DEVELOPMENT OF A DYNAMIC RISK ASSESSMENT FRAMEWORK FOR LPG TRANSPORTATION PIPELINES

Galagedarage Don Mihiran Pathmika

(149260E)

Degree of Master of Science

Department of Chemical and Process Engineering

University of Moratuwa

Sri Lanka

December 2017

DECLARATION

I declare that this dissertation is my own work, and it does not contain any material previously submitted for a degree or diploma at any other university or institute of higher learning without acknowledgment, and it does not contain any material previously published or written by another person, except where acknowledgement is made in the text.

In addition, I offer University of Moratuwa the non-exclusive right to reproduce and disseminate my dissertation in whole or in part in print, electronic, or other media. I maintain the right to incorporate this content into future works in whole or in part (such as articles or books).

Signature: UOM Verified Signature …. Date: 25/07/2021…………………….

The above candidate has carried out research for the master's thesis under my supervision.

Signature of the supervisor: UOM Verified Signature……………………………….. Date: 2021-07-25……………………..

Name of the supervisor (s): Prof. Mahinsasa Narayana / Mr. Tissa Dodangoda

ABSTRACT

The present study introduces an innovative methodology for dynamic risk assessment of a hypothetical Liquid Petroleum Gas (LPG) offloading pipeline. The study mainly focuses on the determination of the probability of a catastrophic event dynamically, which is a major component in risk assessment. The output of this study is an open model for dynamic risk assessment of an LPG offloading pipeline with the potential of adopting it in any other application.

The developed model presents the identification of the site and an analysis of the surrounding land uses, design, and related operations. Then it identifies the potential hazards. The traditional Bow-Tie diagram is created based on the identified risks and safety barriers. The Bow-Tie Diagram is then converted to a Bayesian network. The Bayesian network uses conditional probability tables which can be further improved for better reliability by introducing updated knowledge and experience.

The method was trialled using a hypothetical scenario followed by a consequence analysis. A jet fire simulation is done using FLACS®, which is an industrial Computational Fluid Dynamics (CFD) code, to support the risk analysis. Financial losses connected with environmental damage, cleanup, evacuation, and lost output are among the consequences.

The dynamic risk assessment framework presented in this study facilitates systematic decision-making on the LPG pipeline at almost any probable event. Further, it can be trained with experience and expert judgement.

Keywords: Dynamic Risk Assessment, LPG offloading Pipeline, Bayesian network, FLACS®, CFD

DEDICATION

To my loving parents, Somapala Galagedara and Indrani Kolambage, who brought me up to this level, and to my loving wife, Lekshika, for all the support given.

ACKNOWLEDGMENT

My foremost sincere gratitude is expressed to my supervisor (s), Professor Mahinsasa Narayana and Mr. Tissa Dodamgoda, who gave me the opportunity to carry out this research work and for the immense help and guidance given throughout the project work.

I would also like to thank Dr. Manisha Gunasekara, and Mr. Samith Rathnayake (former student at Memorial University of Newfoundland, Canada) for helping me by providing correct guidance through the project work.

In addition to that, I like to express my thanks to all the academic staff members of the Department of Chemical and Process Engineering, University of Moratuwa for their assistance and contribution to my research work.

2021

In conclusion, I would like to express my pardon if I have inadvertently omitted the name of those to whom thanks is due.

G.D. Mihiran Pathmika

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

BN	Bayesian network
BT	Bow-Tie
CFD	Computational Fluid Dynamics
COF	Consequence of Failure
CPT	Conditional Probability Tables
DRA	Dynamic Risk Assessment
DyPASI	Dynamic Procedure for Atypical Scenarios Identification
EC	Environmental consequence Cost
ETA	Event Tree Analysis
FT	Fault Tree
HAZID	Hazard Identification
HAZOP	Hazard and Operability Study
IC	Inspection Cost
IO	Integrated Operations
LDS	Leak Detection System
LNG	Liquefied Natural gas
LOP	Lost Production Cost
LPG	Liquefied Petroleum Gas
MLV	Main Line Valve
OREDA	Offshore and On shore Reliability Data
PCA	Principle Component Analysis
QRA	Quantitative Risk Analysis

CHAPTER 1 : INTRODUCTION

1.1 Rationale

A liquid fuel offloading pipeline is an asset to a country in many aspects. On the other hand, it comes with an inherent risk at times which can be catastrophic. The risk associated with this can be assessed qualitatively or even quantitatively with numerous available techniques. Most of the risk assessment techniques used in the industry are static though the risk is dynamic, which is an obvious fact. The severity of the risk might depend on weather conditions, natural disasters, political reasons and many more. Therefore, there is a high demand for a dynamic technique to evaluate the risk associated with this kind of key resource of a country.

As mentioned in [1], it is clear that accidents related to hydrocarbon pipelines are not rare. Figure 1.1 shows a picture of the hydrocarbon pipeline explosion that occurred in Milford, USA, in 2013. It was severe enough to make evacuate people from the town. As mentioned in [2], the 'Ufa train disaster' is one of the worst pipeline accident occurred in the world's history. As furtherer explained in [2], Gas escaping from an LPG pipeline near Ufa, Russia, exploded due to sparks from two passing trains. Workers on the pipeline saw that pressure was lowering in the line, but instead of looking for a leak, they raised pressure. The blast destroyed trees up to 4 kilometers away, while two engines and 38 passenger cars on the trains were derailed. According to reports, about 645 persons died in June, 1989.

Figure 1.1: Milford pipeline explosion [3]

As mentioned in [4], most of the accidents were initiated by welding defects and physical damages to the pipeline during reparations and careless excavations.

Therefore, it is very important to have a methodology developed to analyze the associated risk for these kinds of applications. There are no published Dynamic Risk Assessment studies found in literature specifically done for Liquid Petroleum Gas (LPG) offloading pipelines in Sri Lanka. Therefore, as the output of the present study, it provides a complete methodology to determine the dynamic risk associated with a given LPG offloading pipeline. The study is performed based on a hypothetical LPG pipeline a which runs from the Port of Colombo to Kerawalapitiya. Similar to the work done in [5], this method of risk assessment can be used to calculate the level of risk in Sri Lankan Rupee (LKR) value. Operators will be able to select when and where to take risk mitigation action if they have this information.

1.2 Aim and objectives

This study aims to develop a framework that facilitates the dynamic risk assessment of LPG transportation pipelines.

The objectives of this study can be listed as follows.

- Identify the potential hazards of the hypothetical LPG transmission pipeline
- Develop a framework to quantify the Dynamic failure probability of the LPG offloading pipeline
- Trial framework for a given scenario and estimate the potential consequences in monetary values

1.3 Chapters and their respective content

A literature review associated with the study is presented in Chapter 2. Important data, concepts, and techniques are introduced which support the successful completion of the objectives. Chapter 3 is allocated to elaborate on the methodology used in meeting the objectives of this project. Further, this chapter contains all the sample calculations and information on computer simulations. Chapter 4 is allocated for results and discussion, while Chapter 5 gives the conclusions.

CHAPTER 2 : LITERATURE REVIEW

This section will explore the current risk assessment techniques and tools in use to support the risk assessment process. Further, the limitations of the current approaches and the selection of the most appropriate methods to achieve the objectives will be highlighted.

2.1 Current risk assessment techniques used in the field for LPG pipelines

The risk assessments of transmission pipelines, found in the literature, are mainly static. As mentioned in [6], The typical reasons of failure, as well as the conditional dependencies between the safety barriers, are not captured by Event Tree Analysis (ETA). As a result, doing Dynamic Risk Analysis (DRA) is critical for updating risks and allocating appropriate safety measures.

According to [5], Two important quantities must be determined in order to quantify risk. Specifically, the aggregated probability of the pipeline and its Leak Detection System (LDS) failure, as well as the consequences of failure. Financial losses connected with environmental damage, oil spill cleanup, and missed output are among the consequences. The following methodology is presented in [5] for assessing pipeline risk.

- *Gather information on the pipeline.* Pipeline mechanical features, pipeline operational characteristics, and the level of corrosion, for example.
- Determine the events of failure: The main leakage events are considered as leakage or burst.
- *Evaluate corrosion growth:* Using mathematical models available in the literature
- *Probability of failure of the pipeline:* The limit state approach can be used to calculate the pipeline's probability of failure.
- *Determine the LDS probability of failure:* The probability of LDS failure is equal to the likelihood of missed detection.
- *Determine the joint probability of failure* (P)*:*

$$P = P(LDS) \times P(PL) \tag{1}$$

Where $P(LDS)$ is the Probability of failure of Leak Detection System $P(PL)$ is the pipeline's probability of failure.

— *Determine the failure consequences:* The leaked product quantity is determined using mathematical models available in the literature. On the other hand, the financial losses attributable to lost production cost (LPC), inspection cost (IC), segment replacement cost (RC) and environmental consequences cost (EC) are listed under the consequences of failure (COF).

$$COF = LPC + IC + RC + EC \tag{2}$$

Finally, as mentioned in [5], the following equation calculates the risk associated with the scenario.

$$Risk\ (T) = P_{failure}(T) \times Cost_{failure}(T) \tag{3}$$

2.2 Dynamic risk assessment and its applications

According to [7], despite the general approach of QRA is static, the Quantitative Risk Assessment (QRA) approach has been developed since the early 1980s. Although it was primarily developed for chemical and nuclear process safety, it has since expanded to include typical applications such as process design, safety system implementation, inspection and maintenance planning, and operations management. Furthermore, QRA has evolved into a critical instrument for process development, day-to-day operations, and expansion. Although QRA performed better than that of Qualitative Risk Assessment, it had some shortcomings as the risk profile is static and therefore could not provide many accurate predictions.

Nevertheless, the developments presented in [8] have made the techniques more accurate and precise by introducing the Bayesian network approach. First, prospective accident scenarios are discovered and recorded in the form of an event tree; then, end-state probabilities are evaluated using the event tree and available failure data. Safety system failure likelihood and event tree end-state probabilities are then changed using the existing accident precursor data.

Further, those techniques have been successfully validated in [9], and [10] by applying them in real scenarios. On the other hand, the work presented in [6] has successfully applied the technique in risk assessment of Liquefied Natural Gas (LNG) offloading process and has been able to determine the most probable accident scenario. He also mentions that the Bayesian network may be utilized to figure out what caused an accident scenario to fail. The method can be applied to the prediction of any process's potential risks. The challenging part is the development of conditional probability tables (i.e. CPT).

Furthermore, [11] has developed a Principal Component Analysis (PCA) based fault detection and diagnosis technique to risk-based fault detection and diagnosis framework aimed at process system safety challenges. When compared to univariate approaches, this strategy has been shown to provide a substantially earlier warning.

According to [7], The most recent tendency is to fine-tune current Risk Assessment methods in order to maximize their applicability. They also point out that the main development path is provided by the use of dynamic risk assessment methodologies since there has been a significant advancement in computer-related technology for the real-time monitoring of process facilities. Upon that, the highest potential area to be developed is identified as the system development integrated with dynamic procedure for hazard identification. Considering the methodologies addressing the dynamic risk, [12] argues that, despite several techniques of HAZard IDentification (HAZID) and Quantified.

Risk Analysis (QRA) has proven to be beneficial in the industry, but it lacks the ability to dynamically update based on real-time data. Based on their possible appropriateness with Integrated Operations (IO) solution, they offer Dynamic Procedure for Atypical Scenarios Identification, Dynamic Risk Assessment (DRA), and Risk Barometer approach for dynamic risk assessment.

New dangers may be developed as the process and facility become more complicated, and these hazards must be discovered early. DyPASI, which functions based on early warnings or risk conceptions, was established as a way to detect and assess atypical probable accident situations related to materials, equipment, and plants [10].

The Dynamic Risk Assessment (DRA) technique which was developed in [8], wants to use Bayesian inference to estimate accident scenarios based on real-time aberrant conditions or incident data. The modified frequencies will then be used to calculate the overall risk.

According to [13], the technique is being developed to support decision-makers in everyday operations by continuously monitoring risk picture changes. According to [7], it has many advantages over other methods such as “drilldown” capability and the use of “transparent box” philosophy.
The development of these techniques would not only cater the nuclear or chemical process industries but also other applications such as high-speed trains, military applications, weather predictions, and aerospace applications etc. In brief, this is applicable in any scenario depending on the effectiveness.

2.3 Safety analysis techniques

2.3.1 Hazard and Operability Study (HAZOP)

Hazards arise in a plant due to deviations from normal behaviour. Hazards and Operability (HAZOP) study gives insight into the hazards that are present in the plant. A comprehensive HAZOP analysis identifies all possible hazards and operability problems, recommended changes and studies etc.

This research does not include a comprehensive HAZOP. It entails current process flow diagrams (PFDs); process and instrumentation diagrams (P&IDs); detailed equipment specifications, construction materials, and mass and energy balances; and, most importantly, a team of experts comprised of a cross-section of experienced plant, laboratory, technical, and safety professionals.

