2013)	
	20-year	100-year
CO2	1	1
CH4	85	30
N2O	264	265

4.2.1 LCA of LNG

Liquefied natural gas (LNG) is a colourless and odourless liquid, which is made by cooling natural gas to a temperature of about -160 ℃ (-260 °F) at atmospheric pressure. The liquefaction process reduces natural gas volume to one six hundredth of its original volume, making it feasible to transport over long distances [68].

Using a natural gas heating value of 1,027 Btu/cf [69] and a density of 0.042 lb/cf [69], the total amount of natural gas required to generate 3 billion kilowatt hours of electricity can be estimated as 1,270,080,000 lbs using the equation below [70]:

$$Amountoffuelusedperk Wh = \frac{powerplantheatrate(BtuperkWh)}{fuelheatcontent\ (Btupercubicfeet)} \tag{4.1}$$

An LNG plant is supposed to be developed in Goldboro in Nova Scotia, Canada, by 2018 [71]; thus, we assume that LNG fuel required for the power plant in Holyrood, Newfoundland, can be provided from Goldboro. After being extracted and processed at Thebaud platform, located offshore Nova Scotia, the natural gas is transported through the pipeline to Goldboro plant. Natural gas is then liquefied (i.e., converted into LNG) and stored in Goldboro plant for exporting. LNG is then transported to Holyrood by ship, stored, and then re-gasified in a re-gasification terminal. At last, the gas is sent to the hypothetical power plant in Holyrood through pipeline.

It is assumed that the regasification plant is close to the power plant, so that the emission associated with natural gas transportation to power plant is negligible. Furthermore, as LNG storage has insignificant emissions compared to the other stages, it will not be taken into the account in the respective LCA in the present work. The sequence of the aforementioned processes considered in the LCA of LNG is depicted in the left-hand side block of Figure 7. It is worth mentioning that the results and assumptions of National Energy Technology Laboratory (NETL) inventory [45] for conventional offshore gas have been mostly used for LCA of LNG in the present study.

4.2.1.1 Natural gas extraction

Extraction of natural gas (NG) is the first section in the LCA of LNG and depending on the well type can include sub-sections such as well construction and installation, well completion, liquid unloading, and workovers. These activities all result in GHG emission either by energy combustion or by gas release occurring during the operations. Another key source of air emission, which contributes to almost all sections of LCA, is fugitive emissions from the operational equipment. The emission sources accounted for NG extraction in this study include well completion, gas venting from wet seal degassing, and fugitives from the equipment.

The emission related to well completion is the NG release that occurs during a well development, before equipment have been installed for NG recovery. Well completion causes a significant amount of air emission although it is not a part of daily operations. The methane emission from the completion of a conventional well is based on emission factor developed by EPA; 36.65 Mcf of methane per completion [45]. The emission factor for wet seal degassing accounts for the NG lost during the regeneration of wet seal oil, which is used for centrifugal compressors. In this study, we use the emission factor calculated by NETL, which is based on sampled venting emissions from 15 offshore platforms by EPA, and production rate of a year in US. This emission factor is 0.0069 m3 of vented gas per m3 of produced NG [45]. The fugitive emissions considered in this study include two sorts of emissions; the emissions that cannot be and those that can be captured for flaring. The former is related to the methane leakage of pneumatic valves and other process control systems. The emission factor for these devices, which is estimated like that of wet seal degassing, is 1.95 E -06 lb of methane per lb of produced NG [45]. Likewise, gas released from mishaps and equipment such as separators and pumps cannot be captured for flaring. NG is also released from wellhead and equipment like heaters and blowdown vessel, which can be captured for flaring. For conventional wells, 51% of these emissions are flared, while the balance is vented to the atmosphere [45]. Table 2 shows the emission factors for fugitive emissions from extraction section. The emission factors for unprocessed NG flaring based on API [69] are shown in Table 3.

Table 2. Emission factors for fugitive emissions during extraction

NG extraction emission source	Value	Unit
Fugitive emissions (captured for flaring)	3.90 E -05	lb CH4/lb NG extracted
Fugitive emissions (not captured for flaring)	2.41 E -04	lb CH4/lb NG extracted
Valve fugitive emissions (including pneumatic devices)	1.95 E -06	lb CH4/lb NG extracted

Table 3. Unprocessed Natural Gas Flaring Emissions

Pollutant	Value	Unit
CO_2	2.67	lb CO_2/lb flared NG
N_2O	8.95 E -05	lb N_2O/lb flared NG
CH_4	1.53 E -02	lb CH_4/lb flared NG

4.2.1.2 Natural gas processing

To meet pipeline quality, raw NG must be cleaned from contaminants such as water, carbon dioxide, and hydrogen sulfide (H_2S). This is a pre-treatment of raw NG at extraction site such that a complete process is usually done at a processing or liquefaction plant. This process takes place through different operations depending on the NG type. Figure 9 shows a schematic diagram of the typical natural gas processing. In this study, we consider key processing operations including acid gas removal (AGR) and dehydration.

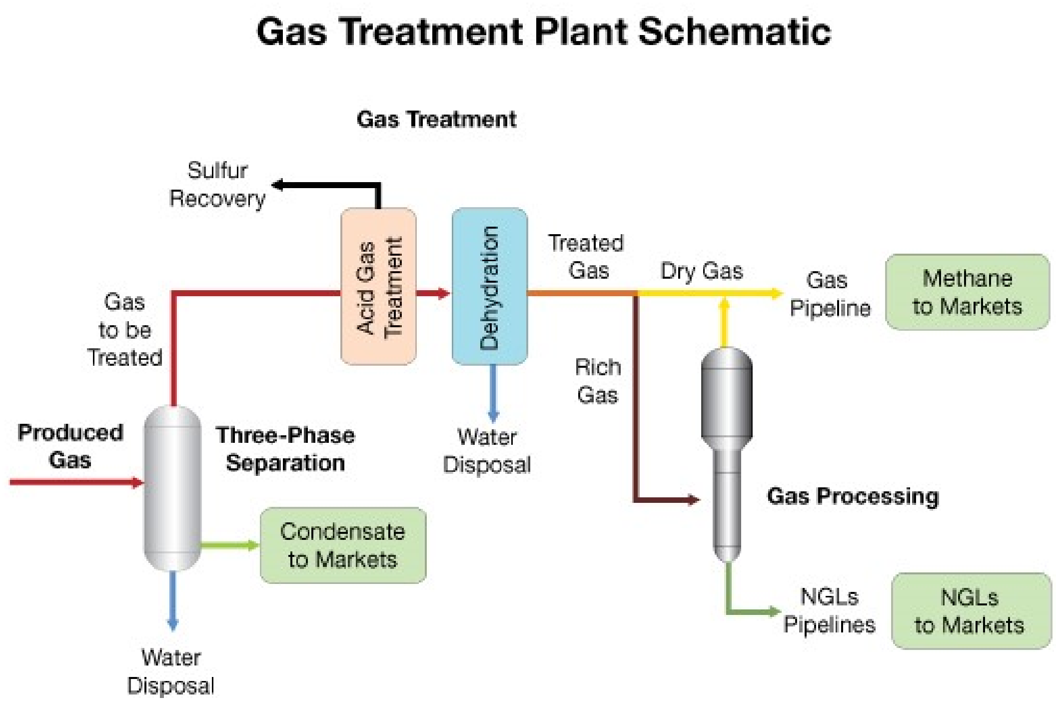

Figure 9. A schematic diagram of natural gas treatment process (www.ihrdc.com)

Amine-based processes are technologies widely used in AGR. The energy combustion by an amine reboiler is the major source of GHG emissions in AGR process. In order to estimate air emissions by amine reboiler, EPA emission factors for industrial boilers [51], which are fuelled by NG, are applied in this study. In addition to the emissions resulted from the energy combustion, a portion of CH4 absorbed by amine solution and naturally-occurring CO2 in raw NG are vented to the atmosphere [45]. Table 4 shows the emission factors for AGR process.

Table 4. Emission factors for AGR process

Flow Name	Value	Unit
CO2 (combustion)	6.47 E -04	lb CO2/lb NG product
CO2 (vented)	1.30 E -02	lb CO2/lb NG product
N2O	3.54 E -06	lb N2O/lb NG product
CH4 (combustion)	1.27 E -05	lb CH4/ lb NG product
CH4 (vented)	9.71 E -04	lb CH4/ lb NG product

Glycol dehydration is the most common method of water removal from raw NG. Similar to AGR process, air emissions from dehydration operations include fuel combustion and venting emissions. Reboiler, which here is assumed to be heated by NG combustion, is the only equipment in the dehydration system that consumes fuel. In addition to absorbing water, the glycol solution also absorbs methane from the NG stream. Flash separators capture most of this methane during the process; nonetheless, small amounts of it are vented from dehydrators [45]. Table 5 shows the emission factors for dehydration operation.

Table 5. Emission factors for dehydration

Flow Name	Value	Unit
CO2	4.24 E -04	lb CO2/lb NG product
N2O	2.26 E -09	lb N2O/lb NG product
CH4 (combustion)	8.10 E -09	lb CH4/ lb NG product
CH4 (vented)	8.06 E -06	lb CH4/ lb NG product

4.2.1.3 Natural gas transportation (pipeline)

This study assumes that NG after extraction and process in offshore oil field is transported to Goldboro LNG plant by pipeline. Most emissions related to NG transportation are produced due to energy combustion by compressors, used to increase NG pressure. The energy required for compressor operations is based on comparing power requirements to compression ratios. This analysis assumes that the inlet pressure to compressors at the NG extraction and processing site is 50 psig while the outlet pressure is 800 psig, a standard pressure for pipeline transportation of NG.

Gas powered centrifugal compressors are commonly used at offshore NG extraction sites. A two-stage centrifugal compressor with an inlet pressure of 50 psig and an outlet pressure of 800 psig has a power requirement of 187 horsepower per MMcf of NG [72].

The GHG emission for the operation of wellhead centrifugal compressor is shown in Table 6.

Table 6. Centrifugal compressor emission factors

Pollutant	Value	Unit
CO2	8.80 E -02	Kg CO2/kg NG
CH4	6.89 E -06	Kg CH4/kg NG
N2O	2.40 E -06	Kg N2O/kg NG

The pipeline distance in the present study was estimated as 140 miles, which is the approximate distance between the extraction field and the location of the hypothetical LNG plant. To keep the desired NG pressure, compressor stations are necessary every 50 to 100 miles along the pipelines. Therefore, it is assumed that there are two compressor stations along the pipeline; in this regard, the amount of GHG emissions associated with each station is 30% of the total emission produced by the wellhead compressor.

4.2.1.4 Natural gas liquefaction

NG that arrives at a LNG plant, prior to liquefaction, is further treated to remove any residual water, sulfur-containing species, and CO2 that might be still present after the pre-processing. Moreover, other components that could freeze (e.g. benzene) under the low temperatures needed for liquefaction are removed as well as that could be harmful (e.g., mercury) to the liquefaction facility. The liquefaction process entails chilling the cleaned NG using refrigerants. Going through stages of pre-cooling, liquefaction and sub-cooling, the NG reaches the desired temperature and is then stored as LNG in double-walled tanks at atmospheric pressure. Figure 10 illustrates the schematic of the liquefaction process at Goldboro Plant, NS, Canada, comprising a gas treatment unit, refrigerant compression, and a heat exchanger. GHG emissions associated with liquefaction process are mainly due to the fuel gas combustion needed to power refrigeration compressors and electrical generators, fired heaters, flares, incinerators, venting of CO2, and fugitive emissions in the process [73].

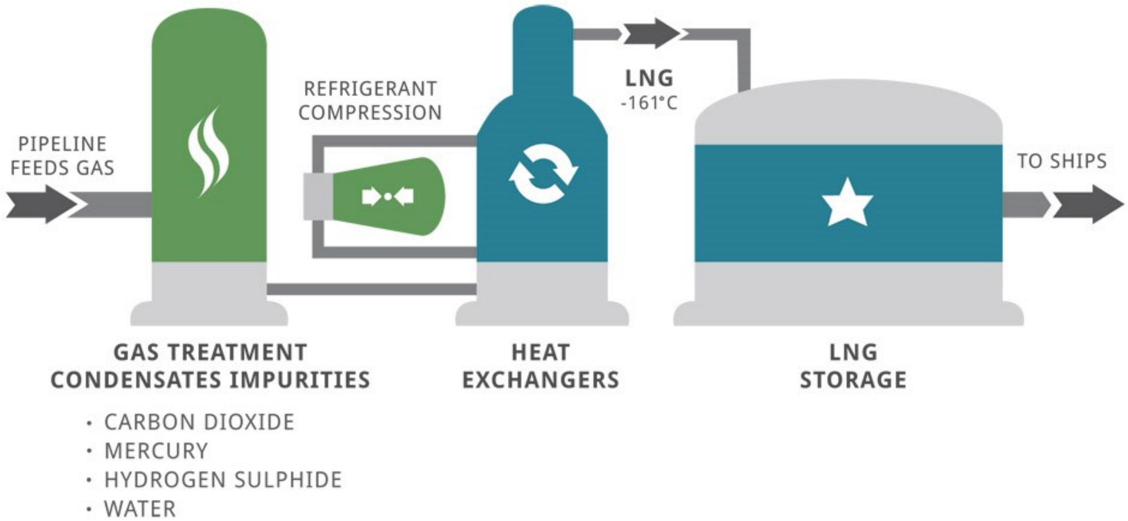

Figure 10. Schematic of liquefaction facility at Goldboro Plant (www.goldborolng.com)

A few studies have been conducted to quantify the amount of GHG emissions from LNG plants. Among those, an estimation of 64 kg CO2 e/MWh by NETL [74] was selected for the liquefaction air emissions in the present analysis.

4.2.1.5 LNG transportation

LNG is transported by specially designed marine tankers (Figure 11) delivering their load to receiving terminals. The main source of air emissions in LNG tankers (ships) is fuel combustion needed to power their propulsion systems. Hence, emissions from LNG transportation relates to the volume of LNG transported and the distance travelled by ships. It is assumed that boil-off gases (BOG) from the vessels are either consumed as fuel in engines or liquefied and returned to the ship tanks.

Figure 11. A typical tank ship used to carry LNG (www.en.wikipedia.org)

Jaramillo et al. [75] conducted a comparative study of LNG, coal, and gas life-cycle carbon emissions, and used an equation for estimation of LNG carriers. Their formula was adapted in this study to estimate LNG tankers air emissions. Furthermore, the distance travelled by the LNG tankers was estimated as 1000 km using Google Map.

$$Emissionfactor = \frac{(EF)\sum[\left(2*roundup(\frac{LNGx}{TC})\right)*\frac{Dx}{TS}*FC*\frac{1}{24}]}{LNGt} \qquad (4.2)$$

where EF is the tanker emission factor of 3,200 kg CO2/ton of fuel consumed; 2 is the number of trips each tanker does for delivery of each load; LNGx is the amount of natural gas (in cubic feet) brought from each country; TC is the tanker capacity in cubic feet of natural gas (assumed to be 120,000 m^3 of LNG); Dx is the distance from each country; TS is the tanker speed of 14 knots; FC is a fuel consumption of 41 tons of fuel per day; and 24 is the number of hours in a day [76].

4.2.1.6 LNG regasification

Regasification plants, generally incorporated into LNG receiving terminals, return the LNG back into its gaseous state. In regasification plants (Figure 12), LNG is initially pumped from the ships into the terminal LNG storage tanks. Then, LNG is either loaded onto trucks for transport to smaller costumers' locations, or pumped to higher pressure through high pressure pumps, vaporized in high pressure, and entered into the transmission and distribution pipeline systems.

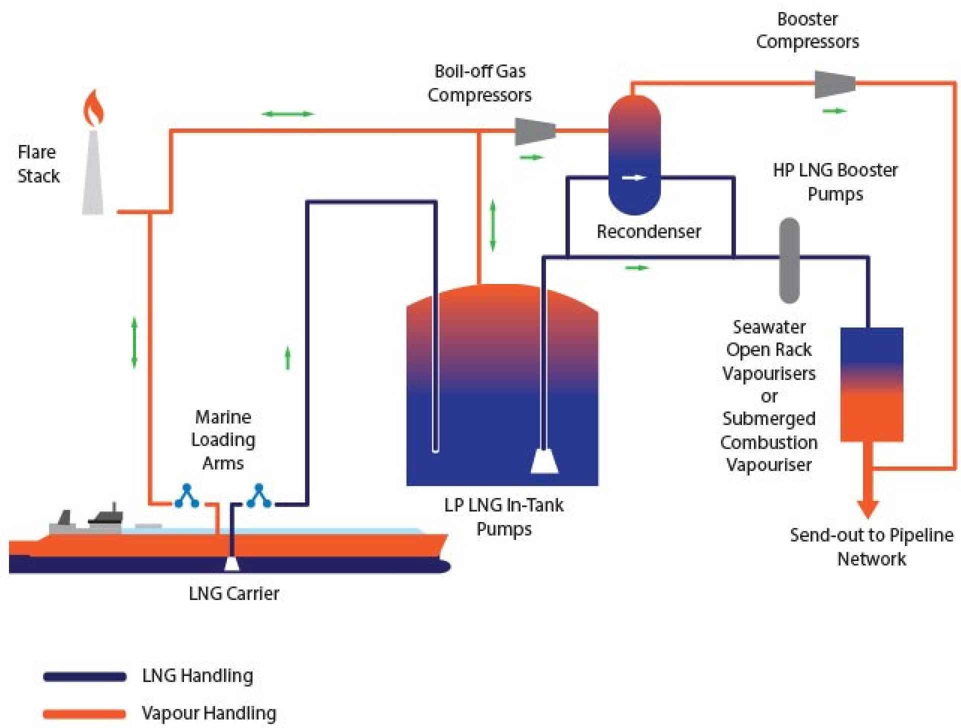

Figure 12. Schematic of LNG re-gasification facilities (www.ema.gov.sg)

In a regasification LNG terminal, GHG emission sources include: methane leakage from equipment such as flanges, valves, compressors and pumps, venting emissions from LNG pumps during maintenance, flaring of BOG from storage tanks during ship unloading (if BOG rate exceeds BOG compressor capacity), emissions from fuel combustion used for the vaporization process, and venting from the vaporization process and from BOG compressors during maintenance [73]. The estimation of 20 kg CO2 e/MWh by NETL [74] was selected for the GHG emissions related to regasification plant in this study.

4.2.2 LCA of HFO

HFO is a high-viscosity residual oil that remains after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations. HFO is the cheapest product of a refinery, used for the production of electric power, space heating, vessel bunkering, and various industrial purposes [77].

Using a HFO heat content of 6.287 MBtu/barrel [78], the total amount of HFO required to generate 3 billion kilowatt hours of electricity in Holyrood power plant is estimated to be 4,929,000 barrels using Equation (4.1). According to American Petroleum Institute (API), based on average of yields for US refineries in 2005, 1.7 gallons of HFO is obtained from one barrel (42 gallons) of crude oil. Therefore, approximately 121,775,300 barrels of crude oil is needed to produce 4,929,000 barrels of HFO.

The required oil fuel for Holyrood thermal plant is supplied by Philips 66 Company, which is an American company that has no refinery in Canada. Thus, in this study the origin of oil fuel has been considered in Gulf of Mexico, US. It is supposed that the crude oil extracted from Mars platform in the Gulf is transported to one of Philips 66's refinery, Alliance Refinery, Louisiana, US, by ships. After processing of the crude oil, the produced oil fuel is stored, and then shipped to Holyrood thermal plant by ship tankers. The sequence of the aforementioned processes is depicted in the left-hand side block in Figure 8.

4.2.2.1 Crude oil recovery

Crude oil recovery is the first section of HFO life-cycle assessment, and includes well drilling, crude oil extraction, and crude oil processing. Rahman et al. [79] quantified the GHG emissions from the recovery of five North American conventional crude oils. One of the crude oils included in their analysis was Mars crude oil, extracted from Mars platform that is used in this study as the crude oil extraction site. Rahman et al. [79] estimated air emissions associated with crude oil recovery operations such as well drilling, crude oil extraction, crude oil processing, and also emissions from venting, flaring, fugitives, and land-use change. Among these emissions, crude oil extraction, crude oil processing, and emissions from venting, flaring and fugitives were taken into account in the present study.

Crude oil extraction consists of a number of steps in order to pull out the crude oil from reservoir to surface. Extraction of crude oil consumes a large amount of energy that consequently results in GHG emissions. It is worthy to mention that this energy is mainly used by recovery techniques – primary, secondary, and enhanced methods – applied to increase the production of the oil reservoir. At the primary method that extraction is at the early stages, reservoir pressure is enough to flow the oil through the production well; although, artificial lift technologies such as pumps are used when the pressure falls within the reservoir. Aging the reservoir and consequent decrease of the pressure, makes it necessary to use secondary method, such that water/gas is injected into the reservoir to boost the reservoir pressure for production. Further, the enhanced recovery method including thermal recovery (steam injection), gas injection (i.e., natural gas, nitrogen, carbon dioxide), and chemical injection (i.e., polymers and detergent) is used to mobilize the remaining oil. Rahman et al. [79] calculated air emissions of crude oil extraction based on basic energy combustion equations for pumps, compressors, and other electric equipment. The emission for Mars crude oil was estimated to be 1.26 g-CO2 equivalent per each MJ of crude extracted [79].

Being mixed with water and gas after extraction, the crude oil needs processing to meet transportation quality requirement. The energy consumption needed to remove and treat these phases contributes to GHG emission. A gravity separator is usually used to separate oil, gas, and water, which is not a significant source of air emission. Natural gas-fired reboilers providing the heat required for crude oil stabilization, and pumps, are considered main causes of emissions for stabilizing of crude oil. Treatment of associated gas using an amine treater and a glycol dehydrator is the next step in crude oil processing, which has been already explained in of NG processing (see Section 4.2.1.2). The water that comes out from reservoir along with the oil crude, must meet environmental regulations before discharging. Therefore, the last step of crude oil processing entails treatment of the water associated with crude oil. This treatment includes reduction of oil, grease, sodium, and TDS (total dissolved solids) in water, which is energy consuming and a source of GHG emission. The emission factor for Mars crude oil processing estimated by Rahman et al. [79] is 0.79 g-CO2 e/MJ.

Venting – release of associated NG – and flaring – combustion of associated NG – are inevitable sources of air emissions in extraction sites. Venting and flaring may occur during emergency operations and necessary where a stream of NG cannot be safely or economically recovered. The flaring combustion product of NG includes carbon dioxide, methane, and nitrous oxide. The mass composition of unprocessed NG, used in this study to model NG flaring, is 78.3% CH4, 1.51% CO2, 1.77% nitrogen, and 17.8% non-methane hydrocarbons [80]. The emission factors for unprocessed NG flaring are shown in Table 3.

The leakage of NG through equipment such as valves, pumps, compressors, and other devices during extraction and processing operations is called fugitive emissions. These emissions usually cannot be captured for flaring due to economic limitations [45,79]. Rahman et al. [79] estimated venting, flaring, and fugitive volumes to be 1.33, 0.78, and 0.21 m^3 of NG per m^3 of crude oil extracted, respectably.

4.2.2.2 Crude oil transportation

Transportation of crude oil along the ocean is generally done through subsea pipelines or ocean tankers (Figure 13). In this study marine tankers are assumed to transport the crude oil from the producing filed to the refinery, and the HFO from the refinery to the power plant. Ocean going vessels are among the major sources of GHG emissions in the world. This is primarily due to the large quantity of fuel, mostly residual fuel oil, consumed by engines to propel the vessels. Air emission associated with maritime vessels is highly debated, and many studies have been conducted to evaluate their impacts. In this study, the approach of Clarkson [81] is adopted. That is, ocean oil tankers with slow-speed diesel main engine, medium-speed diesel auxiliary engine, and a capacity of 700,000 barrels are assumed to be used for both crude oil and HFO transportation. Since the difference between crude oil and HFO densities, which in turn affects the volume of the liquids transported by each marine tanker trip, is insignificant, we assume that the amount of crude oil and HFO transported in each trip are the same. The ocean tankers specifications are listed in Table 7.

Figure 13. A typical marine oil tanker used for oil transportation (www.wsj.com)

Table 7. Oil tanker specification

Average service speed	Maximum speed	Average main engine power	Average Aux engine power
14.7 Knots	16 Knots	9667 kW	2040 kW

The emissions produced by main and auxiliary engines are calculated separately. The load factor for the main engine in each mode is calculated based upon the propeller law relationship equation [82]. Since the vessels do not operate at 100% maximum continuous rating (MCR), the correction of 0.83 is added for compensation [83].

$$LF = 0.83 \times (\frac{AS}{SS})^3 \quad (4.3)$$

Where *LF* is load factor; *AS* is actual speed of the vessel, and *SS* is the service speed of the vessel.

In order to calculate the vessel emissions, individual emission factors are required for each pollutant being investigated. Emission factors suggested by Goldsworthy & Renilson [84] were used in this study. These emission factors are presented in table 8.

Table 8. Emission factors of marine tanker (g/kWh)

Engine type	N2O	CO2	CH4
Main (SSD)	0.031	622	0.006
Aux. (MSD)	0.031	692	0.004

The amount of emissions produced by both the main and auxiliary engines is then calculated using Equation (4.4), proposed by Corbett et al [85].

$$E = \frac{P \times LF \times A \times EF}{1000} \quad (4.4)$$

Where E is the amount of emission in kg; P is the installed power of engine; A is the time of operation in that mode, and EF is the emission factor in g/kWh. The distances were estimated as 200 km from the oil field to the refinery, and 4,500 km from the refinery to the power plant using Google Map.

4.2.2.3 Crude oil refining

After crude oil arrives at refinery, it is refined (i.e., separated into smaller fractions) to produce various petroleum products. Figure 14 illustrates a schematic diagram of a typical refinery process. Refineries are considered one of the largest GHG-emission sources in industrial activities around world, mainly because of vast amount of energy consumption. Rahman et al. [86] developed a refinery model in HYSYS to quantify the energy consumption in each process unit of the refinery. The amount of energy consumed and the volume of the final products produced in the refinery were used as inputs to a spreadsheet-based model, FUNNELGHG-CCO, which traces energy combustion and quantify GHG emissions associated with each final product. They ran the model for different crude oils to process 150,000 barrels per day. Considering that electricity, heat, and steam are required for the refinery processing unit, it was assumed that NG is used to produce the heat and steam. To calculate the amount of NG required for heating and steam production, the heater and boiler efficiencies were taken as 80% and 75%, respectively. The total GHG emissions were determined from the amount of NG, required electricity, and emission factors for the combustion of NG and grid electricity. The model estimated the emission associated with Mars crude oil refining to be 7.97 E 09 gr-CO2 equivalents per day [86].

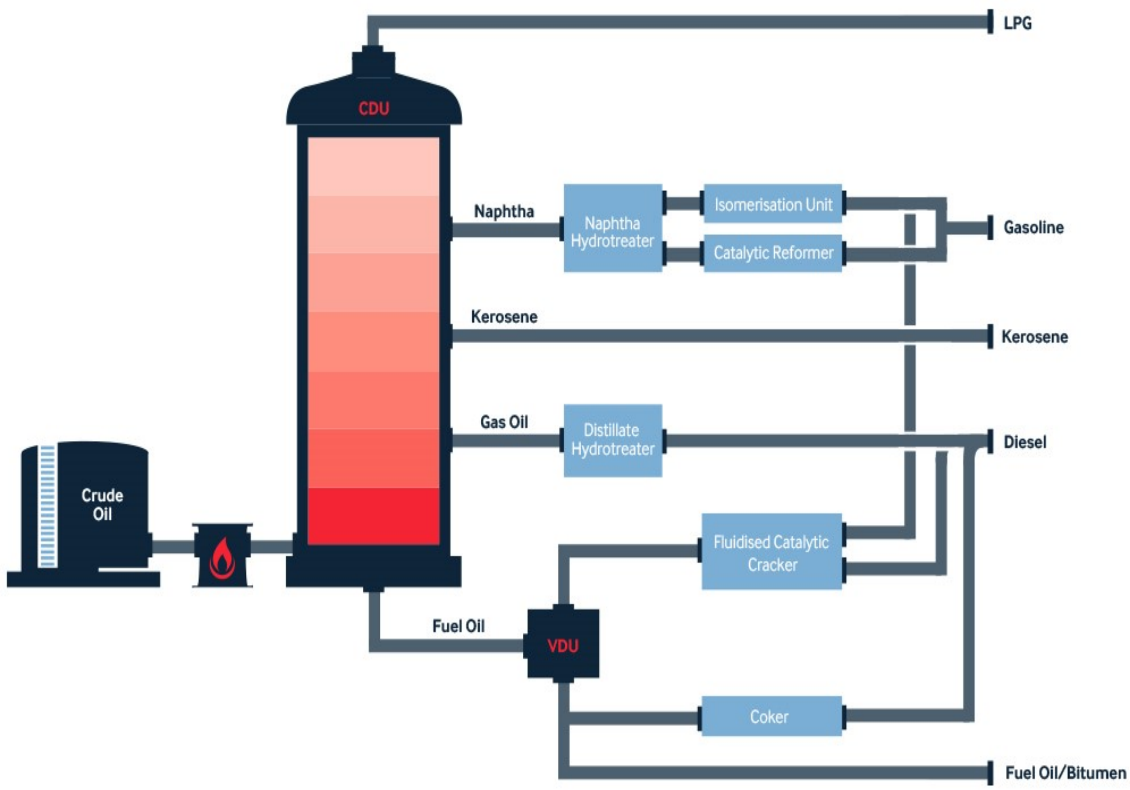

Figure 14. A schematic diagram of a typical refinery process (www.varoenergy.com)

4.3 Risk Analysis

In order for a holistic risk analysis, the risks of potential fires and explosions for likely release of LNG and HFO at different stages from the extraction at offshore drilling platforms to the consumption at the power plant are to calculated though for a limited number of dominant stages. For this purpose, we employ FT technique to analyze the root causes of unwanted release of flammable materials LNG and HFO. The FTs developed in this way for each fuel are then mapped to the corresponding BNs to account for dependencies and conditional probabilities. Accordingly, ET technique is used to explore the consequences of such a release. In the next section the fuels of interest will be analyzed in detail.

4.3.1 LNG life-cycle risk analysis

The sequence of the processes which will be considered in the risk analysis of LNG life-cycle is depicted in the right-hand side block of Figure 7.

4.3.1.1 Natural gas extraction

As can be seen from Figure 1, the first process considered in risk analysis of LNG life-cycle in this study is the extraction of NG at the offshore drilling rig. Assuming an overbalanced drilling, an undesired kick and the ensuing blowout are considered as the most likely release scenario [52,87]. The developed FT and BN of an undesired kick and the ET of the evolution of the kick to a blowout have been displayed in Figures 15, 16 and 17, respectively.