2.3.2 The conventional Bow-Tie model

The Bow-Tie model (BT) is one of the most popular techniques since it depicts the entire accident scenario, including causes and consequences. However, it has a static structure, which limits its use in real-time monitoring and probability updating, both of which are important aspects of dynamic risk analysis. [14].

As mentioned in [15], The risk control parameters on a shared platform for mitigating an accident are represented by a bow-tie diagram, which combines a fault tree with an event tree. Because it follows the typical assumptions of fault and event tree analyses, quantitative analysis of a bow-tie is still a substantial difficulty. The assumptions take into account the input events' crisp probabilities and "independent" relationships. Crisp probability for the input events is frequently lacking or difficult to obtain, resulting in data ambiguity. Model uncertainty is introduced by the assumption of "independence." Expert knowledge elicitation as a replacement for missing data may be an option; nevertheless, such information contains uncertainties and may jeopardize the credibility of risk assessments.

In [16], the authors claim that the Bow-Tie diagrams have become a popular risk analysis and safety management tool. This tool graphically depicts the entire risk scenario and suggests preventative and protective barriers to lower the risk's occurrence and severity, accordingly. The drawback of Bow-Tie diagrams is that they are limited to a graphical representation of many scenarios created solely by experts, ignoring the dynamic nature of real-world systems. As a result, creating Bow-Tie diagrams in an automated and dynamic manner remains a significant difficulty.

2.3.3 Bayes rule and Bayesian networks

As described in [17], Bayesian networks (BNs), also known as belief networks, are a type of probabilistic graphical model that belongs to the family of probabilistic graphical models (GMs). These graphical structures are used to describe information about a domain that is ambiguous. The edges between the nodes in the graph represent probabilistic dependencies among the associated random variables, while each node in the network represents a random variable. Known statistical and computational methods are frequently used to estimate these conditional dependencies in the graph. As a result, BNs incorporate graph theory, probability theory, computer science, and statistics principles.

A Bayesian network model can be used to examine the structures of gene regulation networks, as discussed in [18]. It is capable of combining data from both prior knowledge and experimental data.

As mentioned in [19], conditional independence and joint probability distribution are the fundamental ideas of the Bayesian network. Equation (4) and (5) explains it mathematically.

$$P(V_1, V_2, \dots, V_k|\nu) = \prod_{1}^{k} P(V_i|\nu) \qquad (i = 1,2, \dots, k) \tag{4}$$

$$P(V_1, V_2, \dots, V_k|\nu) = \prod_{1}^{k} P(V_i/Parent(V_i)) \quad (i = 1,2, \dots, k) \tag{5}$$

Where $P(V_1, V_2, \dots, V_k|\nu)$ stands for different variables, ν facilitates the expression of the conditional probability and it is the normal node. Also, parent nodes of V_i are indicated as Parent (V_i).

2.3.4 Mapping algorithm of Bow-Tie diagram to a Bayesian network

2.3.4.1 Fault Tree mapping to a Bayesian network

There are two steps involved in this approach namely graphical and numerical. The structure of BN is built from the fault tree in the graphical step, with primary events, intermediate events, and the top event of the fault tree being represented as root nodes, intermediate nodes, and leaf nodes, respectively, in the equivalent BN. The nodes of BN are connected in the same way that the fault tree's corresponding events are [20]. The occurrence probabilities of the primary events are allocated as prior probabilities to the appropriate root nodes in the numerical step. A Conditional Probability Table (CPT) is assigned to each intermediate node and leaf node. CPTs show how intermediate nodes are related to root or intermediate nodes that came before them. [20].

2.3.4.2 Event Tree mapping

According to [20], each event tree safety barrier is represented by a safety node with two states, one for failure and the other for the success of the safety barrier. In addition, the network gains a consequence node with the same number of states as the number of event tree consequences.

2.3.4.3 Bow-Tie mapping

The BowTie diagram developed is to be further processed to map into Bayesian networks. Although the Bayesian network can be developed directly, it is always recommended to develop the BowTie diagram beforehand as it will provide a better background in developing the Conditional Probability tables (CPT). An example for a BowTie Diagram which can later be mapped to a Bayesian network is shown in Figure 2.1. Here, PE, IE, TE, SB, and C stand for, Primary Event, Intermediate event, Top Event, Safety Barrier, and Consequences respectively.

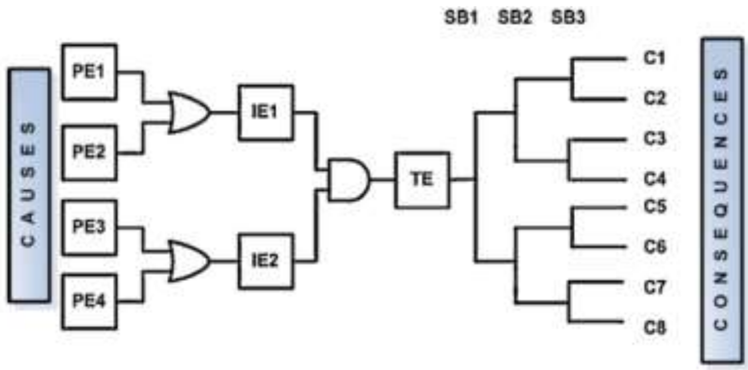

Figure 2.1: A Model Bow-Tie diagram [21]

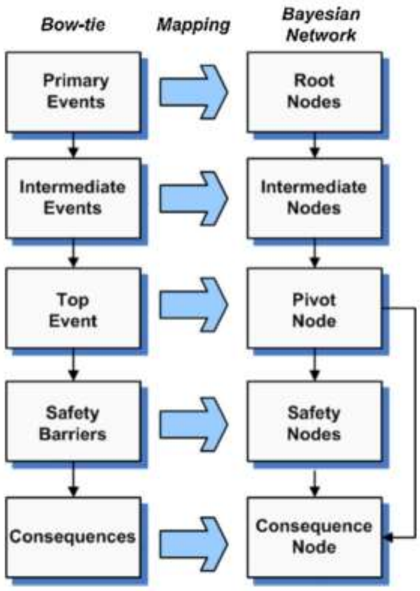

Figure 2.2: BT into BN Mapping algorithm [21]

As shown in Figure 2.1, the left-hand side consists of a Fault Tree and the right-hand side consists of an Event Tree. The fault Tree is developed with the use of logic gates. (i.e. AND and OR Gates). In the event tree, the safety barriers are considered for success and failure. Subsequently, the probabilities for each consequence are determined. The developed BowTie Diagram can be mapped to a Bayesian network using the algorithm shown in Figure 2.3.

2.4 Software packages

There are a number of software packages available for the assessment of the probability of failure and consequences. It can be seen that in most of the applications, Microsoft Excel can be used in numerical calculations. Nevertheless, there is some specialized software for risk assessment available to make the analysis concise and professional. GeNIe 2.2 software package is widely used by academics and commercial users for analysis with Bayesian networks. In this study, the same software is used which is specially designed for academic purposes.

2.4.1 Computational Fluid Dynamics (CFD) and Acceleration Simulator (FLACS®)

Computational Fluid Dynamics (CFD) is a widely used technique in a range of applications. There are several software packages in use such as OpenFOAM®, ANSYS Fluent®, FLACS®, SolidWorks®, and Autodesk CFD®. FLACS® is a specially developed software for simulating fires, explosions, and spills. It also has the following basic characteristics of a CFD software.

2.4.1.1 Pre-processor

The user should effectively use this utility to optimize the computation power and the accuracy of the results. This utility includes the generation of the geometry if any, meshing of the computation domain, introduction of physical properties of the substances, boundary conditions, and initial conditions. CASD serves as the pre-processor for FLACS®. [22]

2.4.1.2 Solver

Basically, in this step, the governing equations are discretized and solved numerically. (i.e. Navier-Stokes Equations and their derivations). The run manager provides the interface to use the solvers available embedded in FLACS®. [22]

2.4.1.3 Post-processor

This step is done to visualize data developed through the numerical solving process. It has the capability to display the created geometry and the mesh. It also has the capability to create vectors, contours, 2D and 3D surface plots to enhance the visualization. The utility called Flowis serves as the post-processor. [22]

2.5 Risk assessment

2.5.1 Individual risk

Individual risk is described as the risk to an individual or a person in the vicinity of a hazard, which comprises the type of injury, the possibility of injury, and the time span over which an injury can occur. In other words, individual risk refers to the likelihood of a person dying in a dangerous situation at a specific point in time. Chances per million per year (pmpy) is its usual unit of expression [23]. It is also defined as the frequency at which an individual is at a particular distance from a pipeline is expected to sustain a particular level of harm from the hazard available in those surroundings [24].

Individual risk contours depict the geographical distribution of individual risk around a specified area, displaying the frequency of an occurrence capable of causing a specific amount of harm at a specific location without regard to whether or not any individuals there are harmed. Therefore, individual risk contour maps are formed by estimating individual risk at every location assuming that somebody will be there 100% of the time. In other words, the annual exposure is 8760 hours. [24]

2.1.1 Societal risk

After the individual risk assessment, societal risk assessment is the other important analysis that should be done to know the effect on the society level. Therefore, societal risk measure is a graphical presentation to estimate the risk on a group of people [25]. Some major incidents or catastrophic accidents have had a detrimental effect on property and groups of people in past decades. Even, nowadays there are incident and accident which can occur and has potential to affect a large number of people. So, societal risk assessment comes in an existence here to calculate the risk on a group of people or on a society level. The frequency distribution of numerous casualty events is commonly used to measure societal risk [26]. However, as societal risk assessment requires the same information (frequency and consequences) as individual risk assessment, it can also be expressed in terms similar to individual risk assessment. Furthermore, societal risk assessment also requires the information of people at risk in the affected zone. The information can be of different types for example (residential, industrial or school) likelihood of many people are present at a particular location and at which time.

According to [27], individual and societal risks are different outputs for the same input values (frequency and consequences). Both these assessments are very important in terms of reducing risk and assessing the acceptability of the facility in absolute terms.

2.6 Selection of techniques

Based on the literature survey, it can be deduced that the Bayesian techniques outperform other techniques in dynamic risk analysis. Additionally, it facilitates fault diagnosis which is not available in conventional techniques. The Conventional techniques can be used to systematically arrange the failure events and safety barriers identified from HAZOP. With the determination of consequences based on the identified criteria and available models, the risk can be estimated. In estimating consequences, CFD codes such as FLACS® can be used.

CHAPTER 3 : METHODOLOGY

In this section, the proposed framework is presented and it is trialled through applying it for a case study. The framework presented in Figure 3.1 is followed throughout the project. It is divided into three segments namely, determination of dynamic probability; quantification of consequences; and quantification of risk. A discussion of this process is presented in the following sections.

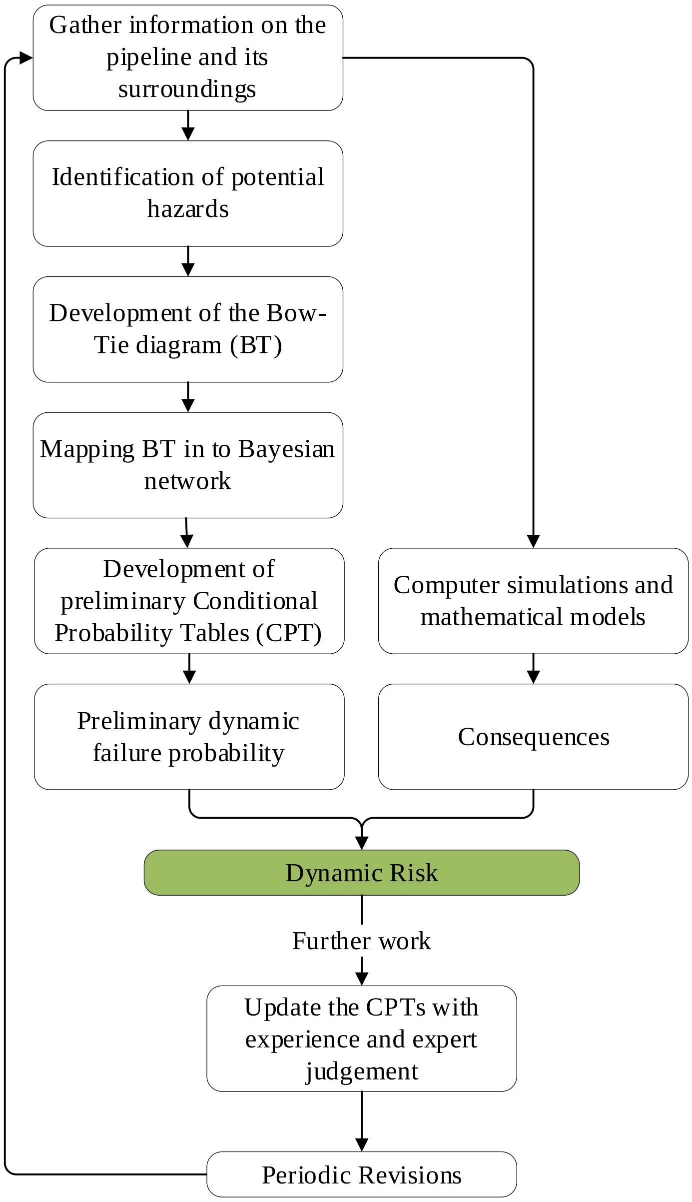

Figure 3.1: The methodology

In this proposed framework, the potential hazards are identified using a Hazard and Operability Study (HAZOP). Afterwards, a Fault Tree (FT) and an Event Tree (ET) are developed to identify the failure events and the safety barriers. The FT and ET are connected through the top event of the given scenario.

To introduce the dynamic characteristics to the analysis, the ET and FT are mapped to a Bayesian network based on the algorithm available in the literature. For this task, the initial probabilities are derived from the available literature such as Offshore

Reliability Data (OREDA). Then the conditional probability tables can be developed based on accessible data and reasonable assumptions. The result is a Bayesian network model, which can dynamically calculate the failure probabilities upon the provision of available evidence.

Subsequently, a consequence analysis is done in monetary values which finally makes the provision to dynamic Risk Assessment. Simulations such as Computational Fluid Dynamics (CFD) or Finite Element Modelling (FEM) are used to estimate the consequences. Finally, the dynamic risk is determined.

The model generated for a given system, in this framework, can be further trained to get more accurate and reliable estimations. The subject experts involved in the system being assessed can convey their experience and knowledge to continuously improve the model. Updating the conditional probability tables can be done throughout the period while a periodic HAZOP can identify the current situation of the already identified hazards and new additions. Based on the changes identified, the simulations and calculations can be refined.

The framework presented above is applied in a case study as an illustration. A hypothetical scenario is defined and the risk estimation is performed accordingly.

3.1 Case study

Identification of the site location and the analysis of the surrounding land usage is the first step of the methodology. Then the design and operation-related details of the site are identified. This information will be used in quantifying the risk associated with the accident scenario.

This hypothetical pipeline runs from Colombo Port to Kerawalapitiya through Modara, Mattakkuliya, Hekitta, and Dikkowita. The total length of the pipeline is 10 km from the port to the destination. Nearly 75% of the total pipe length runs through a highly-populated area while the rest through medium and low population density regions. Figure 3.2 illustrates the pipeline route from the port to the hypothetical destination.

Figure 3.2: Pipeline route -Google Maps, 2017

As illustrated in Figure 3.3, the population density over the length of the pipeline can be approximated with respect to the location of Port of Colombo. The information is provided based on the most recent census report in Sri Lanka. The pipeline traverses two districts of Sri Lanka (i.e. Colombo and Gampaha) and two Divisional Secretary divisions (i.e. Colombo and Wattala).

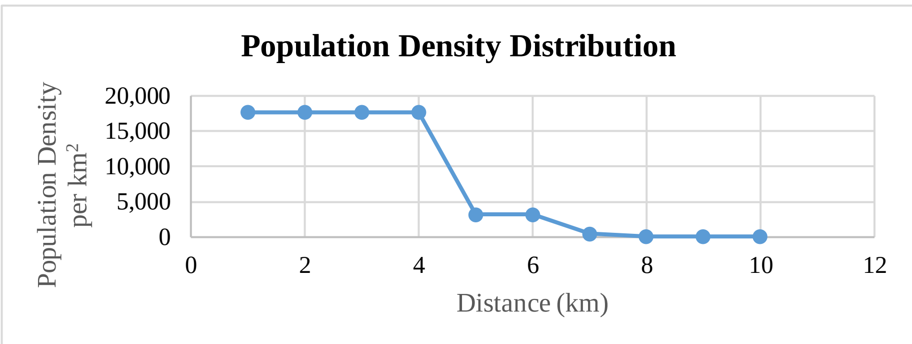

Figure 3.3: Population density distribution over the length - Census, 2011

3.1.1 Accident scenario

The following scenario is assumed in order to calculate the probability of consequences. The incident is assumed to take place in Mattakkuliya area.

It is assumed that, according to the evidence, the Mattakkuliya area is under attack by a terrorist group. (i.e. the probability of a terrorist attack is almost equal to 1). And some nearby explosions are reported which has caused a fire. (i.e. the probability of nearby explosion and probability of ignition are equal to 1). Further, previous quality reports indicate that the pipeline in the same region is corroded due to exposure caused by severe erosion.

In addition to that, the details in Table 3.1 are assumed in order to quantify the consequences due to the above scenario. The complete analysis is made based on the above assumptions. This scenario can be altered for several probable scenarios and tabulate the results for quick reference.

Table 3.1: Design and failure information

Description	Details
Diameter of pipeline	482 mm (Nominal Bore)
Thickness	9 mm
Crack size	40 cm
Design pressure	2500 kPa
Delivery pressure	1500 kPa
Delivery temp.	30 (Celsius) (max.)
Leak duration	3 hours

3.2 Identification of potential hazards involved with LPG pipelines

Under this topic, a comprehensive exploration of potential hazards is done. The hazards involved with different pipelines types in the world are considered while the case-specific scenarios are also considered. One catastrophic consequence identified through this will be selected from this study for the rest of the study.

Table 3.2: Identified potential hazards involved in LPG pipelines

Event	Reason	Possible accident	Failure prevention measures
• LPG pipeline physical damage can cause a leakage of LPG	• Due to earthwork, such as digging etc.	• Projection of solid particles with high speed can cause damage. • Explosion	• Buried pipeline to meet the standard. • Rural zoning. • Accurate drawings and signing. • Pipeline design with required dimensional properties, correct material quality, and use correct fabrication techniques and standards. • Proper fencing about Main Line Valves (MLV)s • If a major hole in a pipe is detected, the system will automatically shut down and close the valve. • The network controller must manually shut down the system.
• A leak of LPG from the gas pipeline can be initiated due to corrosion.	• Digging or inspection can damage pipeline coating that leads to corrosion. • Damage during construction, damaged	• Gas release. Ignition may cause a Jet fire. • Property damage and physical injuries.	• External corrosion protection with cathodic protection. • Internal corrosion is almost non-existent when using a clean hydrocarbon. • Coating applied on the outside of pipelines. • Inspection of the pipeline on a regular basis (including regular patrol and pigging). If there is a leak, there are visual and audible indicators. • A pipeline is built to allowing internal (pigging) inspection. • Cathodic protection as per the available standards.

	coating or defective materials • Soil condition in the route and the probability for corrosion. • Neighbouring metal burials. (Protective or sacrificing)		• Gas is given a unique odour, enabling for early identification and intervention in the event of a tiny leak before it becomes a bigger one. • QA during the manufacturing and installation process.
• An explosion occurred close to an LPG pipeline or tie-offs.	• Wear, mechanical impact, or lightning strike-like incident at the parallel LPG pipeline.	• LPG release is a possibility due to a damage. Ignition source can initiate a jet fire or flash fire. Potential injuries and property damage.	• Gas pipeline operator based internal risk management procedures. • Pipeline integrity plan. • LPG pipeline monitoring 24x7. • Signposting indicating phone numbers to call before digging. • Buried pipelines. • Thickness and grade of pipelines. • Proper fabrication techniques and standards
• Pressure excursion leads to failure of the pipeline.	• Operational error upstream or downstream facility.	• If a gas pipeline is over-pressurized, resulting in failures, leaks, and the leakage of LPG. Ignition may cause a fire. Injury	• Pipelines are constructed, and hydro-tested to meet standards. • The pressure of the pipeline needs to be continuously monitored.

		and property damage is possible.	• Isolating the flow of LP gas by high-pressure tripping and automatic line-break protection • At compressor stations, mechanical overpressure protection and controls can be used.
• Loss of integrity of the pipe without an external interaction	• Construction fault or functioning fault.	• Injury and property damage due to a large LPG release and ignition	• Apply NDT techniques on welds as required. • Correct welding techniques • Use cathodic protection options • Pipelines should be designed so that crack propagation is limited to around two pipe lengths.
• Erosion can expose piping and equipment make them vulnerable to physical damages	• Flooding	• Floodwaters have the potential to wipe away soil cover. The pipeline may be exposed due to this. Damage to the coating and subsequent corrosion difficulties are a possibility. If the problem is not addressed, the pipeline may finally fail.	• after heavy rain or flooding, regular and periodic patrols and inspections need to be done may be using aerial patrols, ground patrols, landowner liaisons. • Use soil cover to repair the erosion.
• Damage to pipelines caused by land subsidence	• Areas affected by mining activity or earthquakes.	• Failure of pipeline resulting in the potential for rupture or massive leak. Release of LPG. An ignition source can initiate a jet fire or flash fire.	• Make sure the site is not affected by mine subsidence. • Adhere to the design standards.

		Potential injuries and property damage	
• Damage to the pipeline occurs as a result of aircraft, train, or heavy vehicle incidents, resulting in hazardous emissions	• Aircraft crash. • Heavy vehicle crash.	• Release of LPG. An ignition source can initiate a jet fire or flash fire. Potential injuries and property damage	• Use buried pipelines whereas possible make them less susceptible to aircraft, train or heavy vehicle crashes. • MLVs can be stationed safely away from areas where a road or train collision could occur • MLVs will be surrounded by security fencing which will assist in containing a vehicle • If a gas pipe is ruptured, automatic line break isolation valves reduce the amount of gas emitted. Remotely activate isolation valves • Adhere to aviation safety standards
• Damage to the pipeline through terrorism/vandalism.	• Malicious damage.	• Massive LPG. If ignition, then the possibility of flash or jet fire.	• Buried pipeline. • MLVs are surrounded by a security fence. • Any building doors will be fitted with intruder alarms.
• Nearby fire	• Wildfire	• Heat radiation from the pipeline is a possibility. • If pipe and equipment are damaged, dangerous materials may be released, posing a fire risk.	• Vegetation control in the easement. • Heat radiation is unlikely to impact the underground pipeline. • Fire-resistant above-ground valves are available.

3.3 Determination of the failure probability using the static approach

Under this topic, the determination of the failure probability using the conventional static approach is discussed. In other words, the probability of consequences is determined using the conventional Bow-Tie diagram approach. The events identified in Table 3.2 are systematically divided into Causes, Safety Barriers, and Consequences.

3.3.1 Assigning the probabilities

The left-hand side of the Bow-Tie diagram should be upgraded as a Fault Tree Diagram and the right-hand side as an Event Tree Diagram respectively. Further, to provide the diagram with failure probabilities, the values presented in Table 3.3 can be assumed. This can be done based on expert judgement or by referring to sources such as [29].

3.3.2 The left-hand side of the Bow-Tie diagram

As shown in Figure 2.1, the fault tree is the left-hand side of the Bow-Tie Diagram. For the sake of clarity, it is presented in figure 3.4 as a regular Fault Tree diagram. The probabilities presented in Table 3.3 are assigned using a Microsoft Excel Sheet. The mathematical relationship between each event can be presented as follows. Here P stands for the probability of failure and R stands for reliability.

For an AND Gate; $P = P_1 \times P_2 \times \ldots \times P_n$ while for an OR Gate $R = R_1 \times R_2 \times \ldots \times R_n$. The relationship between P and R can be given as $R = 1 - P$. In this approach, the failure probability (i.e. the reliability) of the Top Event (i.e. Uncontrolled LPG Release) can be determined as follows. This probability is fed into the Event Tree Diagram in order to calculate the probability of consequences, which is later can be used to calculate the Risk involved with this process.