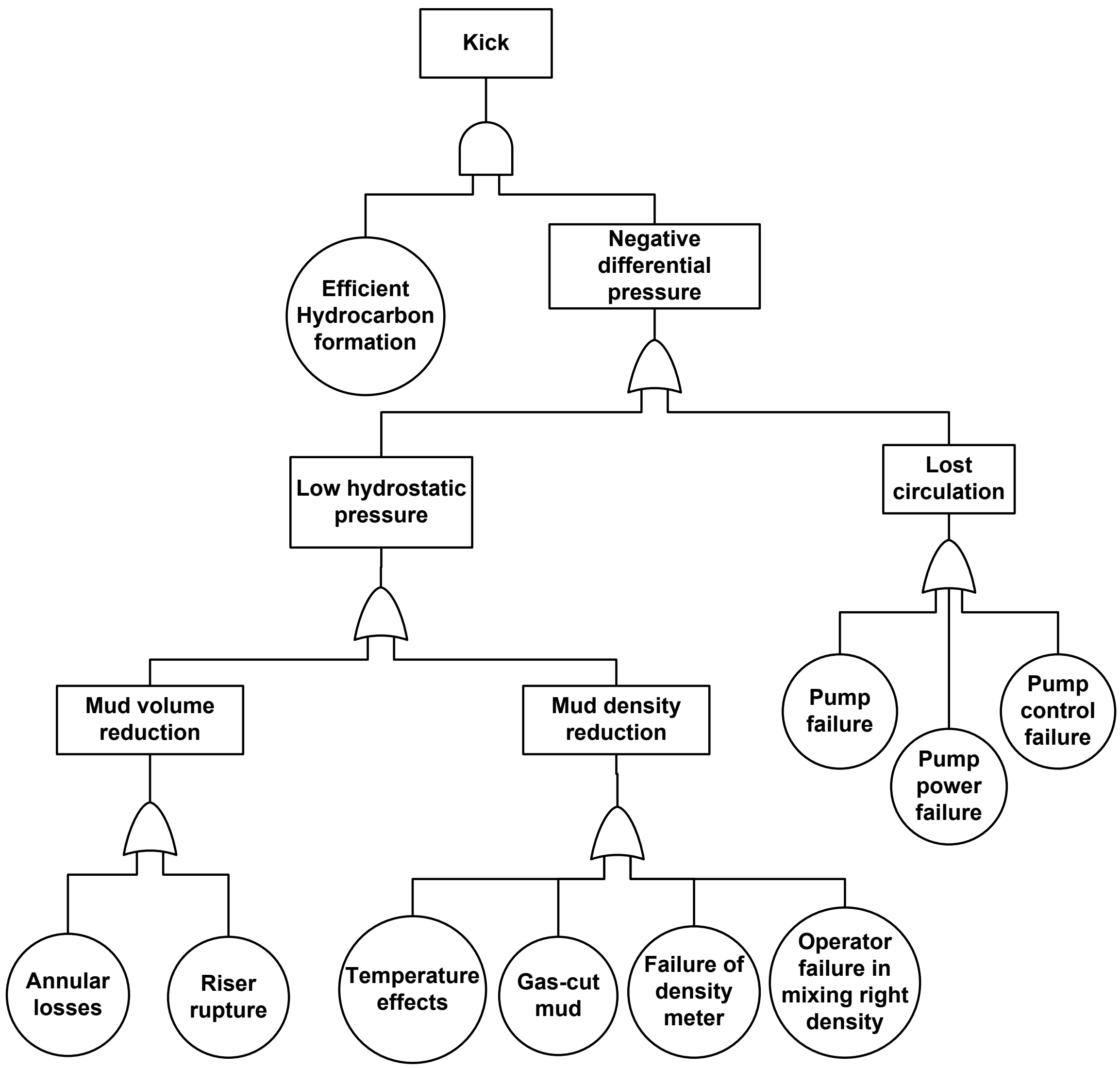

Figure 15. Fault tree analysis of offshore drilling

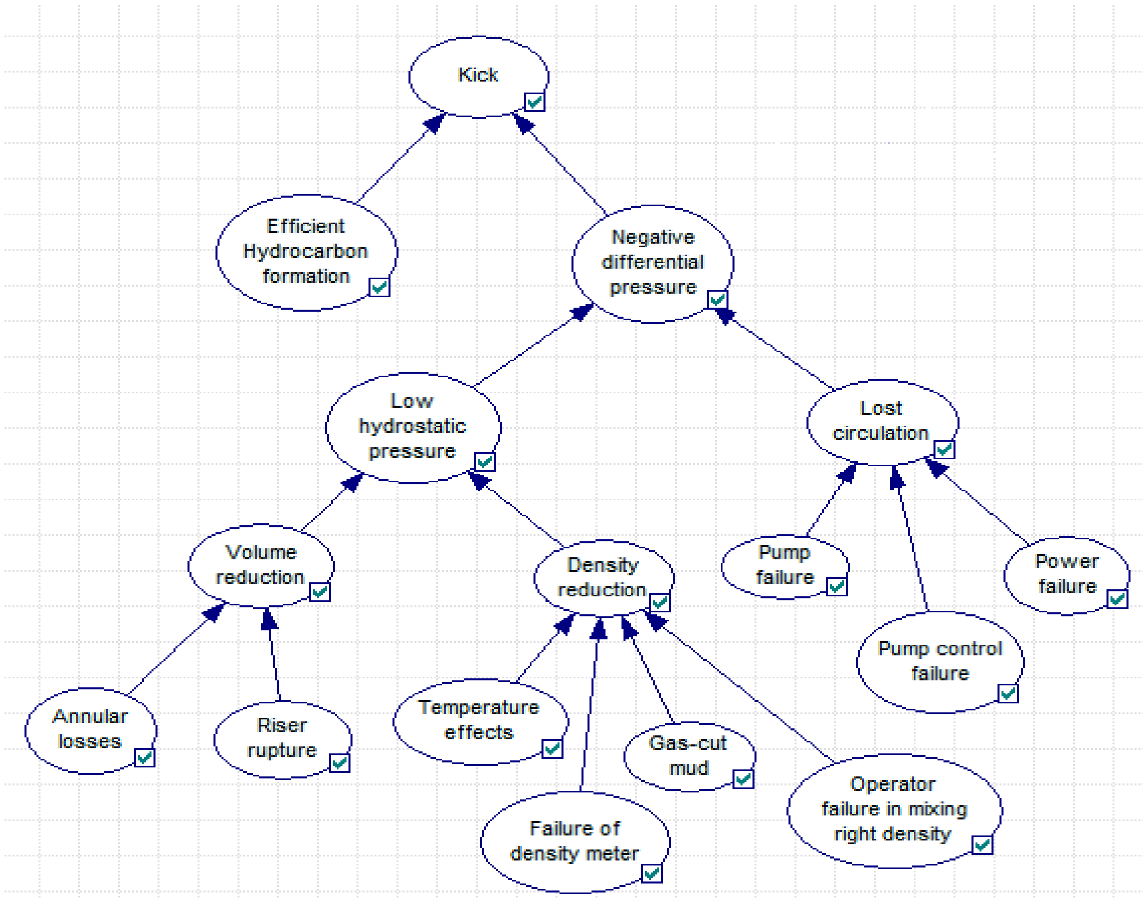

Figure 16. Undesired kick Bayesian network

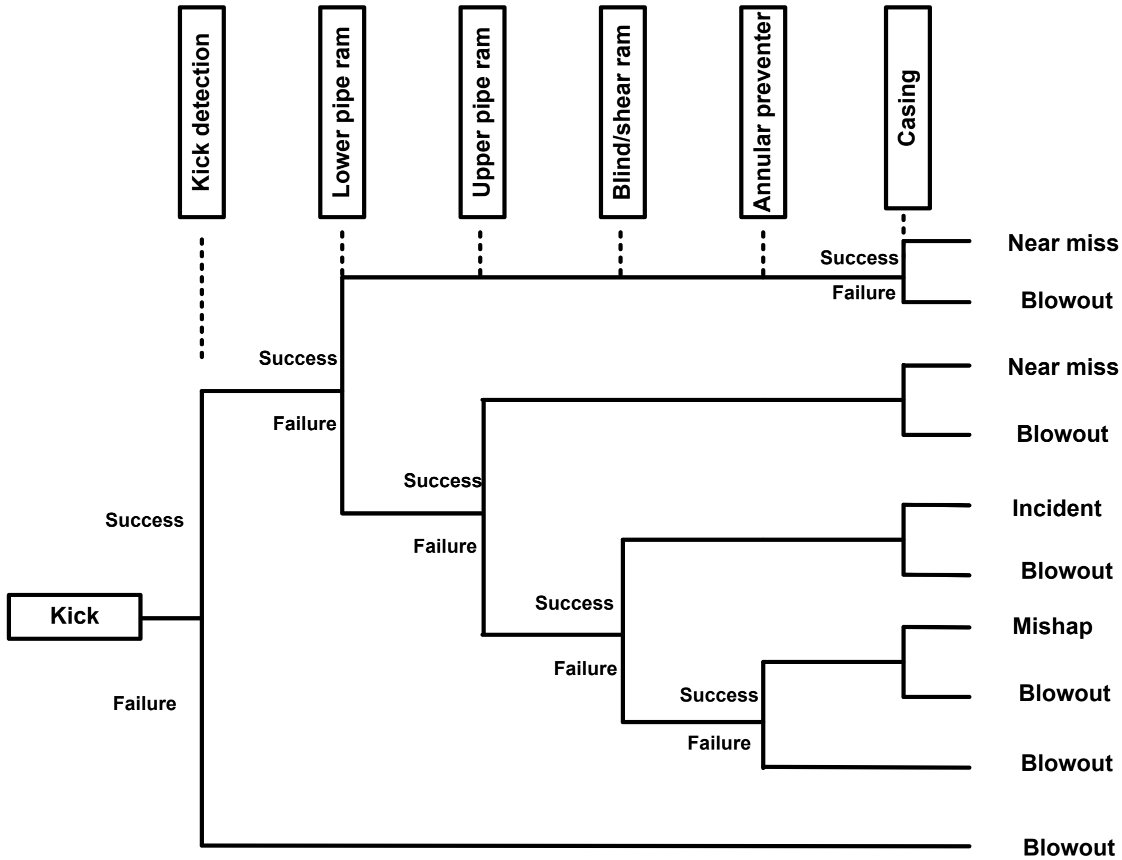

Figure 17. Event tree analysis of offshore drilling

4.3.1.2 Natural gas transportation (pipeline)

After being extracted at Thebaud platform, NG is transported ashore via subsea pipeline. The pipe rupture can then be considered as the most likely release scenario as shown in the FT and BN of Figures 18 and 19. Based on the function/malfunction of the safety measures in place the consequences of a pipe rupture can be investigated using the ET as shown in Figure 20.

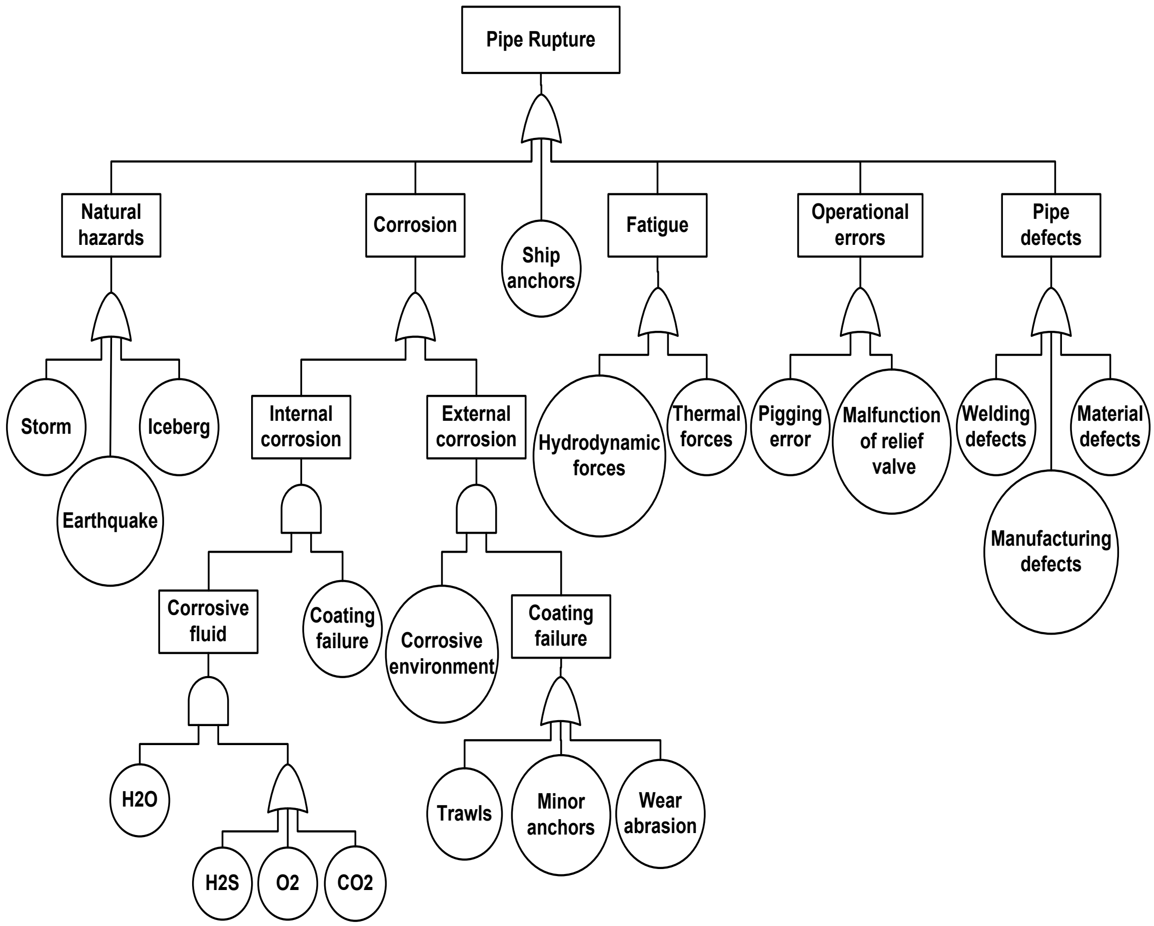

Figure 18. Fault tree of sub-sea pipe rupture

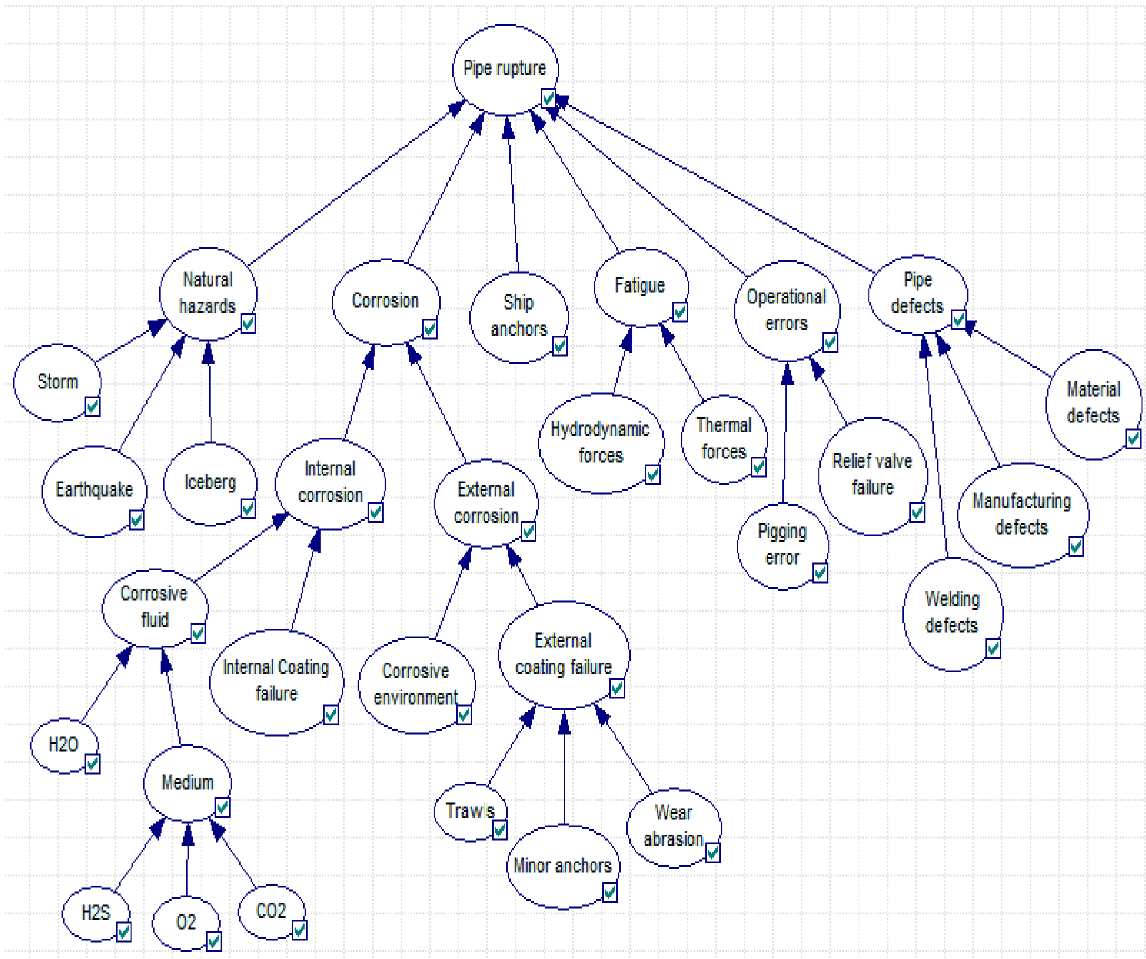

Figure 19. BN of sub-sea pipe rupture

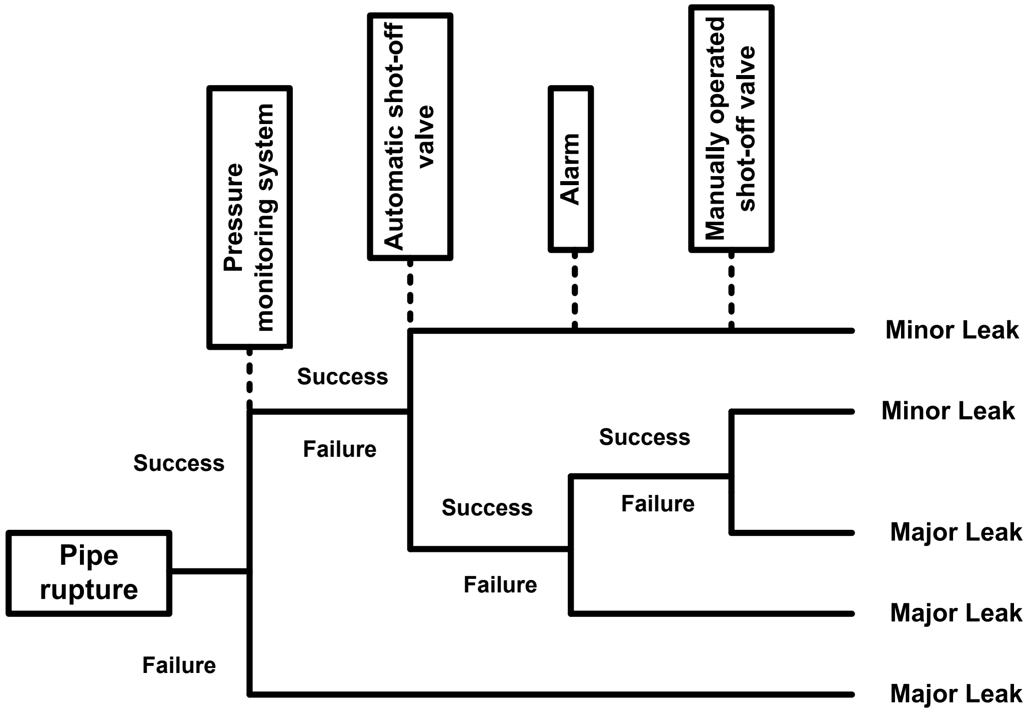

Figure 20. Event tree of sub-sea pipe rupture

4.3.1.3 Natural gas liquefaction

The natural gas which is transported ashore should be liquefied for the ease of storage and transportation. The root causes of a gas release scenario have been displayed in the FT and BN of Figures 21 and 22, respectively. The corresponding ET to investigate the likely consequences of such gas releases has been depicted in Figure 23.

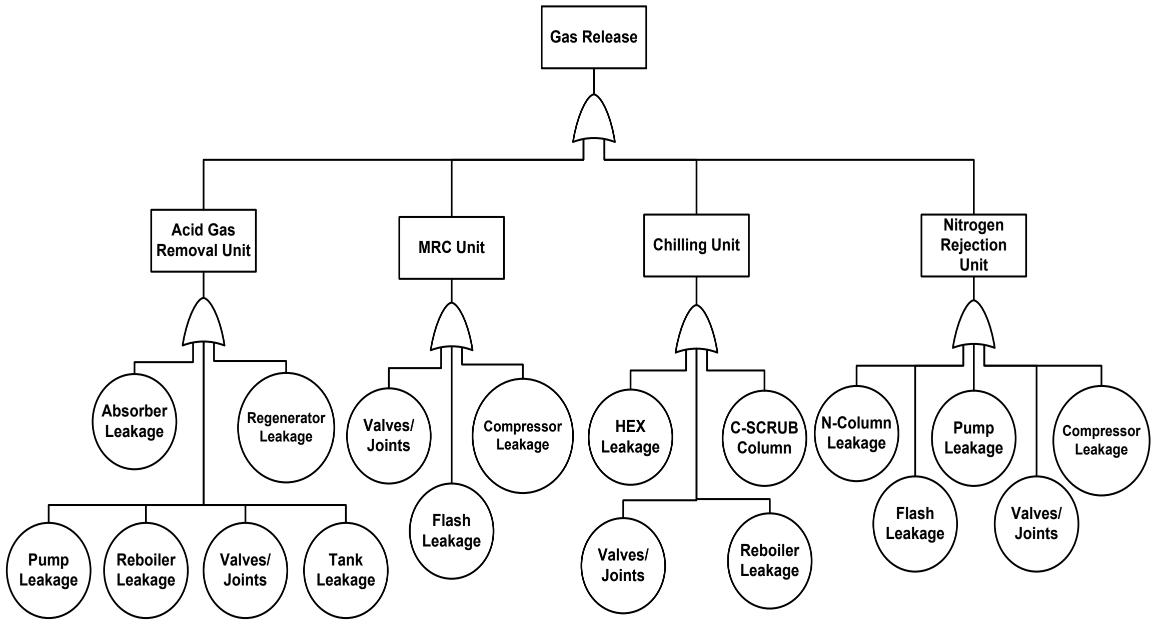

Figure 21. Fault tree of gas release in the liquefaction facility

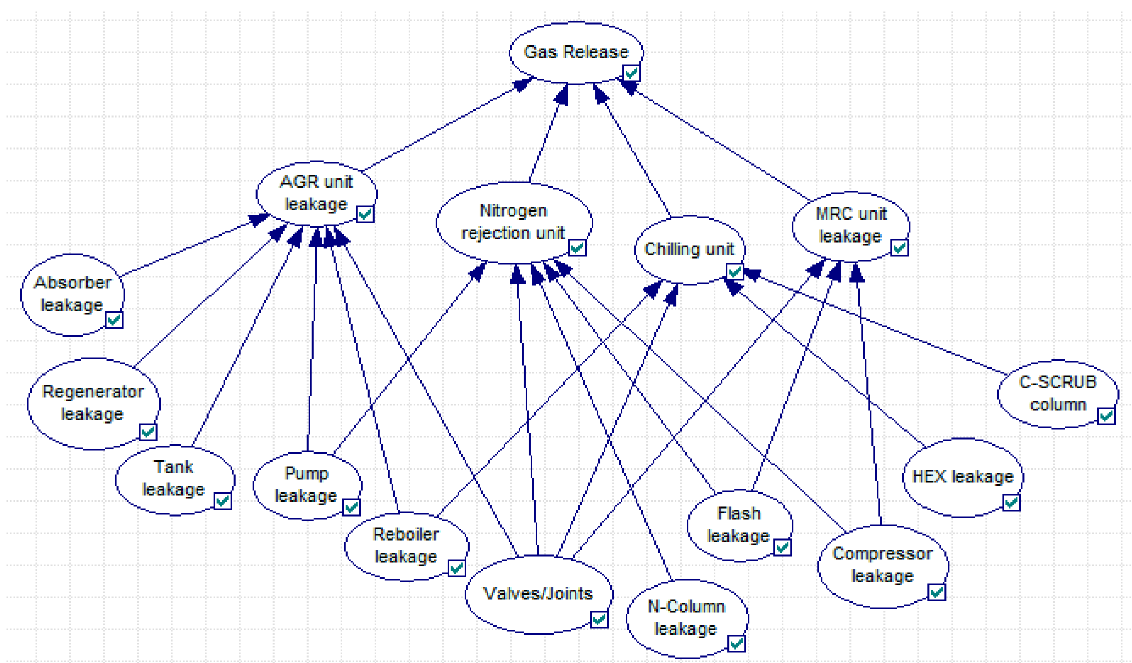

Figure 22. Bayesian network of gas release in the liquefaction facility

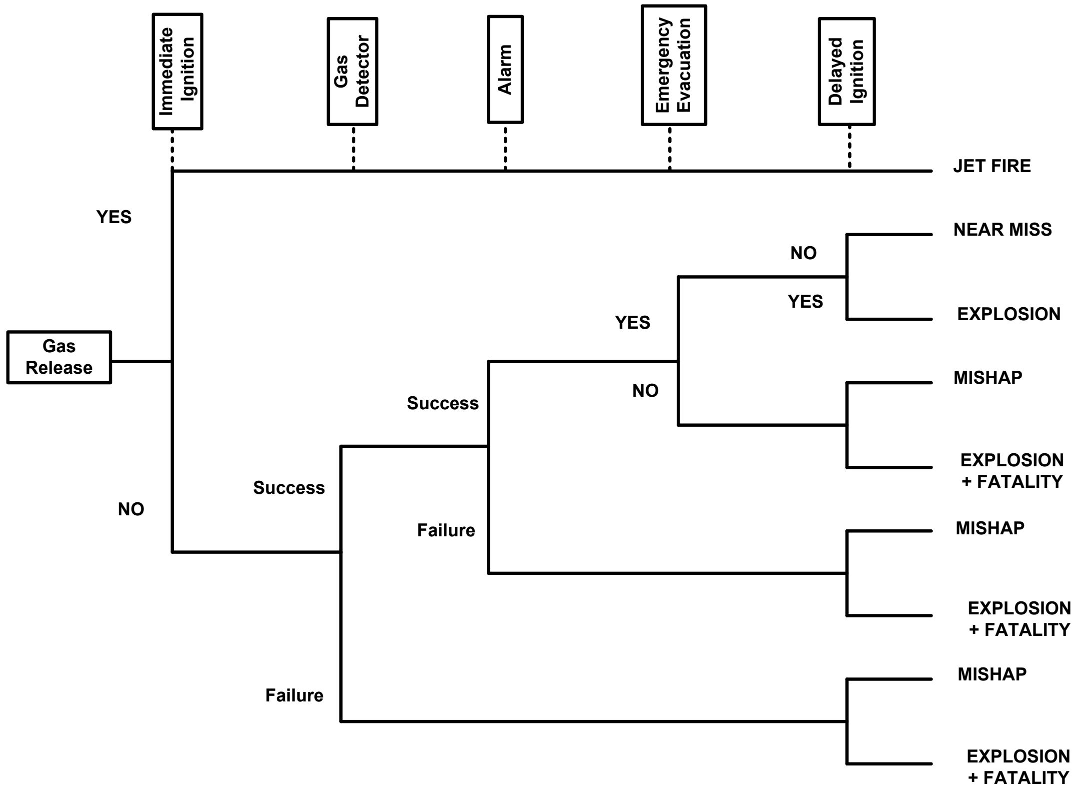

Figure 23. Event tree of gas release in liquefaction facility

4.3.1.4 LNG storage

After being liquefied, LNG is stored in LNG storage tanks. These storage tanks can store LNG at the very low temperature of -162 °C usually thanks to their double-container structure. The inner container contains LNG while the outer one contains insulation materials. In LNG storage tanks if LNG vapors are not released, the pressure and temperature within the tank will increase which in turn can lead to a tank explosion. LNG is a cryogen, and is kept in its liquid state at very low temperatures. The temperature within the tank will remain constant if the pressure is kept constant by allowing the boil off gas to escape from the tank. This is known as auto-refrigeration. The FT and BN in Figures 24 and 25 illustrate the root causes which can result in a gas release, respectively. The consequences of such a release are shown using the ET in Figure 26.

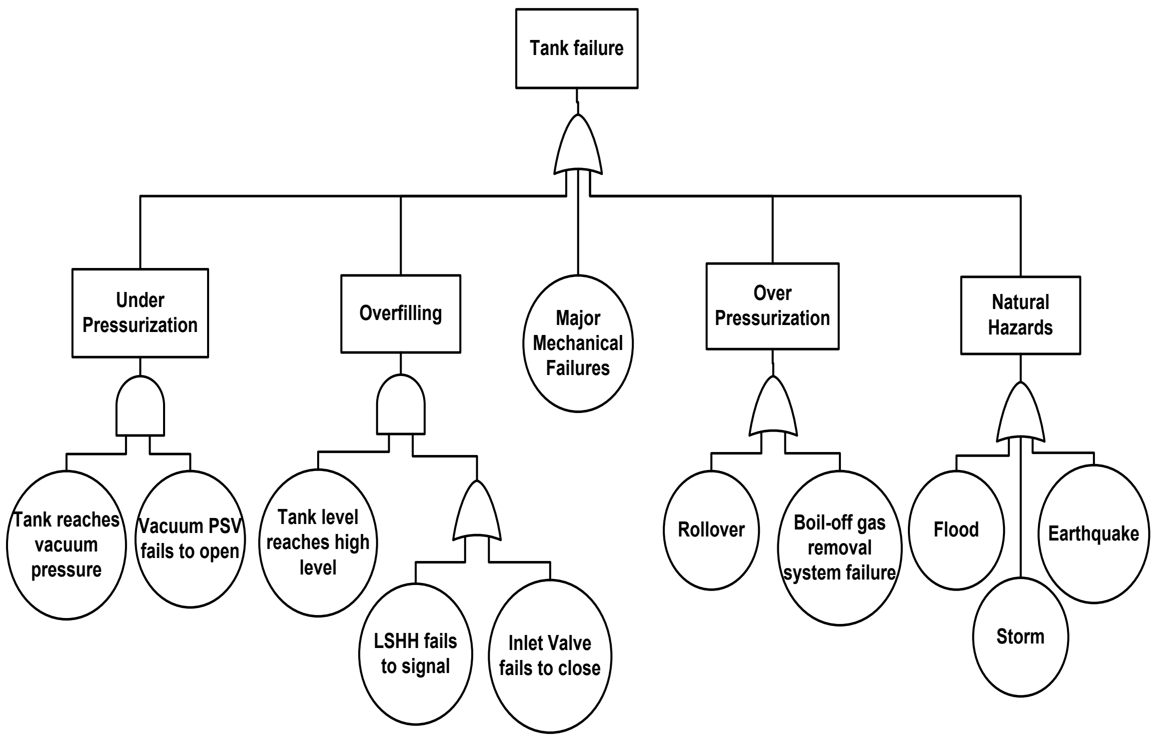

Figure 24. Fault tree of gas release from LNG storage tank

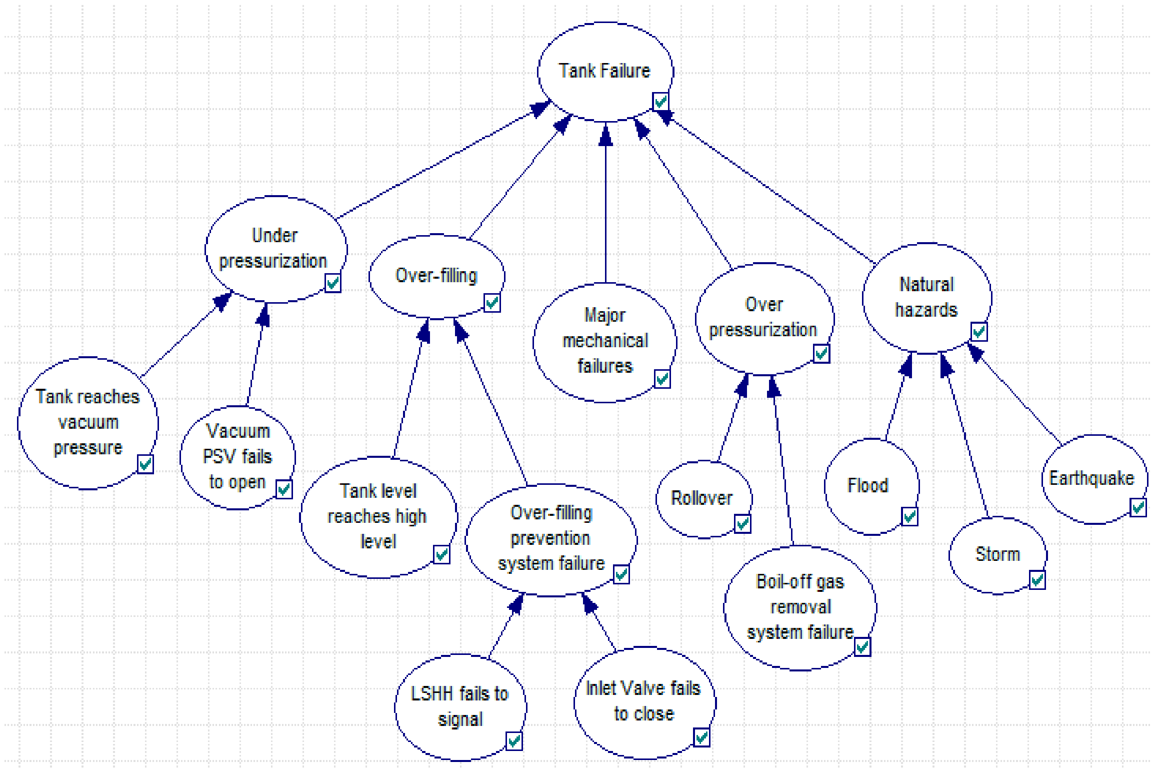

Figure 25. Bayesian network of gas release from LNG storage tank

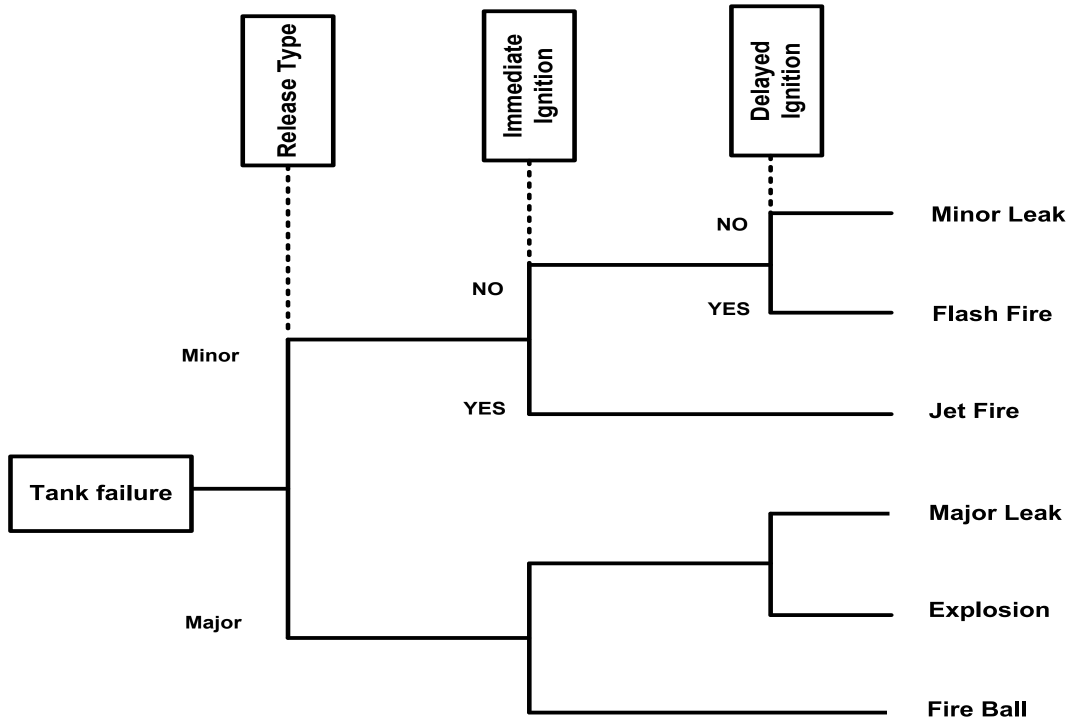

Figure 26. Event tree of gas release in LNG storage tank

4.3.1.5 LNG transportation (shipping)

The LNG stored at Goldboro Plant, Nova Scotia, is shipped by marine tankers to Holyrood, Newfoundland. The major accident scenarios which could result in an LNG release consist of either damages to the tanks or accidents which threaten the ship physical/operational integrity. FTs developed in Figures 27-29 display the root causes of such accident scenarios. Further, Figure 30 shows the BN developed from the FTs of the accident. Likewise, the likely outcomes of such an LNG release can be represented as the ET in Figure 26.