Table 3.3: Assumed probabilities on the respective event

	Event	Code	Failure Probability
1	Corrosion	CRSN	0.004
2	Nearby Explosion	EXPN	0.0001
3	Design Error	DSNE	0.01
4	Over Pressure	OVPR	0.07
5	Material Flaw	FLAW	0.003
6	Fabrication Error	FABE	0.004
7	Erosion	ERSN	0.05
8	Vehicle Collision	VEHC	0.00004
9	Terrorist/ Vandalism	TERR	0.000001
10	Mechanical Damage	MD	OR-Gate
11	Pressure Sensing Manual	PSM	0.00001
12	Human Error (Pressure Reading/Valve operation)	HE	0.02
13	Manual Valve	MV	0.002
14	Manual Valve Operation	MVO	OR-Gate
15	Manual Shutdown	MS	OR-Gate
16	Pressure Sensing Auto	PSA	0.00004
17	Auto Valve	AV	0.0002
18	Valve Controller	VC	0.001
19	Auto valve Operation	AVO	0.00005
20	Auto Shutdown	AS	OR-Gate
21	Uncontrolled LPG Release	ULPGR	AND-Gate
22	Rural Zoning	RUZO	0.000001
23	Buried Pipeline	BURRP	0.000001
24	Automatic Deluge	AUTDE	0.001
25	Ignition Control	IGCTRL	0.003
26	Blast Proof	BLSTPF	0.00000001
27	Personal Protective Equipment	PPE	0.000004
28	Evacuation and Upwind Mustering	EVAQ	0.002
29	Emergency Response	EMRGR	0.004
30	Emergency Respiratory System	ERESPS	0.005

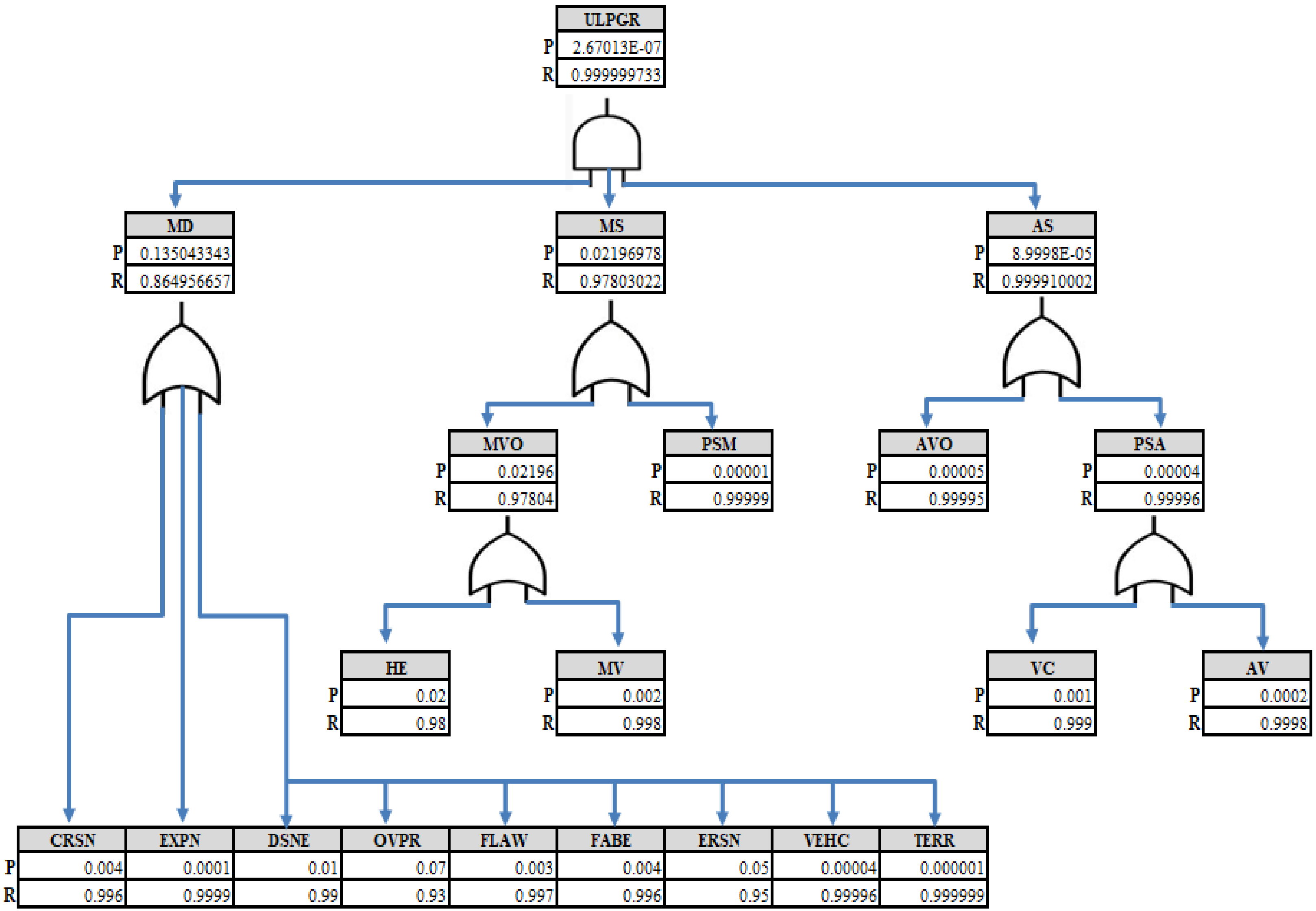

Figure 3.4: Fault Tree diagram (Left portion of the Bow-Tie diagram)

3.3.3 The right portion of the Bow-Tie diagram

Event Tree Diagram can be used to determine the probability of consequences. The first column of the Event Tree is allocated for the Top Event while the rest are allocated for the Safety Barriers, Consequence level, and the probability of consequences. Each branch is divided into two branches to represent the probability of each safety barrier failing and succeeding. The upper branch indicates the likelihood of a safety barrier's success and vice versa. Hence, it is clear that the lowermost branch indicates the probability of the most catastrophic event. Using this method, it is determined that the probability of occurrence of the most catastrophic event is 6.4×10^{-38}. The consequence column indicates three different types of events. The event 'safe' indicates that the process will be safely operating if the sequence of events follows the respective branch. Also 'I&S' indicates Inhalation and Skin Contact. The diagram can be developed using the Microsoft Excel package. The strengths and weaknesses of this conventional Bow-Tie Approach are discussed in detail under the Discussion of this project.

From this event tree diagram, it can be deduced that the total probability of consequences is in the range of 4.3×10^{-26}. This value can be taken by the addition of I&S values and CA values of probability. This value can be considered when deciding the factor (f), which is mentioned in 3.4.2.

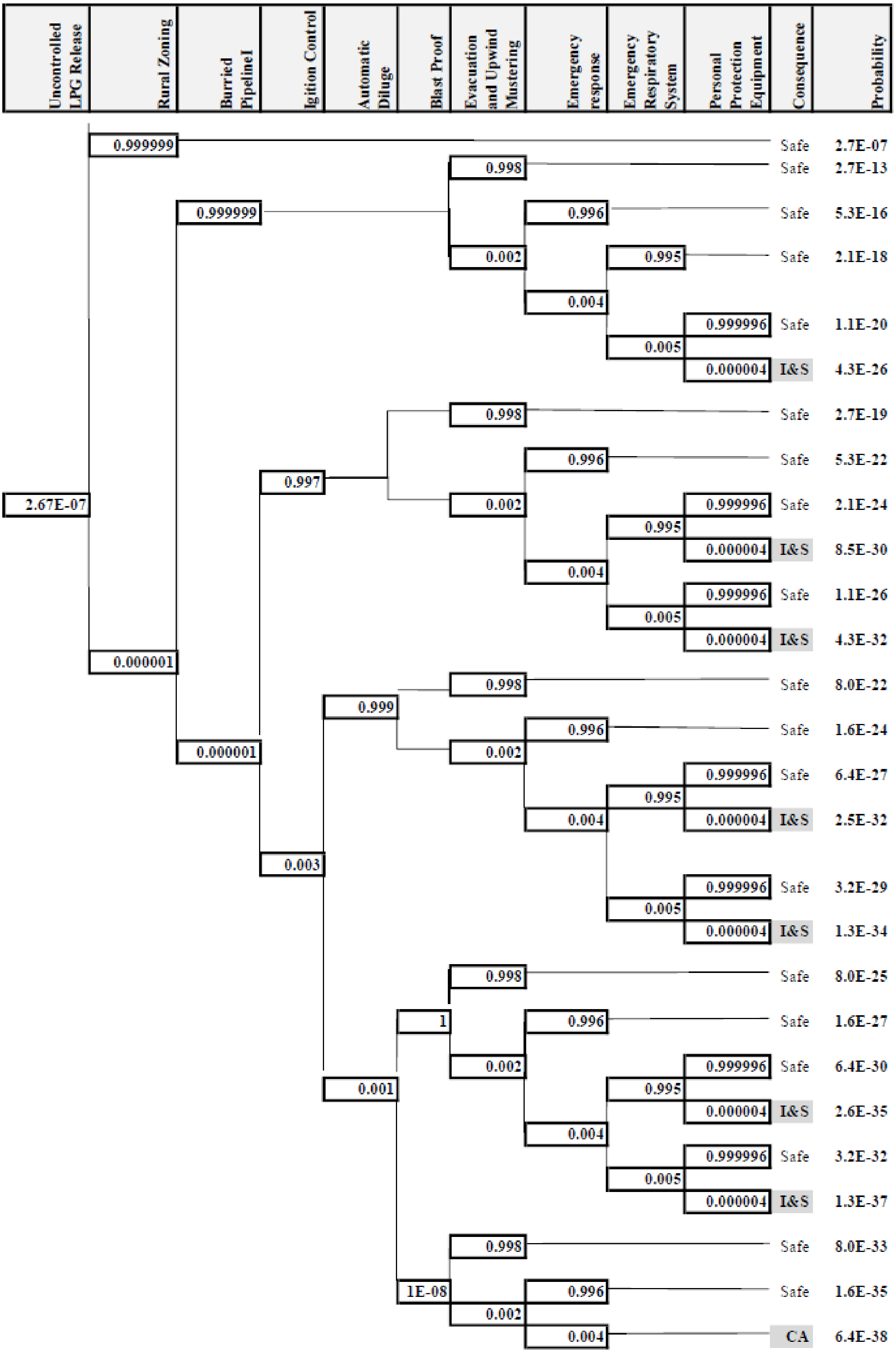

Figure 3.5: Event Tree diagram (i.e. Right portion of the Bow-Tie diagram)

3.4 Failure probability evaluation using the dynamic approach

Under this topic, the determination of the failure probability using the dynamic approach is discussed. In other words, the probability of consequences is determined using the Bayesian network approach. The events identified in HAZOP are systematically assigned to a Bayesian network following the mapping algorithm presented in Figure 2.2 along with the respective probabilities presented in Table 3.3. By this approach, the calculation of the probability of consequences can be made dynamic by providing the evidence and updating the failure probabilities. The most important thing is this system can be made continuously learning by timely updating of failure probabilities and the conditional probabilities. The mathematical base of this method depends on the Bayes Rule.

3.4.1 Mapping FT and ET into Bayesian network

Based on the mapping algorithm presented in Figure 2.2, the Fault Tree and event tree presented, in Figure 3.4 and Figure 3.5 respectively, can be mapped into a Bayesian network as shown in Figure 3.6. The diagram was generated by the use of Genie software introduced in Chapter 2.

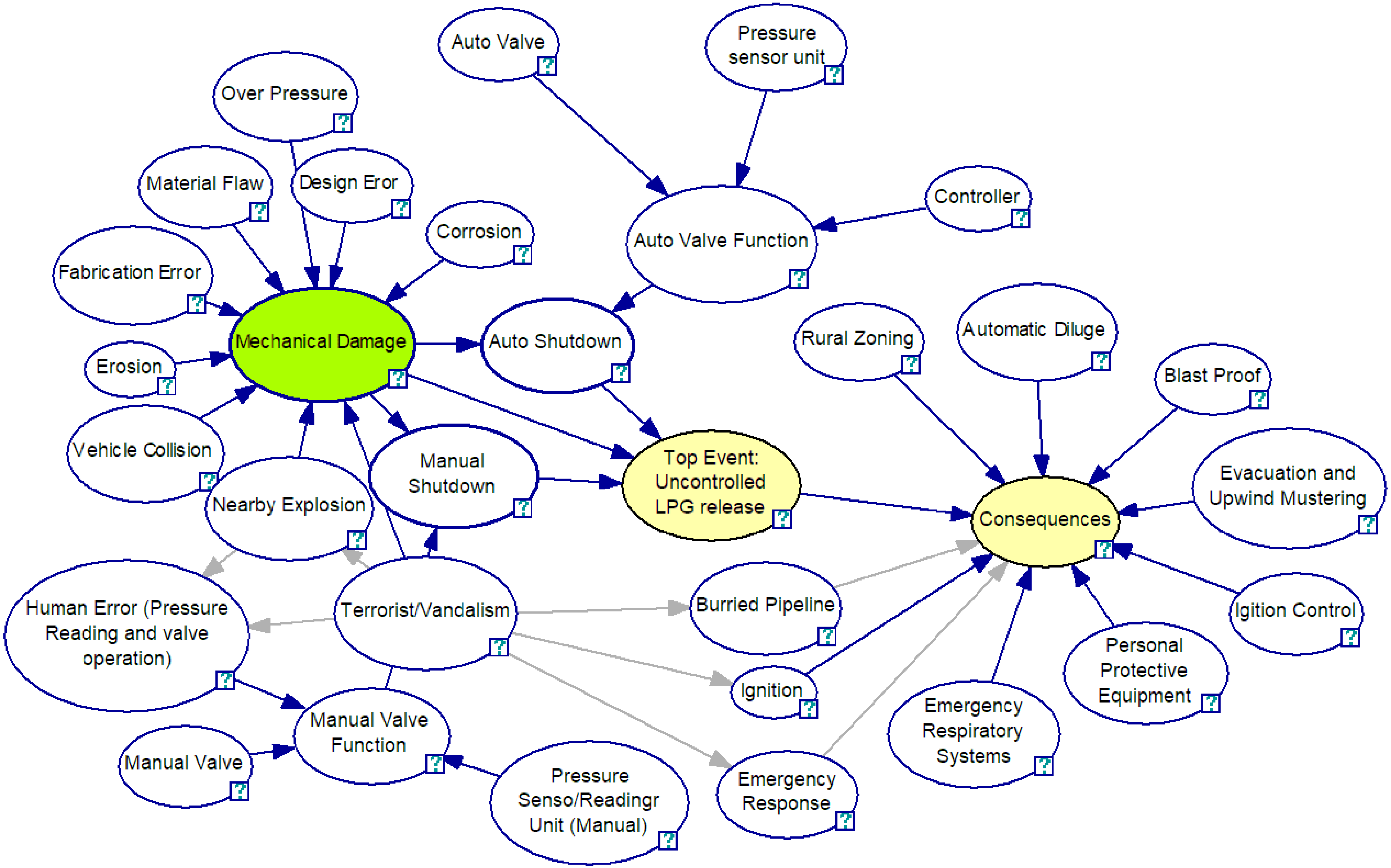

Figure 3.6: Bayesian network for the defined scenario Using GeNIe software

3.4.2 Development of conditional probability tables

Conditional probability tables can be developed based on expert judgements and historical data [30]. The Bayesian Belief network can be updated with experience to increase performance and reliability. This is a continuous learning process. As an initiation, this study assumes the probability of failure is directly proportional to the number of causes for a given event. For example, if there are three causes for a given event the following procedure is followed and is adopted into any number of causes. The probability of failure was calculated using equation 6.

$$P(Failure) = 1 \times \frac{n}{N} \times f \tag{6}$$

Where $P(Failure)$ is the probability of failure, n is the number of causes, and N is the total number of possible causes. Here f is a constant.