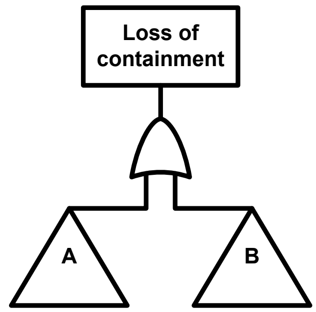

Figure 27. Fault tree for LNG release during shipping

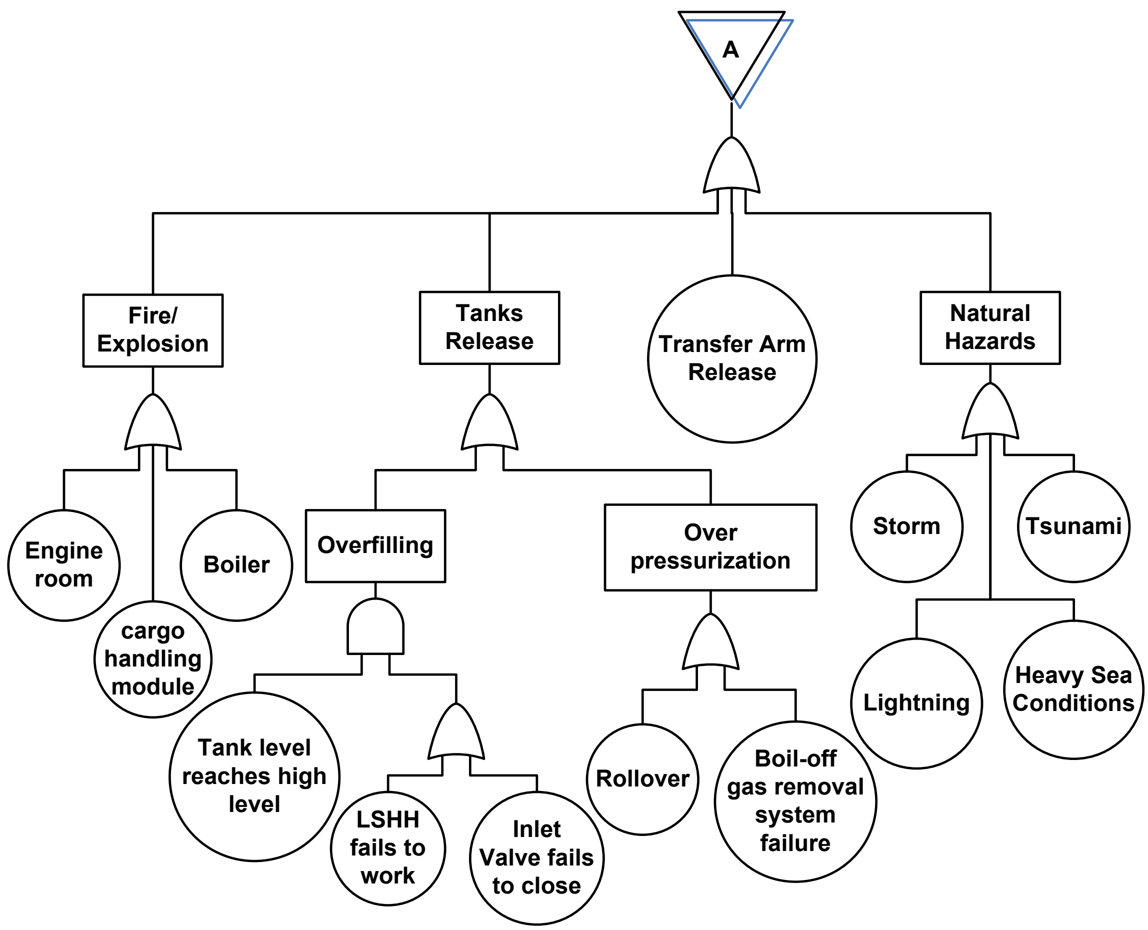

Figure 28. Fault tree for LNG release during shipping (Part A)

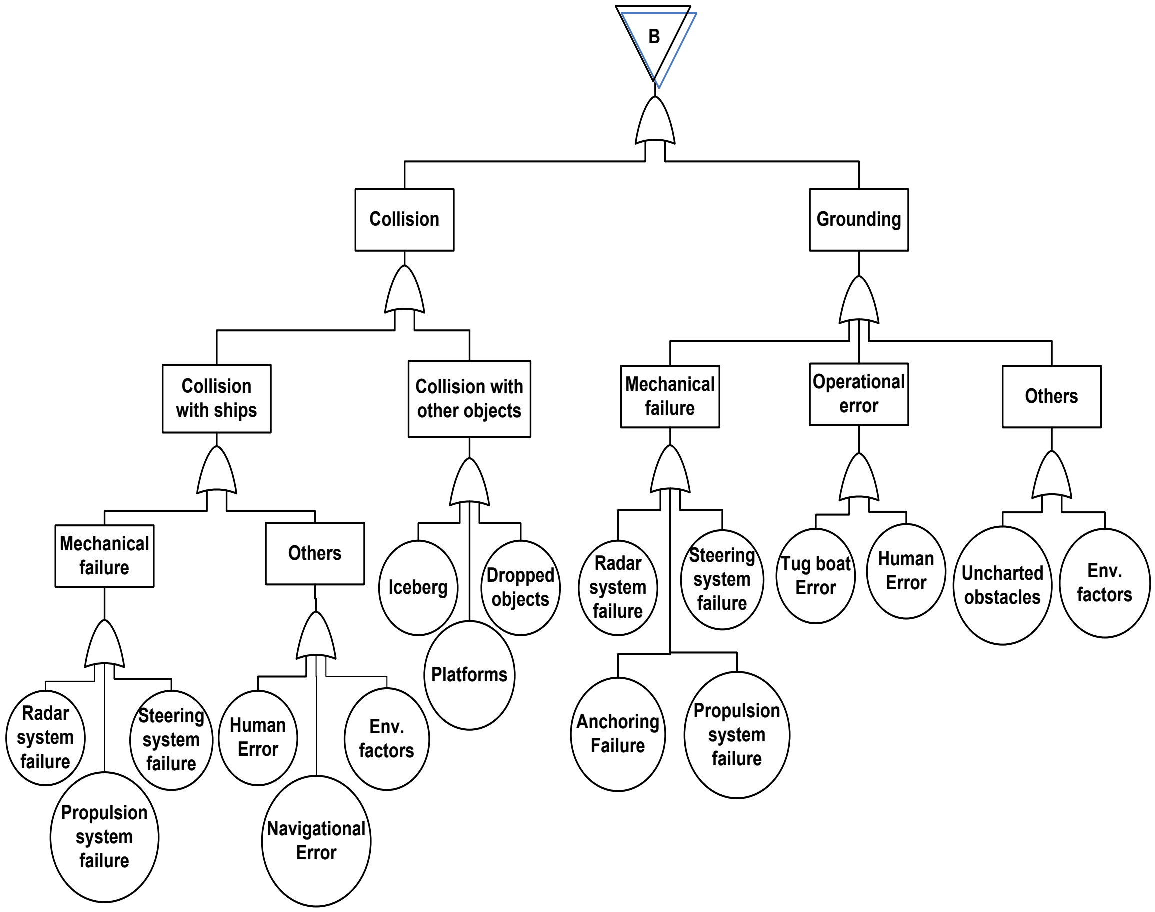

Figure 29. Fault tree for LNG release during shipping (Part B)

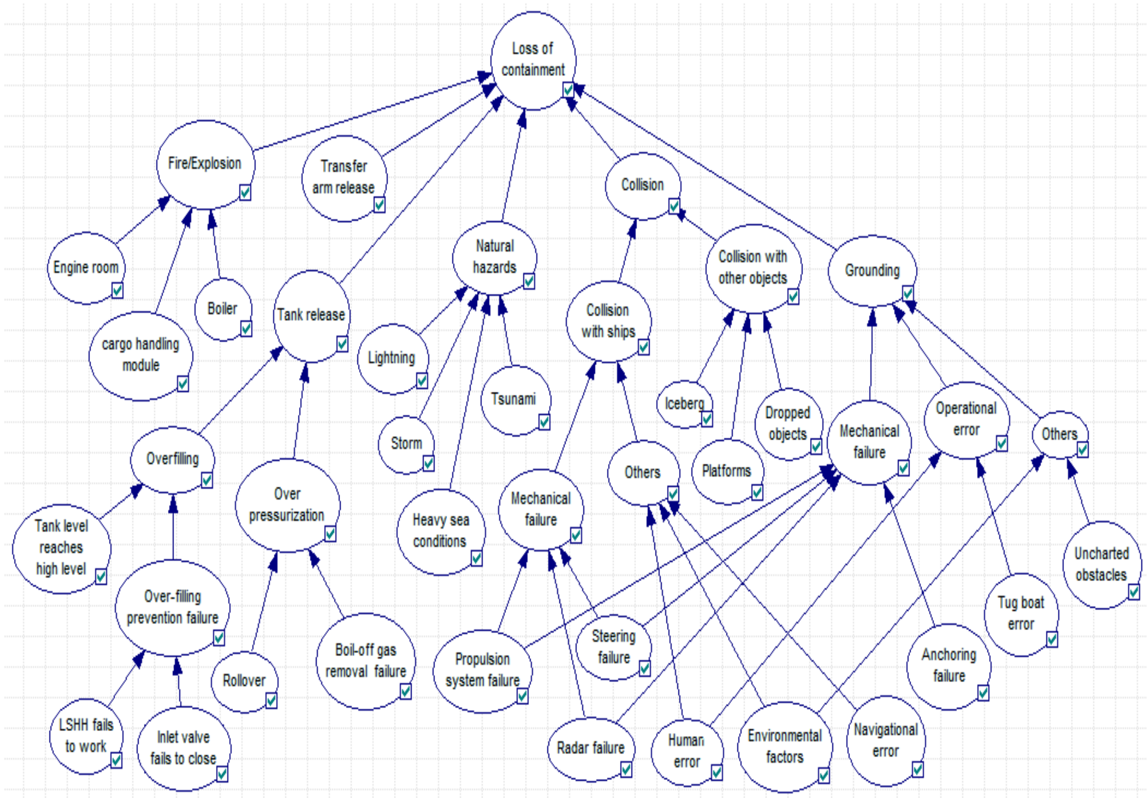

Figure 30. Bayesian network for LNG release during shipping

4.3.1.6 LNG re-gasification

In order to be used as a fuel, LNG should be returned to its gaseous state via re-gasification process. In a conventional re-gasification plant, LNG is heated by sea water to convert it to natural gas/methane gas. The root causes of an undesired gas release during the re-gasification process have been depicted in FT and BN of Figures 31 and 32, respectively. The ET of Figure 23 can also be used to analyze the potential accidents.

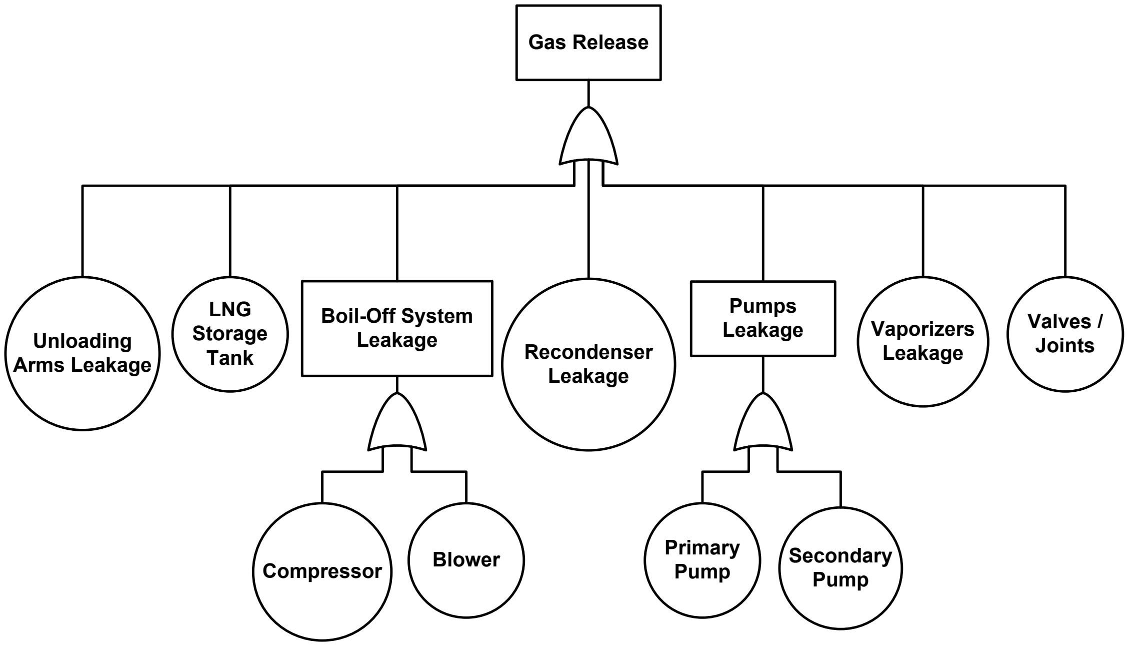

Figure 31. Fault tree for gas release during re-gasification process

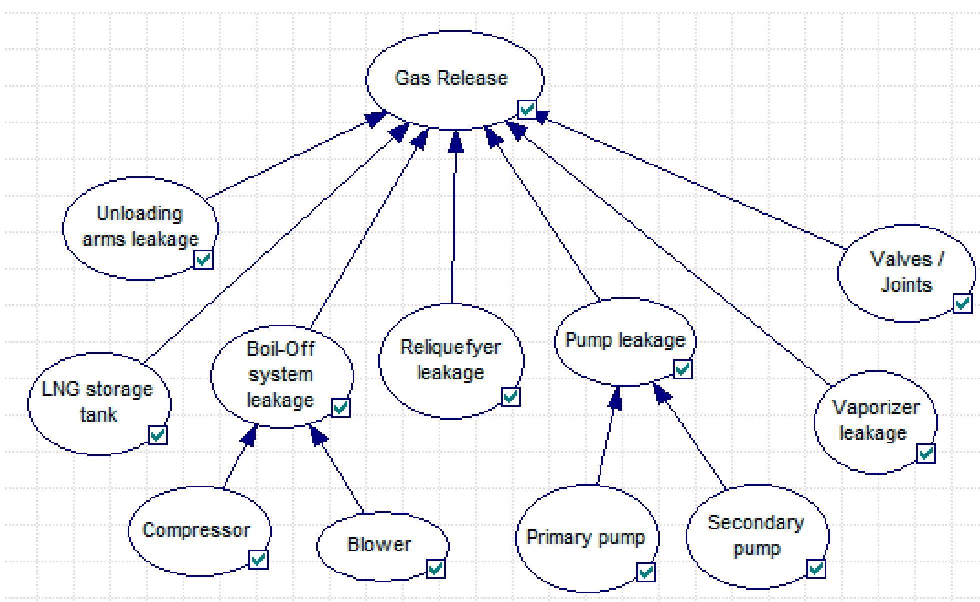

Figure 32. Bayesian network for gas release during re-gasification process

4.3.2 HFO life-cycle risk analysis

The sequence of the processes which will be considered in risk analysis of HFO life-cycle is depicted in the right-hand side block of Figure 8.

4.3.2.1 Crude oil extraction

In the present study, the extraction of both NG and crude oil is conducted using offshore drilling platforms. As such, assuming an overbalanced drilling operation, the root causes of a kick as the most likely release scenario and the potential blowout can be modeled using the same FT, BN and ET as developed in Figures 15, 16, and 17, respectively.

4.3.2.2 Crude oil transportation (shipping)

After being extracted from Gulf of Mexico, crude oil is transported to Alliance refinery via marine tankers. Similar to that of LNG, the root causes of a hydrocarbon release can be depicted in FTs of Figures 33-35. Accordingly, Figure 36 presents the BN developed from these FTs. The likely outcomes of such accident are shown in ET of Figure 37.