Following sample calculation for the part of the Bayesian network in Figure 3.7. The Table *3.4* provides a Sample calculation of Conditional Probability based on assumptions.

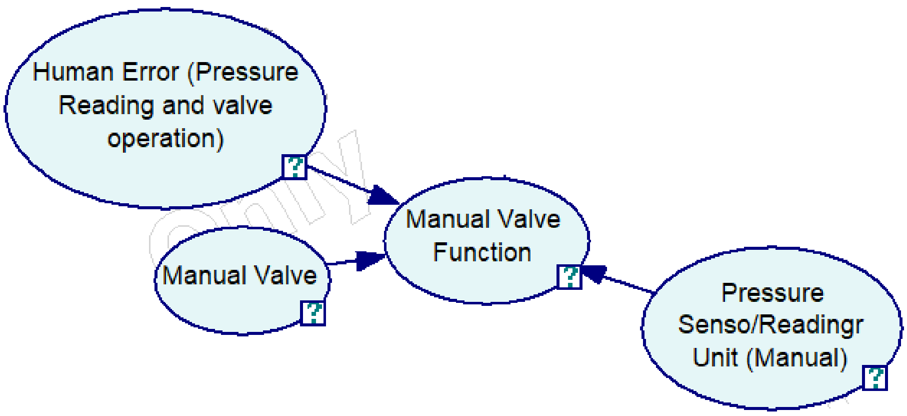

Figure 3.7: Sample section of Bayesian network

Table 3.4: Sample calculation of conditional probability based on assumptions

Possible combinations			Total number of causes (n)	Probability of failure $P(Failure) = 1 \times \frac{n}{N} \times f$
0	0	0	0	0
0	0	1	1	0.3333
0	1	0	1	0.3333
0	1	1	2	0.6666
1	0	0	1	0.3333
1	0	1	2	0.6666
1	1	0	2	0.6666
1	1	1	3	0.9999

Therefore, it is clear that the Bayesian network can be used to determine the dynamic failure probability, given the evidence. This probability can be used in calculating the Risk.

3.5 Determination of dynamic failure probability for the defined accident scenario using Bayesian network approach

As illustrated in Figure 3.8, The information from the defined accident scenario is fed into the Bayesian network. This process is called setting the evidence. This feature of the technique makes this approach dynamic. It can provide the user with a very reliable outcome depending on the quality of the conditional probability tables. This quality is a continually improving one. In other words, the Bayesian network ‘learns’ by the timely updates of conditional probabilities. The reliability of the model can be further increased by bringing the tacit knowledge of the people.

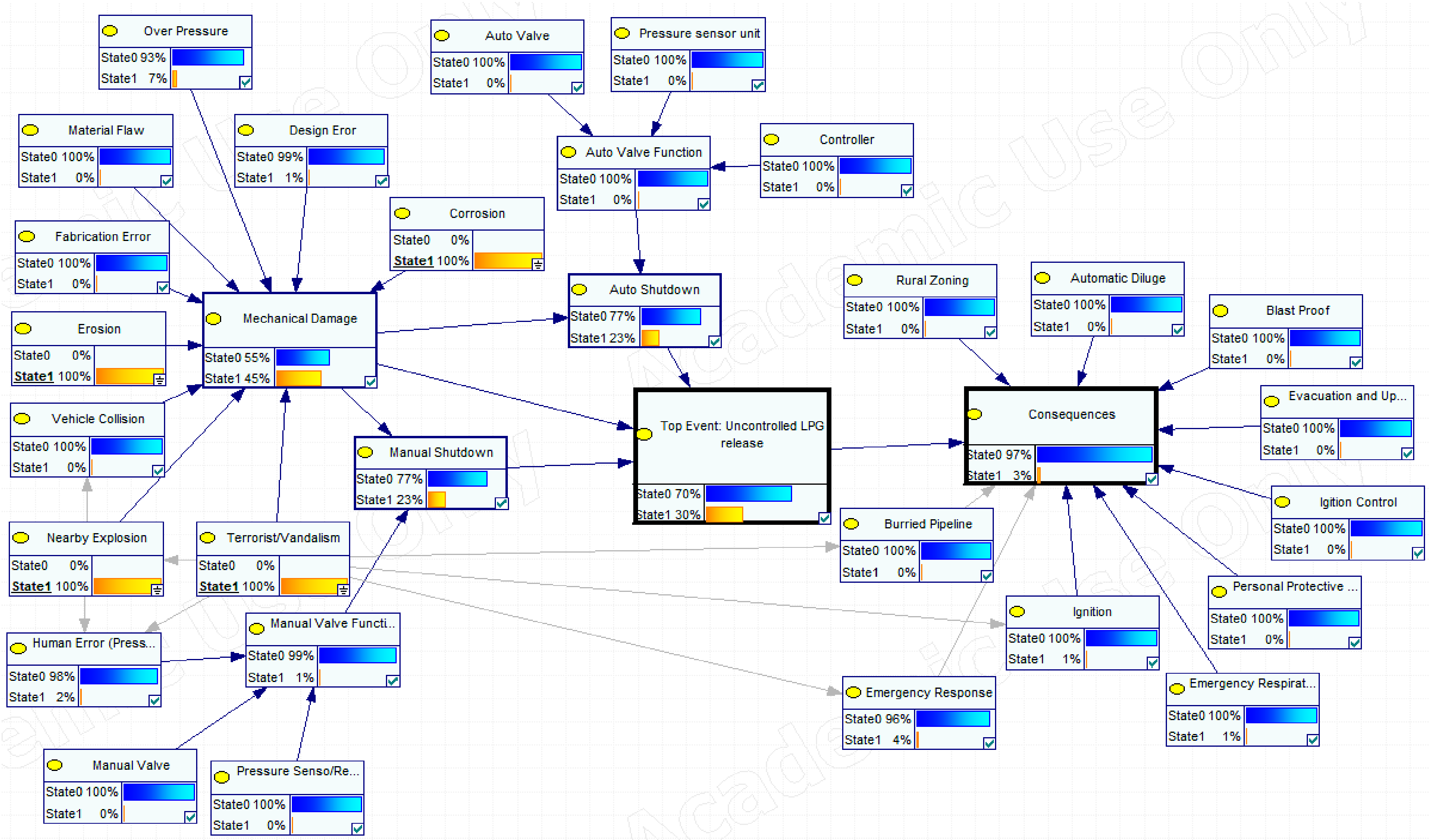

Figure 3.8: Application of the defined accident scenario to the Bayesian network

3.6 Quantification of consequence

In this chapter, the methodology of calculating the consequences is presented. In this case, the largest possible consequence is considered. As shown in Figure 3.5, the worst-case scenario is the Jet Fire. Financial losses due to lost production costs (LPC), inspection costs (IC), segment replacement costs (RC), and environmental repercussions costs will be included (EC). In addition to that, the impact on people also will be taken into consideration. Due to the Jet Fire event, the people will have to evacuate and all the necessary actions for disaster management will be done. The assessment delivers an estimate of the risk in monetary values.

Liquid Petroleum Gas (LPG) is considered non-toxic therefore the most probable accidents will be Jet fire or Explosion. Jet fire will generate heat radiation while an explosion creates pressure pulses. This study assumes the most probable catastrophic event is Jet Fire. The Jet fire will be simulated using the industrial Computational Fluid Dynamics (CFD) software called FLACS®. The temperature distribution and heat radiation will be simulated based on the scenario defined. Based on the simulation results, the evacuation and other related costs will be calculated.

3.6.1 Determination of the quantity of leaked products

3.6.2 Leak rates

The quantification of leak rate is the first step in this process. It can be determined using equation 7 [23]. It is valid for gases or vapour flows given that the flow is a choked flow. The choked flow occurs when the internal pressure is nearly two times or more than the atmospheric pressure.

$$\dot{m} = 0.8\, AP \sqrt{\frac{M\gamma}{zRT} \sqrt{\frac{2}{\gamma+1}}^{\frac{\gamma+1}{\gamma-1}}} \tag{7}$$

Where; A: Area of the hole, P: Pressure, M: Molecular weight, γ: Ratio of specific heats, z: Gas compressibility factor, R: Universal gas constant, T: temperature in Kelvin.

The calculation results of the leak rate can be presented as shown in Table 3.6. It is assumed that the crack creates a circular-shaped opening with a diameter similar to the crack size.

Table 3.5: Results of the leak rate calculation

Parameter	Value	Unit
Gas Flow Rate ($\dot{m}$)	(To be determined)	kg/s
R	8.314	J.K/mol
T	293	K
gamma	1.31	-
z	1	Assume ideal gas
M	1.80×10^{-2}	g/mol
P	1.50×10^{6}	Pa

Table 3.6: Leak rate

Leak Size (m)	Cross section (m^2)	Flow rate (kg/s)
4.0×10^{-1}	1.26×10^{-1}	2.74×10^{2}

3.6.3 Duration

The duration of the leak depends on several factors. The nature of the leak, accessibility, and reliability of disaster management system. The duration can be few minutes to few hours. In this study, it is assumed that the leakage rate does not change with time though practically it reduces with time. Further, it is assumed that the entire amount of leaked liquid gas is subjected to Jet Fire.

In this scenario, the leak duration is assumed to be 3 hours. It is assumed that this amount is completely burnt during the Jet Fire. Practically this can be much higher than this. Nevertheless, due to the development of communication among the people, and the assumption of auto-shutdown and manual shutdown features this may be a reasonable assumption.

3.7 The consequences in terms of monetary values

3.7.1 Loss due to leaked products

Based on the information provided in 3.6.2, assumptions made, and mathematical models, the total monetary value of loss of leaked product (i.e. Q_{LP});

$$Q_{LP} = \text{Flow Rate} \times \text{Duration} \tag{8}$$

$$Q_{LP} = 2.74 \times 10^2 \; kg \; s^{-1} \times 60 \times 60 \times 3 \; s$$

$$= 2,959{,}200 \; kg$$

The approximate value of 1 kg of LPG = $LKR \; 100$

Therefore, The total loss from leakage of product = $LKR \; 200{,}959{,}200$

3.7.2 Loss due to pipeline replacement

On the other hand, as per the assumption, the pipeline was to be repaired by replacing the pipeline segment of 300 m. In the US, the estimated pipeline replacement cost for crude oil pipelines is about $643,800 per kilometre [5]. Therefore, the $700,000 per kilometre is a reasonable assumption for the present scenario. Therefore, the total cost for pipeline replacement will be around $LKR \; 105{,}000{,}000$.