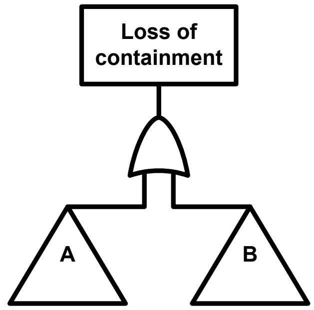

Figure 33. Fault tree for crude oil release during shipping

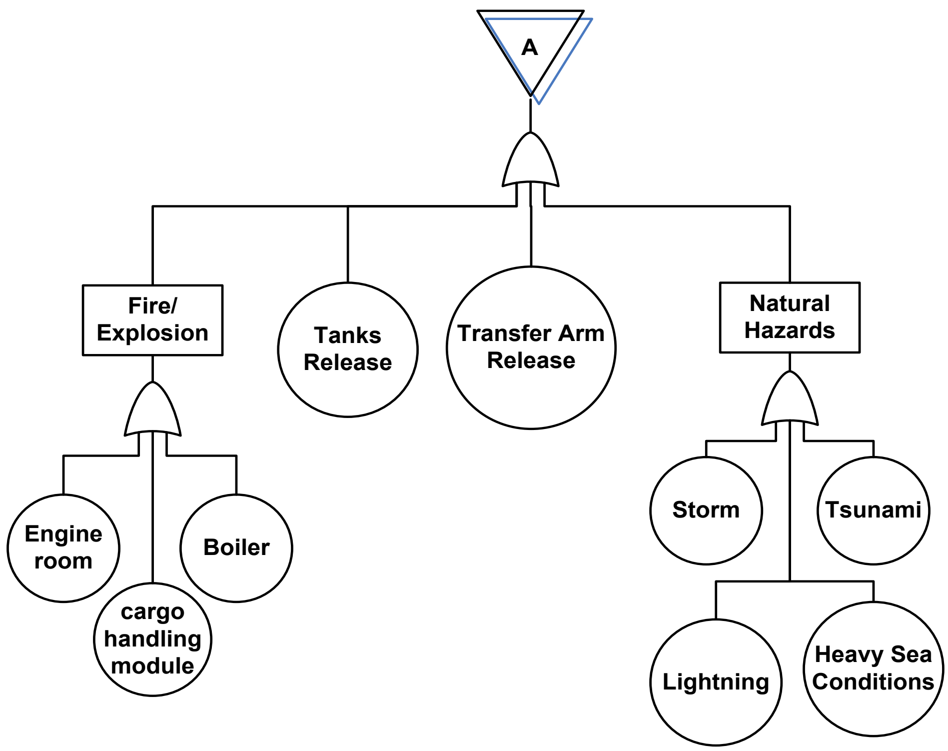

Figure 34. Fault tree for crude oil release during shipping (Part A)

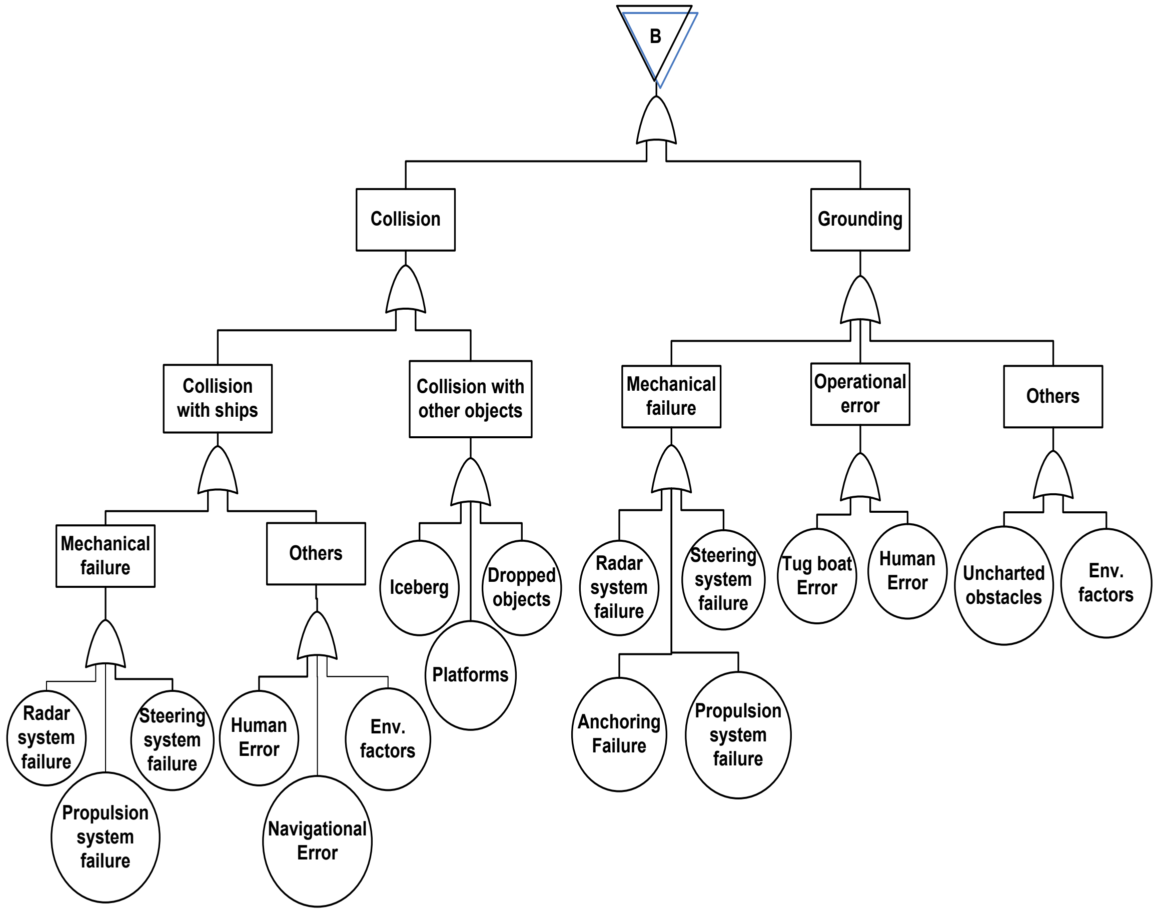

Figure 35. Fault tree for crude oil release during shipping (Part B)

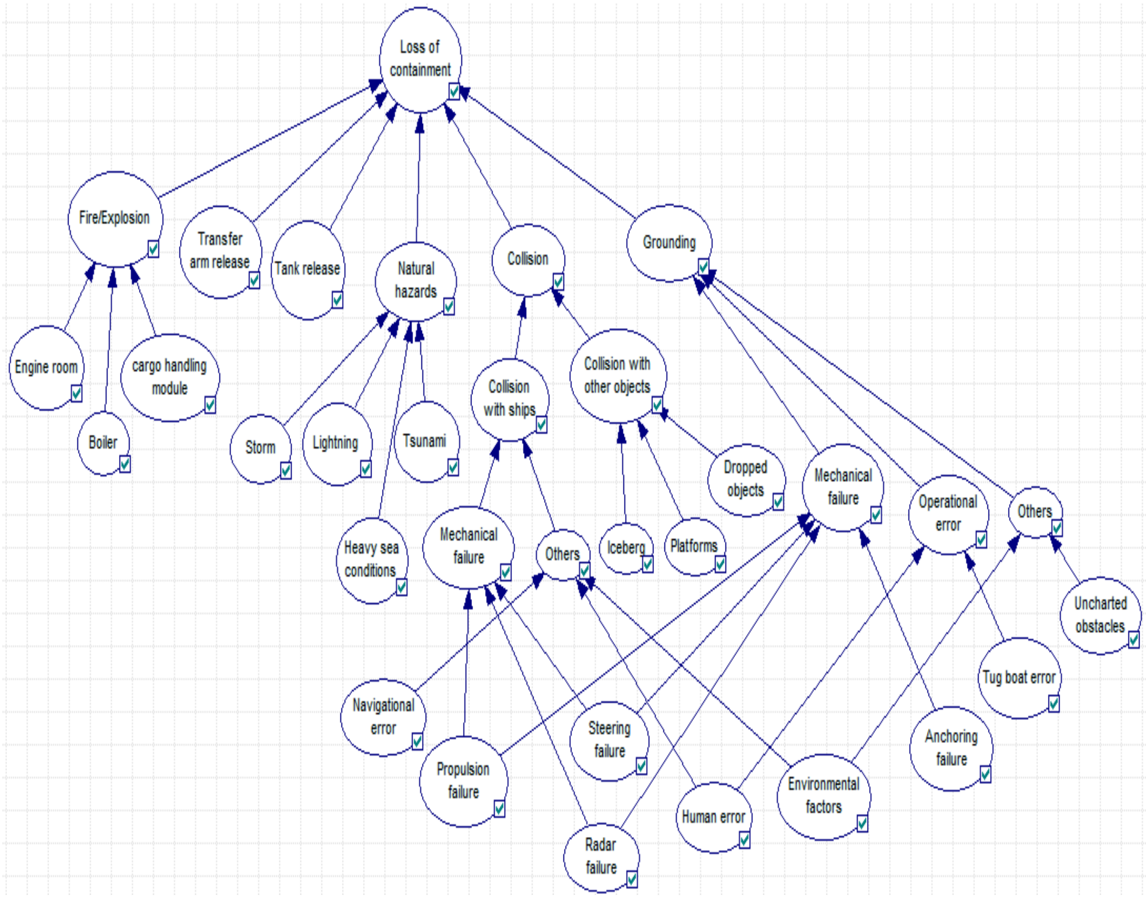

Figure 36. Bayesian network for crude oil release during shipping

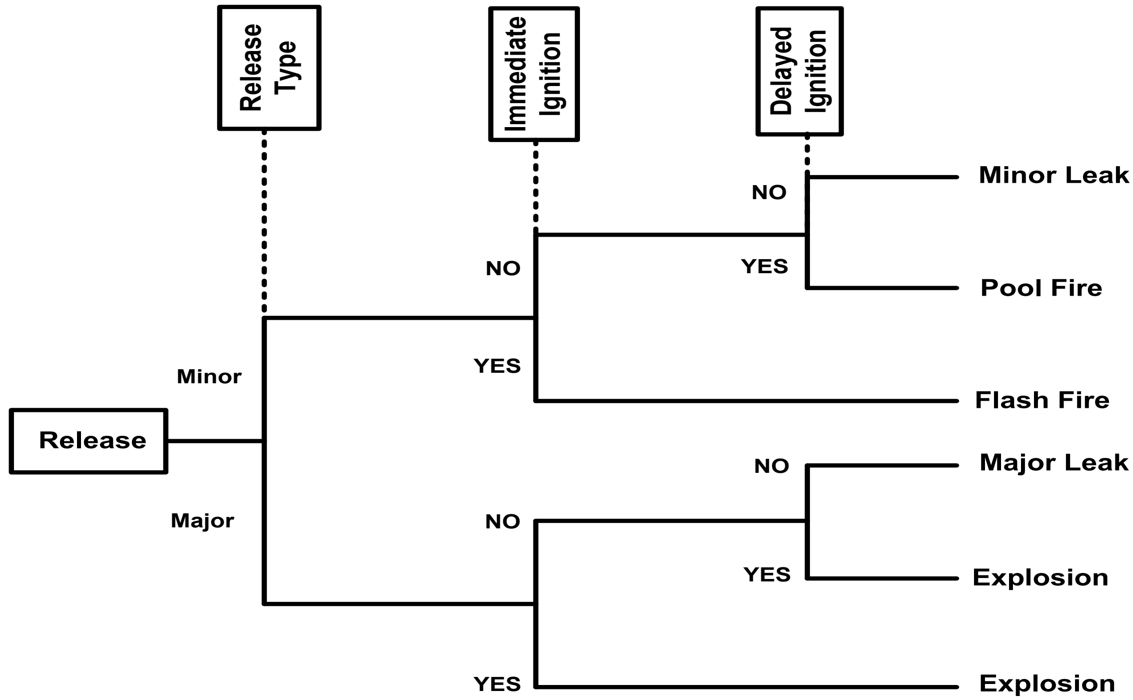

Figure 37. Event tree analysis of crude oil release during shipping

4.3.2.3 Crude oil storage

After arriving at the refinery, the crude is stored in storage tanks before being refined to products of interest. Storage tanks come in different sizes and shapes. Special applications might require tanks to be rectangular, vertical or horizontal cylinders, or even spherical. Horizontal cylinders and spheres are generally used for pressurized storage of hydrocarbon or chemical products. For crude oil and its products, however, the atmospheric or low-pressure storage tanks are usually used which are vertical cylindrical in shape with fixed or floating roofs. The FT and corresponding BN for an unwanted release of fuel oil from the storage tanks are illustrated in figures 38 and 39, respectively. The ET of figure 37 can be used to investigate the potential consequences of such accident.

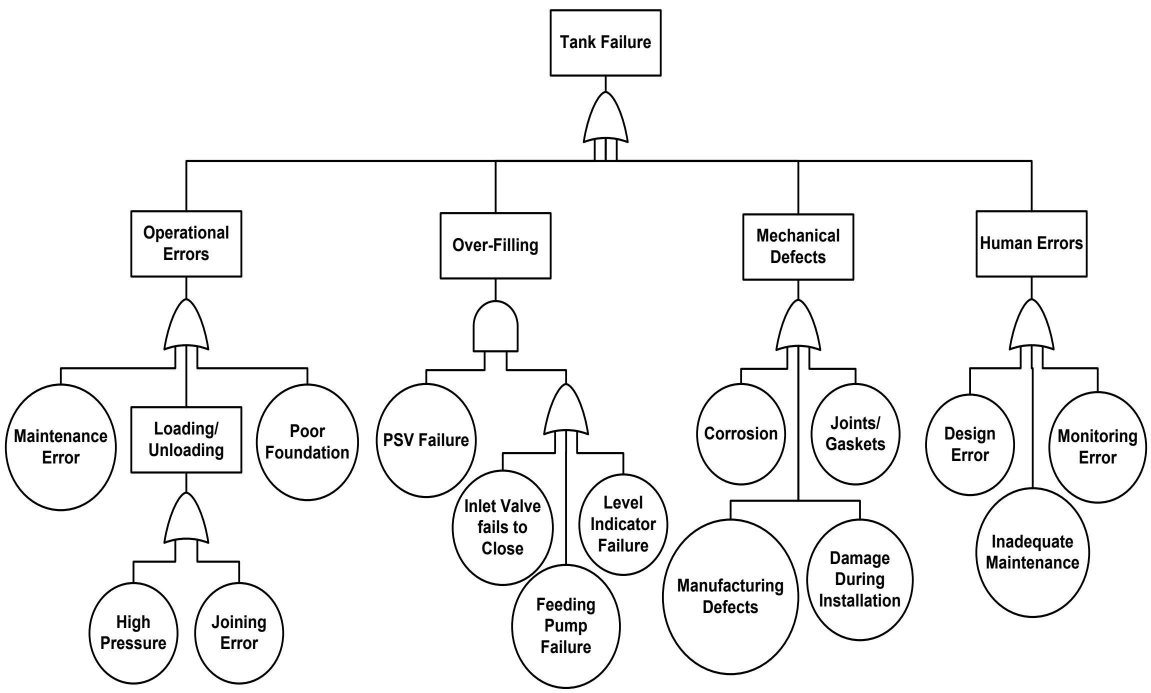

Figure 38. Fault tree of undesired release from storage tanks

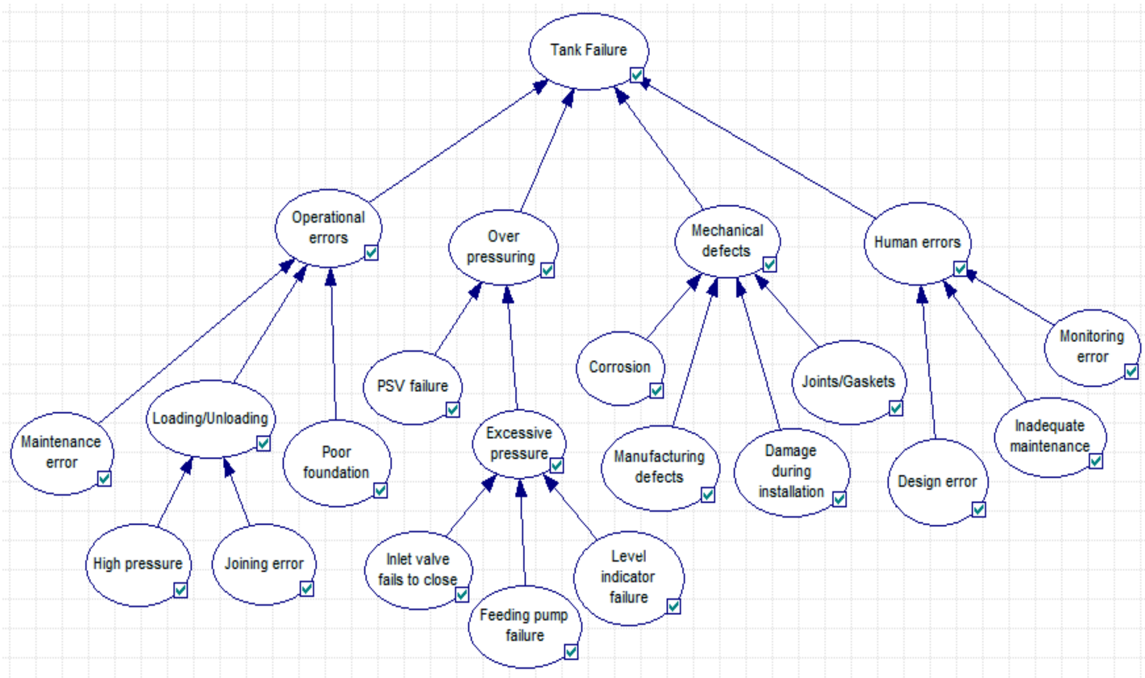

Figure 39. Bayesian network of oil release from oil storage tank

4.3.2.4 Crude oil refining

The crude oil is then processed and refined in Alliance Refinery in order to be converted into more useful products such as petroleum naphtha, gasoline, diesel, asphalt base, heating oil, kerosene and liquefied petroleum gas (LPG). Generally, crude petroleum is heated and changed into a gas using a fired boiler (furnace). The hot gases are passed into the bottom of a distillation column and become cooler as they move up the height of the column. As the gases cool below their boiling point, they condense into a liquid. The liquids are then drawn off the distillation column at specific heights, ranging from heavy residuals at the bottom, raw diesel fuels in the mid-sections, and raw gasoline at the top.