3.7.3 Cost of the evacuation of people from the affected area

Based on the population density in the Mattakkuliya area, the cost of evacuation and damage repayment can be assumed as LKR 5,000 per one person. If all the people live within a 1 km radius area are evacuated, the total cost for evacuation and damage payment can be calculated as follows.

$$Total \; cost = Population \; density \times area \times cost \; per \; 1 \; person \tag{9}$$

$$Total \; cost = 20{,}000 \times \pi \times 1^2 \times 5{,}000 \; LKR$$

$$= LKR \; 314{,}285{,}714$$

3.7.4 Lost production cost (LPC)

A simple mathematical model is used in [5], to determine LPC for offshore crude oil pipeline which is applicable for the present study. The meaning of each parameter is mentioned under Nomenclature.

$$LPC = Q_B \times C_P \times (T_{lp} + T_{dp}) \tag{10}$$

Nevertheless, in this study, it is assumed that the LPC is 50% of the value that is proposed in [5]. Assuming the downtime due to reparations is one week;

$$LPC_{Modified} = Q_B \times C_P \times \left(T_{lp} + T_{dp}\right) \times 50\% \tag{11}$$

$$LPC_{modified} = 273\frac{kg}{s} \times LKR100 \times (24 \times 7) \times 3600 \times 50\%$$

$$LPC_{modified} = LKR\ 8{,}255{,}520{,}000$$

3.7.5 Environmental consequences related cost

As mentioned in [5], the mathematical model presented in equation 12 can be used in quantifying the cost associated with environmental consequences. Compensation paid to fishing and tourism industries, environmental damage repair expenses, and oil spill cleanup costs are among the expenditures connected with environmental effects. During the presence and cleaning of an oil spill, fishing and tourism businesses are paid for lost revenue. Nevertheless, in the present scenario, there is no such severe impact on the environment and the community as LPG is a highly volatile but non-toxic substance. Therefore, it is reasonable to assume that 5% of that offshore oil spillage can be equivalent to an LPG pipeline failure in terms of environmental consequences. Following modified equation 12 is used to approximately calculate the environmental consequences.

$$EC = 51432\left[0.001\left(Q_h \times T_{lp}\right)\right]^{0.728} \tag{12}$$

$$\therefore EC_{modified} = 51432\left[0.001\left(Q_h \times T_{lp}\right)\right]^{0.728} \times 5\% \tag{13}$$

$$EC_{modified} = 51432[0.001(273 \times 3 \times 3600)]^{0.728} \times \frac{5}{100}$$

$$EC_{modified} = LKR\ 863{,}102$$

3.8 Quantification of temperature effects and air pollution

The temperature effect is quantified by the FLACS® simulation. The following procedure is followed to perform the simulation. This eliminates the manual calculations in determining the temperature distribution about the Jet Fire location using the probit approach. Further, the distribution of LPG in the surrounding area also can be calculated along with many other parameters.

Firstly, the grid was defined using the CASD utility available in FLACS® software. An effective grid was defined to optimize the computation power usage and the accuracy of the calculations and visualizations. Figure A.1, and Figure A.2 show the complete set of details and the visualization in CASD utility respectively. The computational domain has a size of $92\ m \times 68\ m \times 32\ m$ of length, width, and height respectively.

Then the parameters mentioned in Table A1 to Table A7, in Annexure I, were assigned in the software. The simulation was performed using FLACS® software to get the temperature distribution and the fuel mole fraction distribution plots shown in Figure 3.9. In addition to that, some important parameters such as Velocity Distribution were also simulated and presented in the discussion. It is clear that the temperature distribution ranges from $2272\ K$ to $300\ K$in the defined computational domain. Due to convection and wind effects, the area in danger increases with the increase of elevation. Therefore, it is clear that a severe temperature effect is possible for the defined scenario.

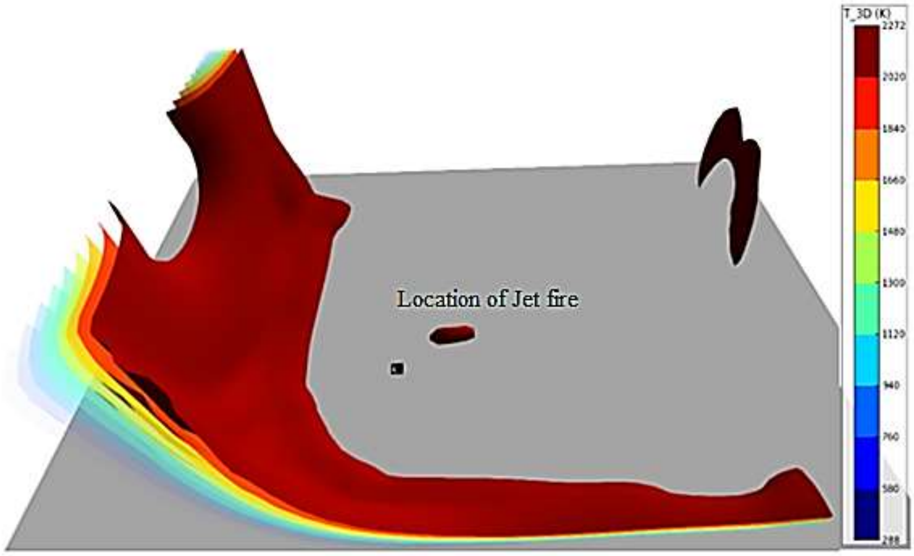

Figure 3.9: Surface diagram of the temperature distribution due to jet fire

3.9 Summary of consequences

A summary of the consequences in monetary values is presented in Table 3.7. The calculations are specifically done for gas leaks where available. In cases where specific models are not available, modified models are used which are adopted from other consequence models.

Table 3.7: Summary of Consequences

Type of consequence	Value (LKR)
Loss due to leaked products [23]	200,959,200
Loss due to pipeline replacement [5]	105,000,000
Cost of evacuation of people	314,285,714
Lost production cost (LPC) [5]	8,255,520,000
Costs Associated with Environmental Consequences [5]	863,102
Total Monetary Value	8,876,628,016 **≈ 9 billion rupees**

3.10 Quantification of risk

Based on the summary presented in Table 3.7, the following calculation can be done to determine the risk associated with the defined scenario.

From equation (3,

$$Risk\ (T) = P_{failure/consequences}(T) \times Cost_{failure}(T)$$

$$Risk\ (T) = \ LKR\ 0.03 \times 8{,}876{,}628{,}016$$

$$\boldsymbol{Risk\ (T)} = LKR\ 266{,}298{,}840\ \approx \mathbf{266}\ \boldsymbol{millions\ rupees}$$

The above risk quantification is for the defined scenario and the same methodology can be adopted for any case.

CHAPTER 4 : RESULTS AND DISCUSSION

The major strength of this study is the ability to do a dynamic analysis of the probability of failure. The conventional Bow-Tie method provides a static solution which is not always efficient in the decision-making process. More importantly, there is a major side benefit of using the Bayesian network approach as it facilitates the diagnosis and prognosis of faults.

Assume there is an uncontrolled LPG release of the pipeline is evident (i.e. The probability of uncontrolled LPG release is equal to 1). As shown in Figure 4.1, the most probable root cause for this is the overpressure of the pipeline. This diagnosis will be more reliable by continually improving the conditional probability tables with the knowledge of experts, the experience of the operators and other historical data. This technique is identified as a very powerful and successful tool in similar applications.

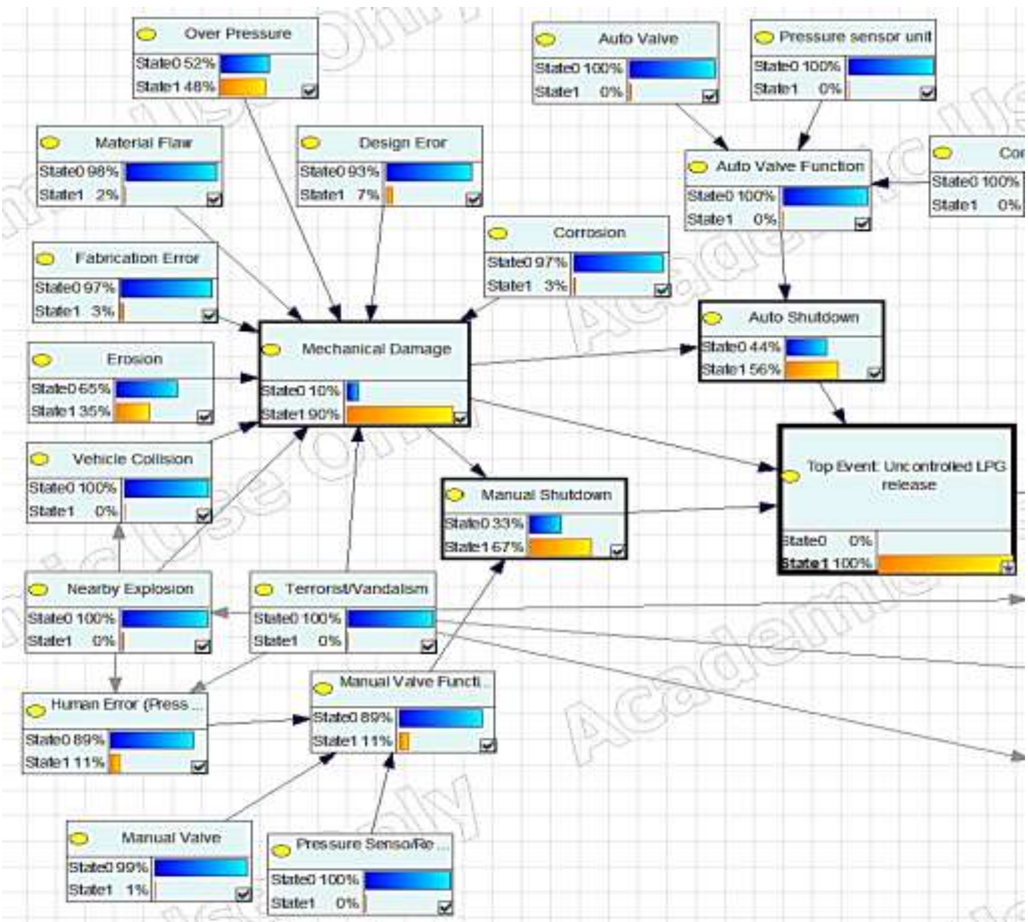

Figure 4.1: Bayesian network with introduced evidence

In real-world situations, the scenario defined may be from the information flows such as News and intelligent systems, or security camera systems. More importantly, the residents will be on alert to protect the pipeline because a catastrophic accident can cause a major influence on their day-to-day life.

The most critical step of developing the Bayesian belief networks is the development of conditional probability tables (i.e. CPTs). With the input from experts in the field and using the historical data, the tables can be updated [30]. This allows the Bayesian network to be a continuous learning system. In this study, a mathematical relation was used to develop the tables.

Also, in [19], expert knowledge and weighted treatments by the Dempster-Shafer evidence theory were used to establish the conditional probability of each BN node. They've also demonstrated that Bayesian networks combined with Dempster-Shafer's evidence theory are a viable alternative to existing methodologies. Because it considers conditional reliance in the evolution process of the NGPN accident, the suggested framework can provide a more realistic consequence analysis. This research could be useful in determining emergency response decisions and preventing losses. As a result, it will be a potential advancement for the strategy suggested in this research.

The pipeline in the defined scenario runs through areas with a variety of population densities. And there is always a considerable amount of risk associated with the people and the properties. In this study, the monetary value of the consequence is considered.

The leakage of gas from the pipeline can occur due to many reasons. Some of the possible incidents are listed below mentioned in [23].

- Construction defect / material failure
- Corrosion
- Ground movement
- Flooding
- Land subsidence or mining activity
- Aircraft, train or truck crash
- Damage to pipe through terrorism
- Other/unknown causes
- Nearby explosion
- The operational error causes

In terms of material failure, pipeline manufacturers should follow the available standards to minimize the issues that can arise during the fabrication process. On the other hand, the installation process also should be well supervised by professionals. Welding and other operations should be performed by well-qualified technicians to minimize human error. A proper study should be done to understand the nature of the soil, movement, constituents etc. A suitable patrol system should be provided to ensure the safety of the pipeline to minimize the risk of vandalism and terrorism. Also, the existence of high tension power lines needs to be considered in designing and suitable safety precautions should be taken. To minimize the damage due to third-party excavations, a proper signing should be provided with ‘Dial Before Dig’ signs. And the valve stations also should be properly fenced and secured.

For the protection, of the pipeline, the following actions can be taken to reduce the risk of damage.[23]

- Cathodic Protection
- Security Fencing
- Auto shutdown systems
- Signage along pipe route
- Rural Zoning
- Buried Pipelines
- Design to facilitate internal inspections
- Routine inspections
- Apply aviation safety standards
- Protect from Erosion
- Use high-quality welding processes
- Apply NDT as appropriate

When it comes to time-dependent risk, it's important to remember that interest and inflation rates influence all future cost aspects. The following equation (14 can be used for the same.

$$i^* = \frac{1+i}{1+I} - 1 \tag{14}$$

Where; i^* the real interest rate; i is the market interest rate, and I is the inflation rate. The future value can be calculated using the following equation (15.

$$FV(T) = PV\ (1+i^*)^T \tag{15}$$

Alternatively; $$FV(T) = PV\ \left(\frac{1+i}{1+I}\right)^{T} \tag{16}$$

Therefore, the cost of failure after time T (i.e. $Cost_{failutr}(T)$) can be given as

$$Cost_{failure}(T) = [Cof]\left(\frac{1+i}{1+I}\right)^{T} \tag{17}$$

Following Figure 4.2 illustrates the increase in risk with time for the defined scenario assuming the inflation rate (I) as 5.8%, and bank interest rate (i) as 8.13%. This shows, in every 10 years time, the cost of failure increases by almost 10%.

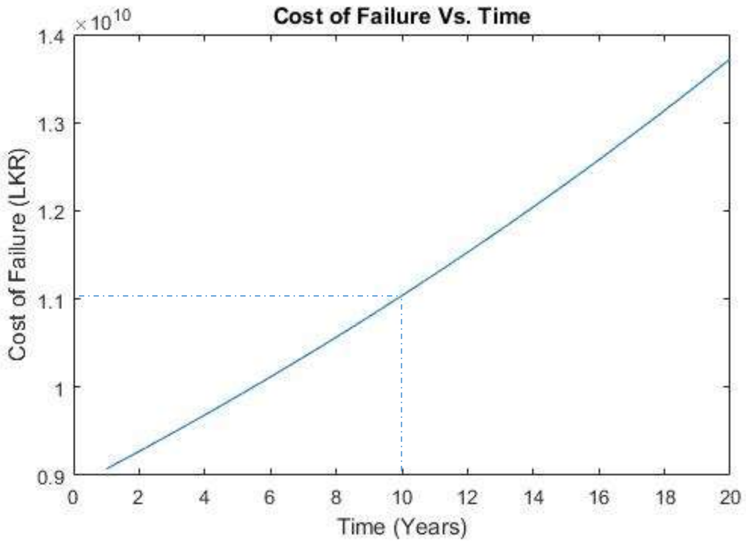

Figure 4.2: Cost of failure vs. time

Most of the risk assessment studies are done based on some realistic assumptions to avoid unnecessary complications during the analysis. Following assumptions were made to keep the scope of work manageable.

- The full scenario along with the accident scenario was assumed and all the calculations and simulations were developed based on it.
- The probability of failures of safety barriers was assumed, which were not directly available in OREDA.
- In determining the conditional probabilities, the probability of failure is considered as directly proportional to the number of causes for a given event

— The most probable catastrophic event is assumed to be Jet Fire.
— The crack of the pipeline creates a circular-shaped opening with a diameter similar to the crack size.
— The leakage rate does not change with time though practically it reduces.
— The entire amount of leaked liquid gas is subjected to Jet Fire.
— The duration of leakage is 3 hours
— The offshore pipeline failure mathematical models can be used with correction factors; i.e. $EC_{modified} = 51432\left[0.001\left(Q_h \times T_{lp}\right)\right]^{0.728} \times 5\%$

$$LPC = Q_B \times C_P \times \left(T_{lp} + T_{dp}\right) \times 50\%$$

— The average cost of evacuation and damage payment per one person is LKR 5000
— Downtime of the pipeline is one week for reparations

4.1 Elaboration of the results of simulation

Following results were generated during the simulation process and their graphs were acquired from the FLACS® Run Manager. As it can be seen from Figure 4.3, the pressure generated is not severe. It is slightly higher than the atmospheric pressure and therefore has no considerable effect due to high pressure. Figure 4.4 shows the reduction of fuel mass with respect to time. It is clear that the combustion process is very quick, and the flames tend to go into the pipeline which subsequently causes an explosion. At this point, we can decide whether an explosion happens. It is obvious that a jet fire will not cause any big pressure pulse which causes a considerable effect on the surroundings and people. The velocity of the air is affected a little but not considerably high. Figure 4.4 shows the velocity distribution around the leak. It is again obvious that there are no unusual changes in velocity due to jet fire, for the given parameters. Nevertheless, it is presented to illustrate the procedure for potential applications.

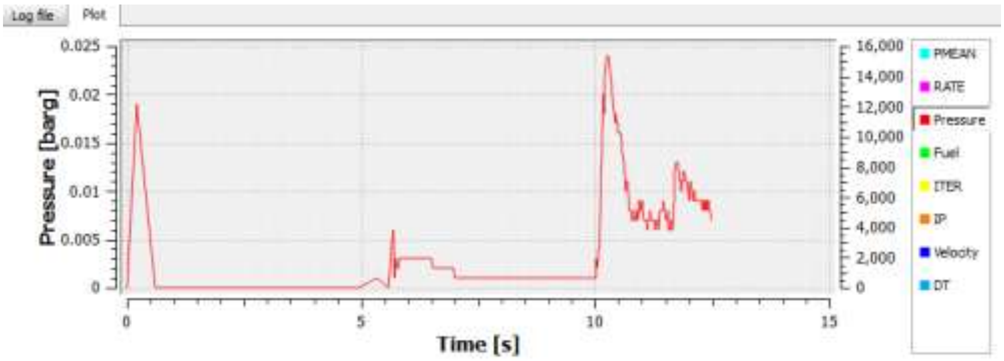

Figure 4.3: Pressure vs. time

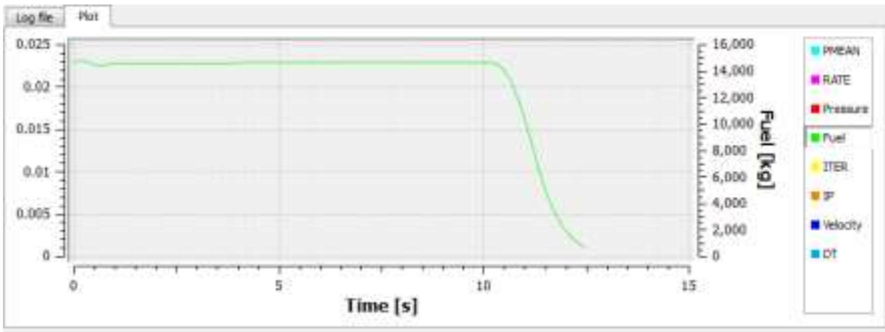

Figure 4.4: Fuel content vs. time

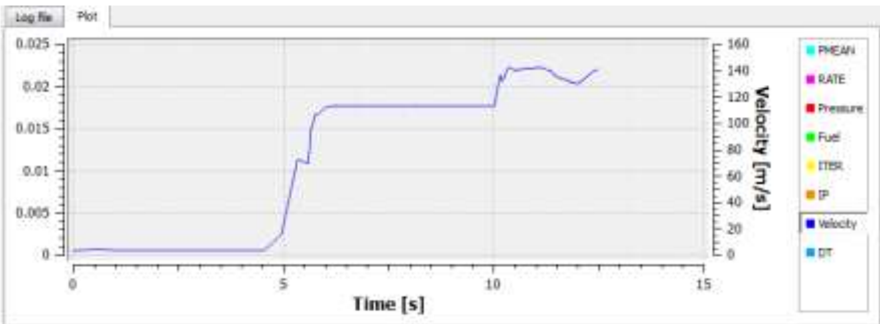

Figure 4.5: Velocity vs. time

Figures 4.3 to 4.5 were generated through FLACS® Run Manager and after Post Processing using Flowis®. It can be seen that the formation of a hydrocarbon cloud is very small as the combustion process is instantaneous. Further, it is possible to acquire an Iso-surface plot as shown in Figure 13. This will be useful to study the effect on people and properties in more severe scenarios. As illustrated in Figure 3.9, it is clear that the temperature within the 10 m region is extremely high sometime after the ignition. Severe burns can occur even during the jet fire stage. Figure 4.8, and Figure 4.9 represent the velocity distribution about the jet fire region and it proves that it is not that critical.

Therefore, it is clear that the CFD simulation is a very versatile tool in determining the consequences. The software is a highly recognized industrially used tool for the analysis of explosions and different types of fires. It provides a special feature that calculates the probability of deaths for toxic substances. In this study, the simulation showed a zero probability of death due to toxicity as expected.

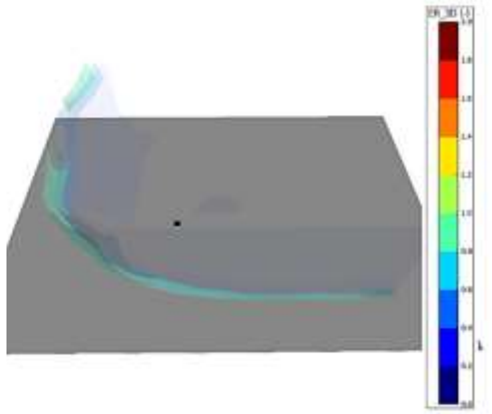

Figure 4.6: Iso-surface diagram for equivalent ratio

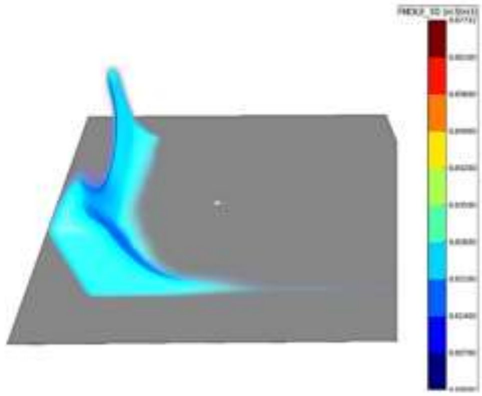

Figure 4.7: FMOLE_ Propane

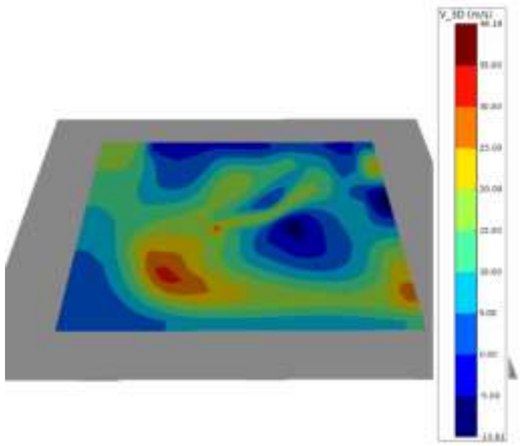

Figure 4.8: Velocity distribution

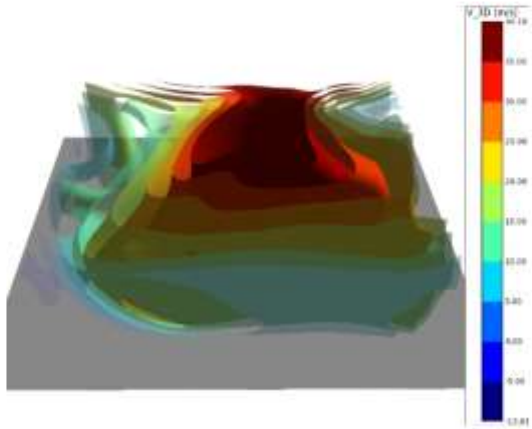

Figure 4.9: Velocity distribution in 3D space

As further developments of the proposed methodology, the following improvements can be suggested. As suggested in [31], further stages in overall risk management concern the assessment of the acceptability of such events and the analysis of the cost and benefit of proposed risk reduction measures. For this practice, it is required to define a comprehensive risk criterion by the regulatory bodies. An example of this can be found in [32].

As a further extension for this project, the Total Risk can be obtained by summing up the results of the risk calculations for Jet fire, Flash Fire, Cloud Formation, and Explosion. To put it another way, total risk equals the sum of the risks evaluated for each scenario.

In addition to the Individual and Societal Risks, Injury risk, and Propagation risk also can be presented. According to [33], Injury risk is the likelihood of humans being injured at various sites along the pipeline as a result of the identical scenarios that were used to calculate individual fatality risk. Propagation Risk, as they define it, is the likelihood that an event at a pipeline may spread to nearby industrial locations.

Looking at the monetary values of the risk calculations for the given scenario, it is obvious that the major loss is due to loss of production. Looking at the impact on a financial loss like loss of production, the authorities can get inputs to make decisions using the methodology proposed in this study.

4.2 Quantification of effects due to a potential explosion

As per the given parameters, the burning rate of jet fire is quite high and there is a possible backfire effect. Therefore, the following equation (18, and (19 are used to quantify the effect due to the explosion. For the risk assessment of the explosion scenario, TNT Equivalent method can be used.

$$m_{TNT} = \frac{\propto H_C \dot{m}_v}{4600} \tag{18}$$

$$\lambda = \frac{r}{m_{TNT}} \tag{19}$$

As a more reliable alternative method, a series of simulations for Flashfire, Explosion and cloud formation can be performed using FLACS® software.

CHAPTER 5 : CONCLUSION

The present study presents a framework that can be applied to determine the dynamic risk of LPG offloading pipeline in Sri Lanka. The dynamic variations in probabilities of failure can be determined using the proposed Bayesian network approach, which can provide reliable inputs to the decision-making processes. This has the potential to minimize human errors and random decision-making during times of crisis.

On the other hand, this approach facilitates the prognosis and diagnosis of faults based on the evidence available. More importantly, the system introduced is a continually learning system because it can work as storage of tacit knowledge of experts to some extent. This part is done using the continual improvement of the conditional probability tables.