These raw fractions are then processed further to make several different finished products.

Considering a distillation column, a furnace, and a heat exchanger as the major hazard installations in the refinery, FTs for unwanted release of flammable materials from those have been developed as depicted in Figures 40-42. A unique BN developed corresponding to the FTs is shown in Figure 43, and the likely consequences such release can pose are presented in ET of Figure 44.

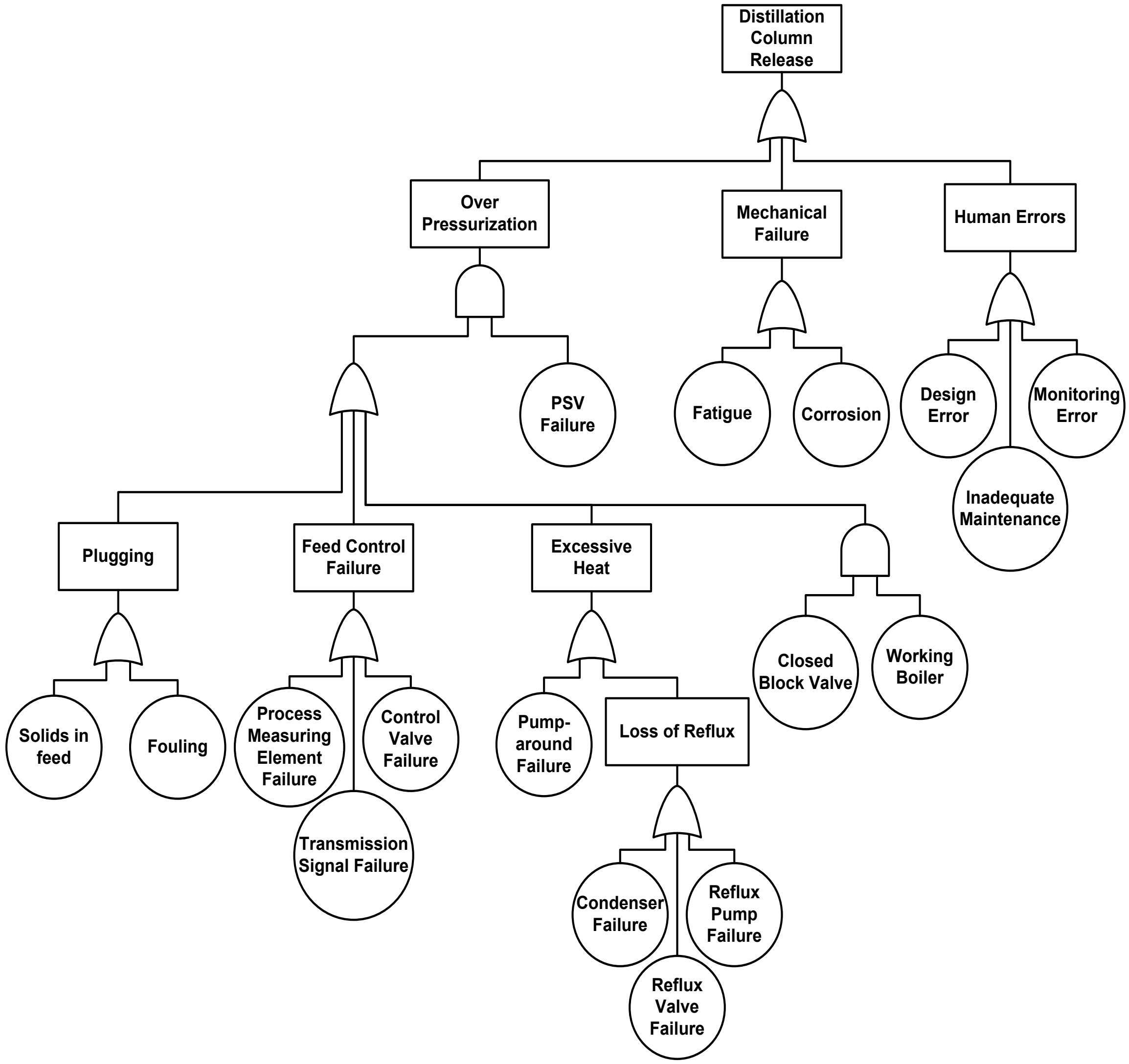

Figure 40. Fault tree of undesired release from an atmospheric distillation column

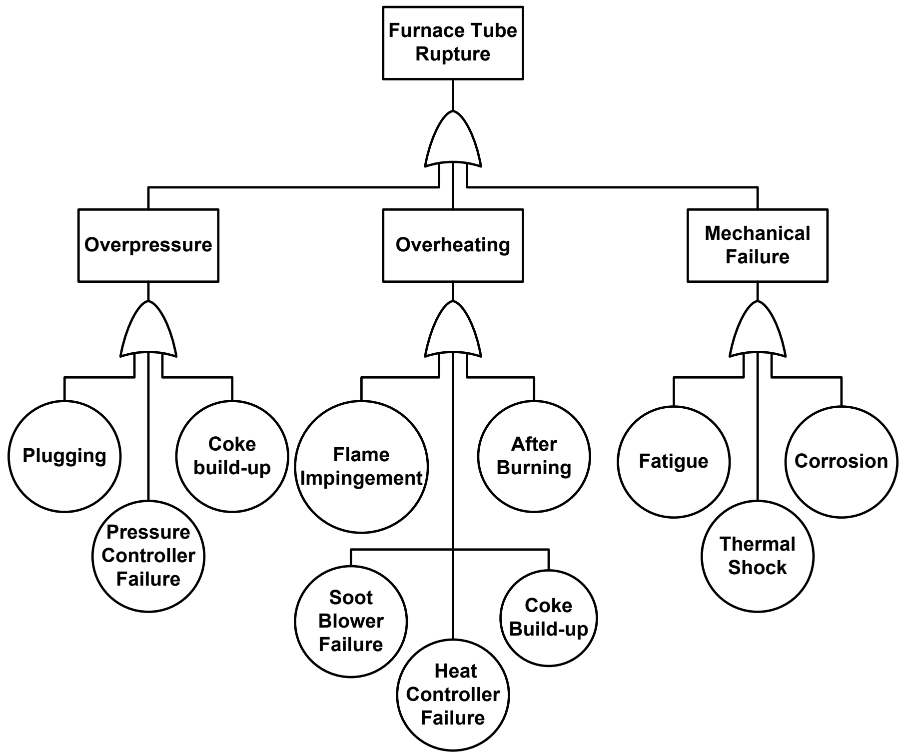

Figure 41. Fault tree of undesired release from a fired furnace

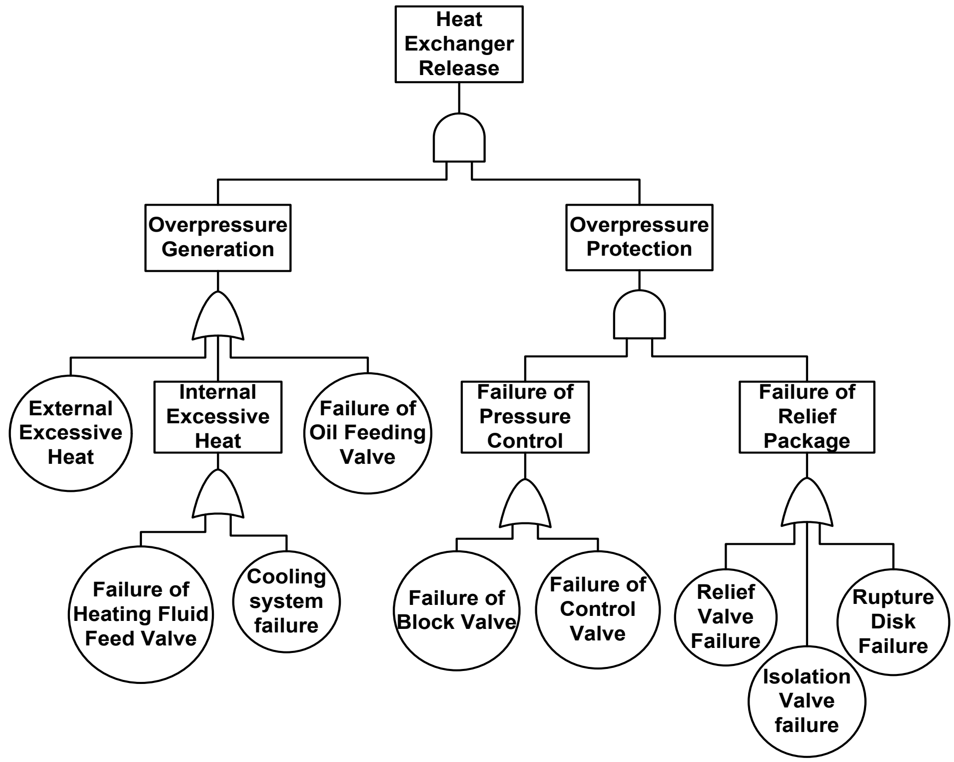

Figure 42. Fault tree for heat exchanger explosion

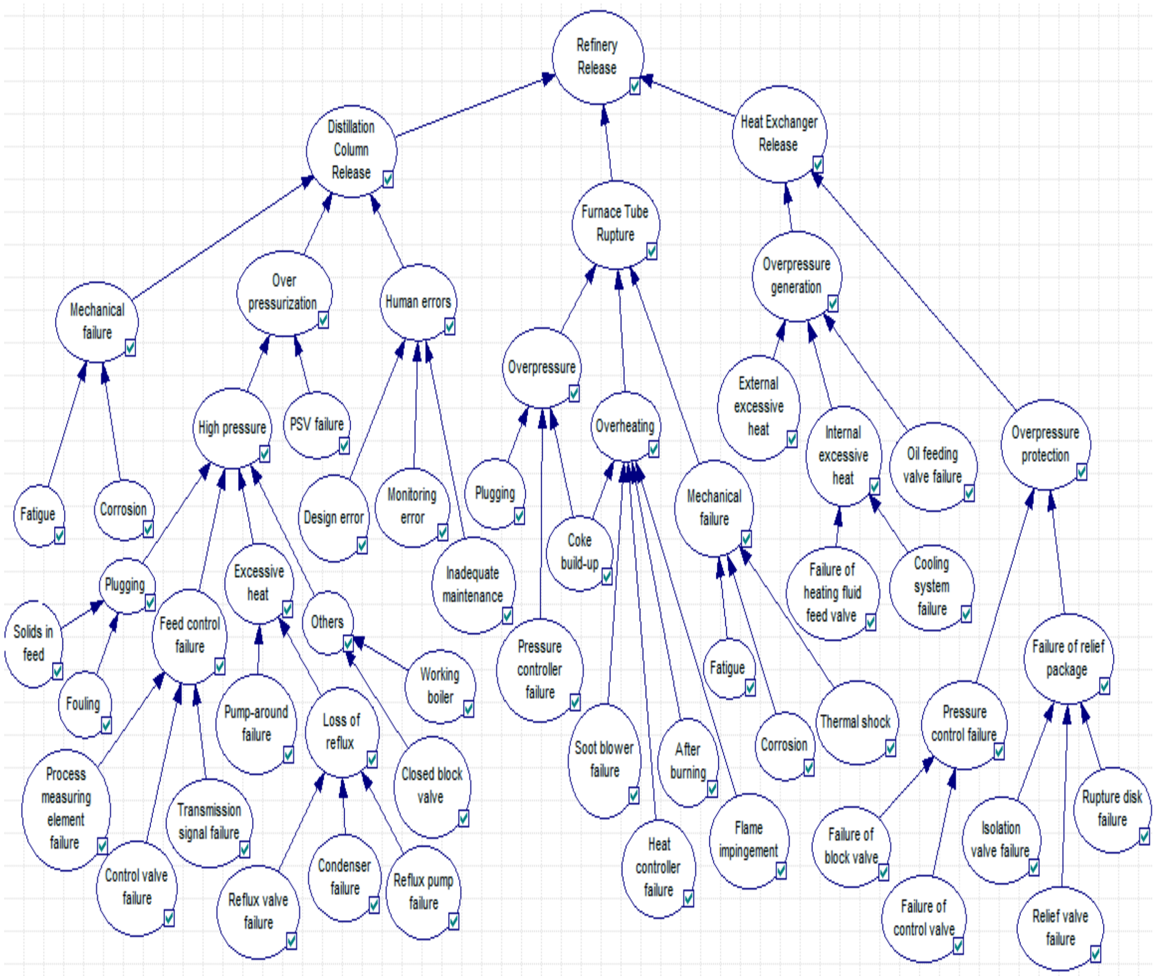

Figure 43. Bayesian network of oil release in refinery

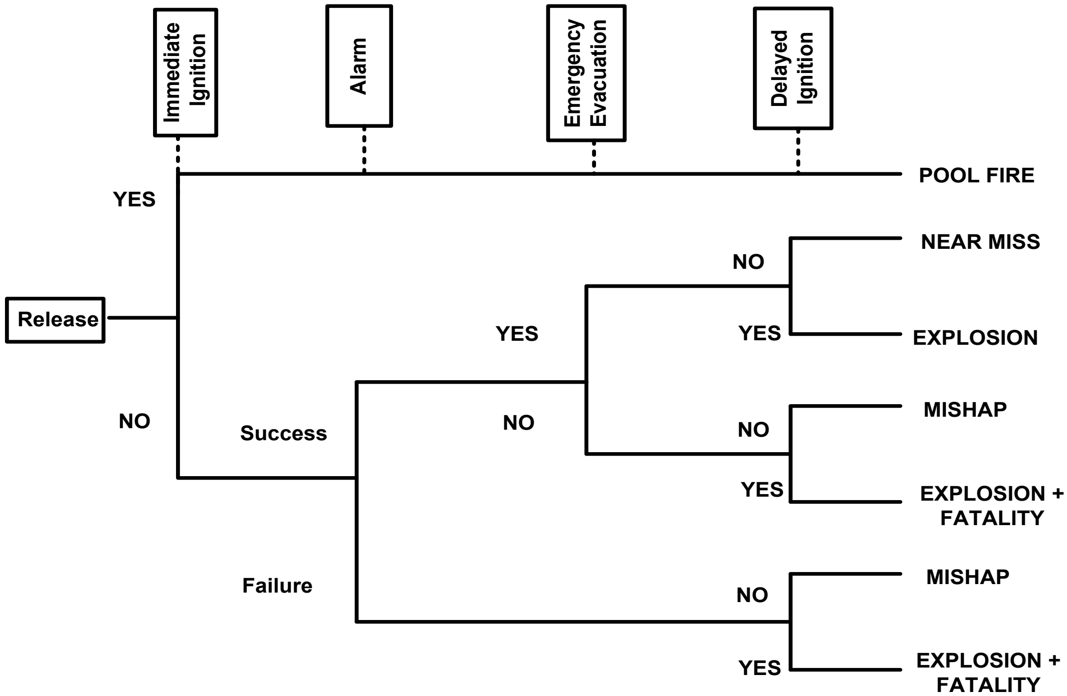

Figure 44. Event tree analysis of oil release in refinery

4.3.2.5 HFO transportation (shipping)

The HFO produced in Alliance refinery is then transported to Hollyrood thermal station. Since marine tankers are assumed to transport both HFO and crude oil in the present study; therefore, the root causes of a hydrocarbon release and likely consequences can be presented using the same FTs, BN, and ET as developed in Figures 33-37, respectively.

Chapter 5

Results and Discussion

5.1 Comparison of life-cycle emissions

Based on the total volume of the fossil fuels required by Hollyrood power plant to generate the annual electricity, the emission factors and the life-cycle GHG emissions were estimated for both LNG and HFO. Theses emissions in form of tons of CO2 equivalent (tons CO2 e) are presented in Tables 9 and 10 for LNG and HFO, respectively. However, it should be noted that due to the generic data and the emission factors, mainly extracted from the literatures, and also the simplifying assumptions made in the calculations of life cycle emissions, there is a high level of uncertainty in the results of the present study. The results of the LCA indicate that the total GHG emissions produced throughout HFO life-cycle (8,460,180 tons CO2 e) are considerably higher than those of LNG (488,437 tons CO2 e), which is in accordance with previous studies [46].

The difference between the emissions of HFO and LNG is partly due to the different processes considered in the life-cycle of each fuel and partly due to different parameters even in case of similar processes. For example, comparing the emissions in the domain of transportation, not only the distances in which the LNG (~225 km) and HFO (~ 4700 km) are transported are different but also the modes of transportation for the fuels are not the same (e.g., LNG pipeline vs. HFO marine tankers). In the HFO life-cycles, the most

GHG emission is related to the refinery stage (76%) whereas in the case of LNG it is assigned to the liquefaction plant (40%).

For the sake of better comparison of the two fuels, the total emissions can be converted into monetary values. To this end, the British Colombia province carbon tax – defined as a tax based on GHG generation – which is 30 CAD per metric ton of CO_2 equivalent (in year 2012) is considered in the present study. The results have been presented as carbon tax in Tables 9 and 10. As can be noted, the carbon tax of HFO is about 17 times larger than that of LNG, making the latter a much economical (and cleaner) fuel than the former.

Table 9. GHG emissions associated with LNG life-cycle

Emission Source	Emission (Tons CO2 e)	Contribution (%)
NG Extraction	123,838	25
NG Processing	25,787	5
NG Pipeline	81,891	17
NG Liquefaction	192,000	40
LNG Carrier	4,920	1
Re-gasification	60,000	12
Total	488,437	
Carbon Tax ($)	14,653,135	

Table 10. GHG emissions associated with HFO life-cycle

Emission Source	Emission (Tons CO2 e)	Contribution (%)
Crude Oil Extraction	938,910	11
Crude Oil Processing	588,690	7
Venting, Flaring and Fugitives	441,450	5
Oil Tanker (oil field to refinery)	10,530	0.5
Oil Refinery	6,470,100	76
Oil Tanker (refinery to power plant)	10,500	0.5
Total	8,460,180	
Carbon Tax ($)	253,805,400	

5.2. Comparison of safety risks

The probabilities assigned to the root nodes of the BNs and to the safety barriers of the ET for the hydrocarbon release scenarios are displayed in Tables 11-13. These probabilities are either extracted from the literature or estimated by experts [58,88-101]. Calculating the top event probabilities (hydrocarbon release) in each BN, the probabilities of the corresponding consequences can also be estimated. The risk of each consequence is then calculated as the product of the probability of the consequence and the envisaged loss values, expressed in monetary value. Table 14 presents the respective loss values used in the present study [93]. As the LCAs were conducted on an annual basis, for the sake of consistency, the risks were also estimated for one year.

Table 11. Root causes probabilities used for LNG risk analysis

No.	Root Cause	Probability	No.	Root Cause	Probability
Extraction			LNG Shipping		
1	Annular losses	1.00E-02	46	Engine room	9.50E-03
2	Riser rupture	1.00E-02	47	cargo handling module	1.20E-04
3	Temperature effects	2.50E-03	48	Boiler	2.30E-04
4	Gas-cut mud	7.00E-03	49	Lightning	3.40E-02
5	Failure of density meter	2.00E-04	50	Heavy Sea Conditions	3.20E-03
6	Operator error in mixing density	3.00E-02	51	Storm	8.73E-02
7	Pump failure	4.00E-02	52	Tsunami	2.39E-02
8	Power failure	2.70E-04	53	Transfer Arm Release	7.80E-03
9	Pump control failure	1.00E-03	54	Propulsion system failure	7.00E-04
10	Efficient hydrocarbon formation	1.25E-01	55	Radar system failure	1.00E-03
NG Liquefaction			56	Steering system failure	5.20E-04
11	Absorber Leakage	2.00E-04	57	Human Error	1.30E-03
12	Regenerator Leakage	1.80E-03	58	Environmental factors	1.00E-03
13	Reboiler Leakage	3.00E-04	59	Navigational Error	4.10E-04
14	Pump Leakage	6.00E-03	60	Iceberg	2.32E-04
15	Valves/Joints	2.30E-04	61	Platforms	6.70E-05
16	Tank Leakage	1.00E-04	62	Dropped objects	2.80E-03
17	Compressor Leakage	1.40E-05	63	Anchoring Failure	3.20E-04
18	Flash Leakage	5.00E-04	64	Propulsion system failure	7.00E-04
19	HEX Leakage	1.00E-02	65	Radar system failure	1.00E-03
20	C-SCRUB Column	2.80E-05	66	Steering system failure	5.20E-04
21	N-Column Leakage	3.00E-03	67	Tug boat Error	1.20E-04

LNG Storage Tank		
22	Under Pressurization	2.90E-10
23	Tank reaches vacuum pressure	1.36E-05
24	Vacuum PSV fails to open	2.12E-05
25	Overfilling	1.20E-05
26	Tank level reaches high level	3.70E-04
27	LSHH fails to signal	1.00E-03
28	Inlet Valve fails to close	3.14E-02
29	Major Mechanical Failures	8.80E-06
30	Over Pressurization	1.04E-03
31	Rollover	1.00E-03
32	Boil-Off Gas removal failure	4.10E-05
33	Natural Hazards	1.33E-01
34	Flood	2.65E-02
35	Earthquake	2.39E-02
36	Storm	8.73E-02
Re-gasification		
37	Unloading Arms Leakage	3.40E-07
38	LNG Storage Tank	2.00E-05
39	Compressor	1.40E-05
40	Blower	4.20E-04
41	Re-liquefier Leakage	2.50E-04
42	Primary Pump Leakage	6.00E-03
43	Secondary Pump Leakage	6.00E-03
44	Valves / Joints	5.00E-06
45	Vaporizers Leakage	3.10E-03
68	Uncharted obstacles	5.30E-04
Gas sub-sea pipeline		
69	Manufacturing defects	1.35E-04
70	Material defects	3.44E-03
71	welding defects	1.08E-02
72	Malfunction of relief valve	2.59E-04
73	Pigging error	1.09E-02
74	Thermal forces	4.20E-03
75	Hydrodynamic forces	5.16E-04
76	Ship anchors	2.15E-03
77	Wear abrasion	8.53E-04
78	Minor anchors	3.05E-02
79	Trawls	4.11E-03
80	Corrosive environment	1.00E+00
81	Internal coating failure	2.41E-04
82	CO2	2.22E-06
83	O2	3.52E-06
84	H2S	1.41E-05
85	H2O	1.99E-05
86	Iceberg	2.32E-04
87	Earthquake	2.39E-02
88	Storm	1.69E-02

Table 12. Root causes probabilities used for HFO risk analysis

No.	Root Cause	Probability
Oil Storage Tank		
1	Maintenance Error	3.10E-02
2	High Pressure	1.00E-04
3	Joining Error	4.60E-03
4	Poor Foundation	2.40E-05
5	PSV Failure	2.59E-04
6	Inlet Valve fails to Close	2.06E-04
7	Feeding Pump Failure	5.00E-04
8	Level Indicator Failure	1.70E-05
9	Corrosion	2.00E-03
10	Manufacturing Defects	1.20E-05
11	Damage During Installation	4.30E-03
12	Joints/Gaskets	2.30E-04
13	Design Error	1.30E-05
14	Inadequate Maintenance	1.20E-03
15	Monitoring Error	3.40E-03
Oil Refinery		
16	Solids in feed	4.20E-05
17	Fouling	6.50E-04
18	Process Measuring Element Failure	1.76E-03
19	Control Valve Failure	2.80E-05
20	Transmission Signal Failure	1.70E-03
21	Pump-around Failure	5.00E-04
22	Reflux Valve Failure	2.80E-05
23	Condenser Failure	2.19E-04
24	Reflux Pump Failure	5.00E-04

25	Closed Block Valve	3.98E-04
26	Working Boiler	2.60E-04
27	Design Error	1.30E-05
28	Inadequate Maintenance	1.20E-03
29	Monitoring Error	3.40E-03
30	PSV Failure	2.59E-04
31	Fatigue (Column)	1.50E-04
32	Corrosion (Column)	2.00E-03
33	External Excessive Heat	1.54E-04
34	Failure of Heating Fluid Feed Valve	2.06E-04
35	Cooling system failure	2.19E-04
36	Failure of Oil Feeding Valve	2.06E-04
37	Failure of Block Valve	3.98E-04
38	Isolation Valve failure	5.90E-05
39	Relief Valve Failure	2.59E-04
40	Rupture Disk Failure	3.30E-04
41	Plugging	3.16E-02
42	Pressure Controller Failure	1.76E-03
43	Coke build-up	5.10E-02
44	Heat Controller Failure	2.50E-04
45	Soot Blower Failure	1.40E-04
46	Flame Impingement	4.20E-03
47	After Burning	3.60E-03
48	Fatigue (Furnace)	1.57E-04
49	Corrosion (Furnace)	1.90E-04
50	Thermal Shock	2.40E-03

Table 13. Safety barrier probabilities used in event trees

ID	Safety Barrier	Probability
1	Minor Release	8.00E-05
2	Major Release	1.00E-04
3	Immediate Ignition	1.00E-01
4	Delayed Ignition	3.00E-01
5	Gas detector Failure	4.00E-02
6	Emergency Evacuation	2.00E-01
7	Pressure monitoring	1.00E-03
8	Automatic shot-off valve	1.00E-02
9	Alarm	1.00E-02
10	Manual shot-off valve	3.00E-02
11	Kick non-detection	8.60E-06
12	Lower pipe ram	1.00E-04
13	Upper pipe ram	1.00E-04
14	Blind/shear ram	1.00E-04
15	Annular preventer	1.00E-04
16	Casing	2.00E-04

Table 14. Risk loss values and categories (Kalantarnia et al. 2010)

Severity class	**Dollar value (USD)**	**Asset loss**	**Human loss**	**Environmental loss**	**Reputation loss**
1	< 1 k	Not significant	No injury	No remediation required	Noticed by operating unit
2	1 K - 10 K	Short term production interruption	Minor injury, first aid attention required	Around the operating unit; easy recovery and remediation	Noticed in the operation line/ line supervisor,
3	10 K - 500 K	Damage of one unit, requiring repair; medium term production interruption	One injury, requiring hospitalization; no life threat	Around the operating line; easy recovery and remediation	Noticed in plant
4	500 K - 5 M	Damage of more than one unit' requiring repair/long term production interruption	More than one injuries, requiring hospitalization; no life threat	Within plant; short term remediation effort	Local media coverage
5	5 M - 50 M	Loss of one operating unit/product	Multiple major injuries, potential disabilities, potential life threat	Minor offsite impact; remediation cost < 1 M	Regional media coverage; brief note on national media
6	50 M- 500 M	Loss of a major portion of facility/ product	One fatality and/or multiple injuries with disabilities	Community alerted; remediation cost < 5 M	National media coverage; brief note on international media
7	> 500 M	Total loss of facility/products	Multiple fatalities	Community evacuation; remediation cost > 5 M	National media coverage, asking for international aid

The risks assessed for the LNG and HFO life-cycles are presented in Tables 15 and 16, respectively. As can be seen, LNG life-cycle has a significantly lower risk (~ 2.5 million USD) than that of HFO life-cycle (~ 5.6 million USD). In LNG life-cycle, the liquefaction (57.5%) and re-gasification (41%) processes contribute the most to the safety risk whereas in HFO life-cycle, the oil refinery (99.5%) accounts for nearly the entire safety risk, mostly due to the occurrence of high-probability high-impact major accidents as fires and explosions. In Figure 45, the total amounts of losses, due to both the emissions and safety risks, of both fuels have been depicted. As can be seen, in terms of both emission and safety risk, LNG can be chosen as a safer and cleaner fuel. Regarding the HFO, the amount of safety risk does not compare to the amount of environmental emission (the safety risk is ~ 2% of the total losses); however, in case of LNG, the safety risk accounts for about 17% of the total losses, which is quite notable. Nevertheless, it should be noted that in the present study the emissions resulted from the combustion of fuels due to accidents, particularly fires and explosions, have been ignored due to the lack of relevant data about the volume of released fuel during each accident scenario.

Table 15. Risks related to the LNG life-cycle

Stage	Risk ($)	Contribution (%)
Drilling	13,334.36	0.5
NG Pipeline	10,527.42	0.4
NG Liquefaction	1,426,205.86	57.5
LNG Storage	50.82	0.002
LNG Shipping	6,652.77	0.3
Re-gasification	1,019,426.91	41
Total	2,476,198.17	

Table 16. Risks related to the HFO life-cycle

Stage	Risk ($)	Contribution
Drilling	13,334.36	0.25
Oil Shipping	7,316.68	0.13
Oil Storage	17.60	0.0003
Oil Refinery	5,551,074.76	99.5
HFO Shipping	7,316.68	0.13
Total	5,579,060.11	

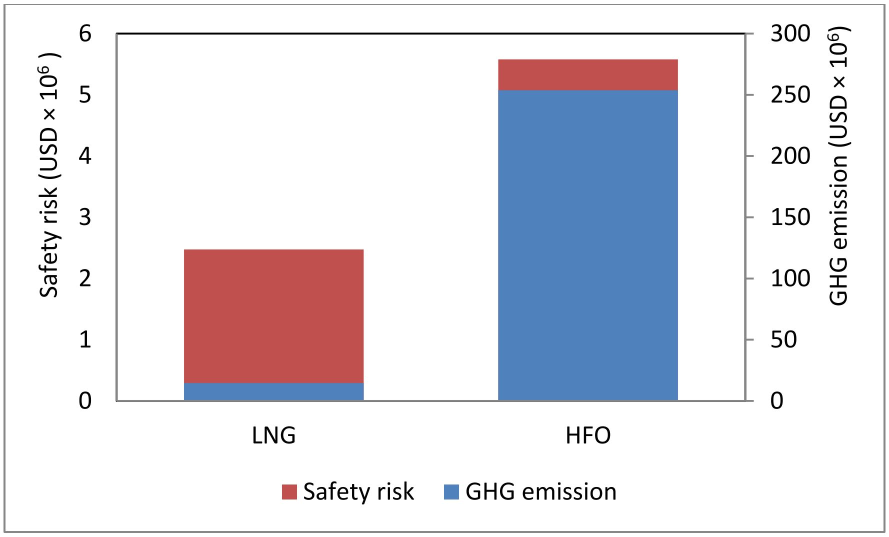

Figure 45. Comparison of life-cycle emissions and safety risks for LNG and HFO

Chapter 6

Conclusions

In the present work, we introduced a methodology for risk-based life-cycle assessment (RBLCA) of fuels, considering both environmental emissions and safety risks incurred during the entire life-cycles thereof. For this purpose, the emissions of greenhouse gases to the atmosphere were calculated, converted into CO2 equivalent, and then quantified to monetary values based on carbon tax imposed by government. Likewise, the safety risks resulted from undesired releases of fuels and the ensuing fires and explosions were calculated using quantitative risk analysis techniques such as event tree and Bayesian network throughout the processes involved in the entire life-cycle of fuels. We exemplified the application of the methodology to liquefied natural gas (LNG) and heavy fuel oil (HFO) as the fuels of a fossil-fuel power plant in Newfoundland, Canada, so that the fuel with the less total losses (i.e., the losses due to both environmental emissions and safety risks) can be determined. Considering the emissions and risks throughout the respective life cycles, from extraction at offshore platforms to combustion in onshore power plants, it was demonstrated that not only LNG is by far a cleaner fuel than HFO (17 times less emissions) but also a safer alternative than HFO. In the present study, the inclusion of safety risks in the life-cycle risk assessment of LNG and HFO did not affect the preference of the fuels that could have been determined solely based on their environmental emissions. Nonetheless, it was demonstrated that in some cases, the safety risks can make a significant contribution to the total amount of losses (e.g., about 17% in the case of LNG in this study) which in slightly different situations can lead to quite different priorities in deciding the safer and/or cleaner fuel alternatives.

Recommendations

This method should be applied to compare other fuels, e.g. Coal and biofuel, with natural gas in order to ensure that NG is the safest fuel. As a matter of fact, considering a real case study, using real data if available, and consequently reducing assumptions would result in more accurate results, which is critical to make any comparison. Moreover, developing techniques that make it possible to estimate the emissions associated with an accident, and considering the amount of emissions as a basis for comparison would lead to more interesting results.

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