A case study was presented to trial the framework presented. The estimated risk associated with the defined accident scenario was approximately 9 billion rupees. This estimation can be further refined by updating the probability values as well as respective consequences.

Regarding the consequence analysis, commercial CFD code can be effectively used in determining the probability of deaths, and temperature effects, environmental impact, and pressure pulse effects on the surroundings. This provides a reliable input in making decisions on surrounding land usage in future events and making decisions in the evacuation of people during an event of an accident.

As further improvements, a procedure to gather information from the workforce, management, experts, and the community can be developed. The knowledge gathered through that process can be used to train the Bayesian network to make the analysis more reliable.

Also, by doing a series of Bayesian network applications and FLACS® simulations, one can develop 'Risk Contours' about the length of the pipeline so it will be a valuable development for decision-makers in land usage.

A comprehensive 'Risk Criteria for Land Use Safety Planning' needs to be developed based on an approach similar to the proposed approach in the present study to make the decisions and recommendations more logical and less subjective.

REFERENCES

[1] PHMSA, "Incident Statistics | PHMSA," 2017. https://www.phmsa.dot.gov/hazmat-program-management-data-and-statistics/data-operations/incident-statistics (accessed Jan. 03, 2018).

[2] J. Stephens, "Careless Workers Blamed for Explosion," *Observer Reporter*, p. 122, 1989.

[3] F. Heinz, "Milford Pipeline Fire May Burn for 36 Hours," *NBCDFW*, 2013. http://www.nbcdfw.com/news/.

[4] NACE, "Investigation report on San Bruno pipeline rupture cites lax safety approach , inadequate oversight as probable causes of accident," *Mater. Perform.*, vol. 50, no. August, pp. 18–19, 2011.

[5] A. Aljaroudi, F. Khan, A. Akinturk, M. Haddara, and P. Thodi, "Risk assessment of offshore crude oil pipeline failure," *J. Loss Prev. Process Ind.*, vol. 37, pp. 101–109, 2015, doi: 10.1016/j.jlp.2015.07.004.

[6] C. T. Yeo, J. Bhandari, R. Abbassi, V. Garaniya, S. Chai, and B. Shomali, "Dynamic risk analysis of offloading process in floating liquefied natural gas (FLNG) platform using Bayesian network," *J. Loss Prev. Process Ind.*, vol. 41, pp. 259–269, 2016, doi: 10.1016/j.jlp.2016.04.002.

[7] V. Villa, N. Paltrinieri, F. Khan, and V. Cozzani, "Towards dynamic risk analysis: A review of the risk assessment approach and its limitations in the chemical process industry," *Saf. Sci.*, vol. 89, pp. 77–93, 2016, doi: 10.1016/j.ssci.2016.06.002.

[8] K. H. Kalantarnia, M, F I Khan, "isk Assessment and Management Using Accident Precursors Modeling in Offshore Process Operation," in *International Conference on Offshore Mechanics and Arctic Engineering*, 2009, pp. 793– 802.

[9] M. Kalantarnia, F. Khan, and K. Hawboldt, "Modelling of BP Texas City refinery accident using dynamic risk assessment approach," *Process Saf. Environ. Prot.*, vol. 88, no. 3, pp. 191–199, 2010, doi: 10.1016/j.psep.2010.01.004.

[10] N. Paltrinieri, A. Tugnoli, J. Buston, M. Wardman, and V. Cozzani, "Dynamic Procedure for Atypical Scenarios Identification (DyPASI): A new systematic HAZID tool," *J. Loss Prev. Process Ind.*, vol. 26, no. 4, pp. 683–695, 2013, doi: 10.1016/j.jlp.2013.01.006.

[11] O. Zadakbar, S. Imtiaz, and F. Khan, "Dynamic Risk Assessment and Fault Detection Using Principal Component Analysis," *Ind. Eng. Chem. Res.*, vol. 52, no. 2, pp. 809–816, 2013, doi: 10.1021/ie202880w.

[12] N. Paltrinieri, F. Khan, P. Amyotte, and V. Cozzani, "Dynamic approach to risk management: Application to the Hoeganaes metal dust accidents," *Process Saf. Environ. Prot.*, vol. 92, no. 6, pp. 669–679, 2014, doi: 10.1016/j.psep.2013.11.008.

[13] N. Paltrinieri and G. Scarponi, "Addressing Dynamic Risk in the Petroleum Industry by Means of Innovative Analysis Solutions," *Chem. Eng. Trans.*, vol. 36, pp. 451–456, 2014, doi: 10.3303/CET1436076.

[14] N. Khakzad, F. Khan, and P. Amyotte, "Dynamic risk analysis using bow-tie approach," *Reliab. Eng. Syst. Saf.*, vol. 104, pp. 36–44, 2012, doi: 10.1016/j.ress.2012.04.003.

[15] R. Ferdous, F. Khan, R. Sadiq, P. Amyotte, and B. Veitch, "Analyzing system safety and risks under uncertainty using a bow-tie diagram: An innovative approach," *Process Saf. Environ. Prot.*, vol. 91, no. 1–2, pp. 1–18, 2013, doi: 10.1016/j.psep.2011.08.010.

[16] A. Badreddine and N. Ben Amor, "A Bayesian approach to construct bow tie diagrams for risk evaluation," *Process Saf. Environ. Prot.*, vol. 91, no. 3, pp. 159–171, 2013, doi: 10.1016/j.psep.2012.03.005.

[17] F. Ruggeri, F. Faltin, and R. Kenett, "Bayesian networks," *Encycl. Stat. Qual. Reliab.*, vol. 1, no. 1, p. 4, 2007, doi: 10.1002/wics.48.

[18] R. E. Neapolitan, "Learning Bayesian networks," *Int. J. Data Min. Bioinform.*, vol. 4, pp. 505–19, 2010, doi: 10.1016/j.jbi.2010.03.005.

[19] J. Wu, R. Zhou, S. Xu, and Z. Wu, "Probabilistic analysis of natural gas pipeline network accident based on Bayesian network," *J. Loss Prev. Process Ind.*, vol. 46, pp. 126–136, 2017, doi: 10.1016/j.jlp.2017.01.025.

[20] D. Husmeier, R. Dybowski, and S. Roberts, *Probabilistic Modeling in Bioinformatics and Medical Informatics*, 1st ed. United States of America: Springer, 2005.

[21] N. Khakzad, F. Khan, and P. Amyotte, "Dynamic Safety analysis of process systems by mapping bow-tie into Bayesian network Dynamic safety analysis of process systems by mapping," *Process Saf. Environ. Prot.*, no. January, 2013, doi: 10.1016/j.psep.2012.01.005.

[22] Gexcon AS, *FLACS v10.5 User's Manual*. Doxygen, Norway, 2016.

[23] K. Nilsson, "Preliminary Hazard Analysis of The Natural Gas Delivery Pipeline Between Young And Bomen in NSW," 2009.

[24] S. N. Jonkman, "The Use of Individual and Societal Risk Criteria Within the Dutch Flood Safety Policy-Nationwide Estimates of Societal Risk and Policy Applications," *Risk Anal.*, vol. 31, no. 2, pp. 282–300, 2011, doi:

10.1111/j.1539-6924.2010.01502.x.

[25] J. M. Schork, “Summary: Societal risk criteria and pipelines,” *Process Saf. Prog.*, vol. 31, no. 4, pp. 409–410, Dec. 2012, doi: 10.1002/prs.11522.

[26] A. Franks, “A Simplified Approach to Estimating Individual Risk A Simplified Approach to Estimating Individual Risk,” *Heal. Saf. Exec.*, pp. 3–54, 2004.

[27] D. Crowl and L. Joseph, *Chemical Process Safety*, 2nd ed. New Jersey: Prentice Hall PTR, 2009.

[28] RPS, “BowtieXP,” 2018. http://www.bowtiexp.com.au/software/bowtiexp-standard (accessed Feb. 10, 2018).

[29] OREDA, *OREDA-Offshore Reliability Data Handbook*, 4th ed. OREDA Participants, 2002.

[30] C. Yeo, J. Bhandari, R. Abbassi, V. Garaniya, and S. Chai, “Journal of Loss Prevention in the Process Industries Dynamic risk analysis of of fl oading process in fl oating lique fi ed natural gas (FLNG) platform using Bayesian network,” vol. 41, pp. 259–269, 2016.

[31] B. R. T. Hill, B. C. Fimeche, A. D. L. Limited, and C. Cb, “Pipelines risk analysis,” pp. 657–670, 1935.

[32] G. of NSW, “Risk Criteria for Land Use Safety Planning,” NSW, 2011. [Online]. Available: www.planning.nsw.gov.au.

[33] K. Nilsson, “Preliminary Hazard Analysis of the Natural Gas Delivery Pipeline Between Young and Bomen in NSW,” Berowra Heights, 2009. [Online]. Available: https://www.apa.com.au.

ANNEXURE

Parameters of FLACS® simulation

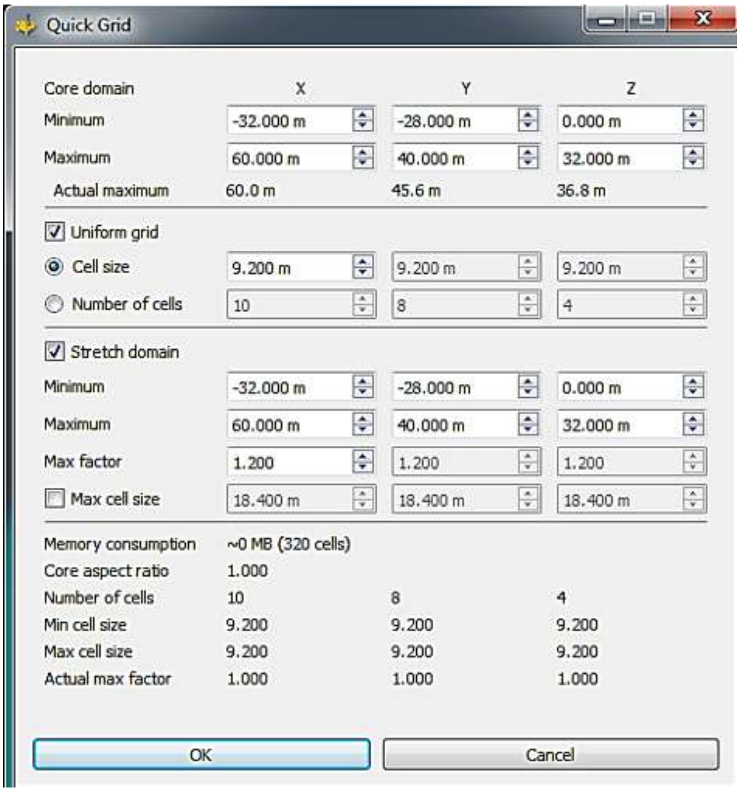

Figure A.1: The definition of the grid

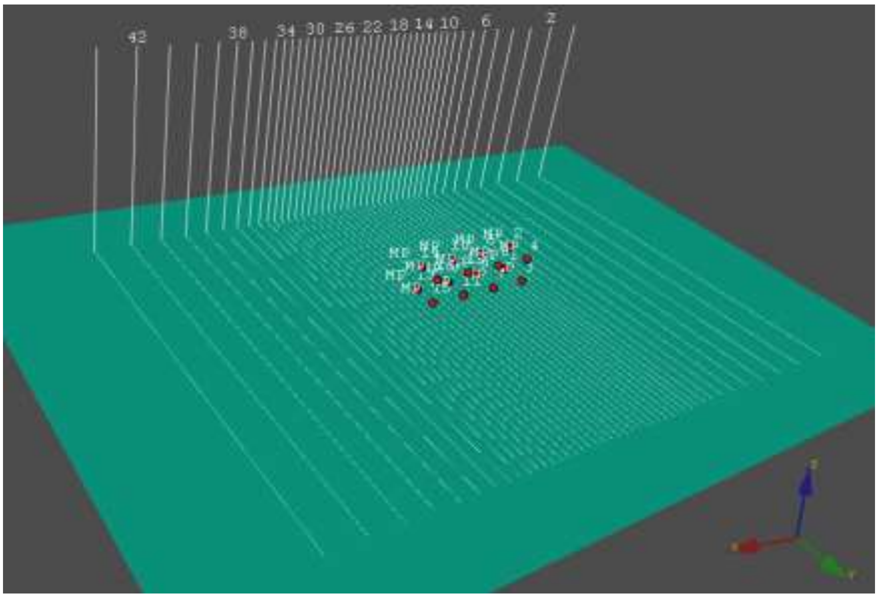

Figure A.2: The computational Domain

Table A.1: Parameters of single field 3D output

Parameter	**Unit**
Fuel Mole Fraction (FMOLE)	(m^3/m^3)
Temperature (T)	K
Radiation	kW/m^2
Velocity Vector (VVEC)	m/s
Equivalence ratio (ER)	-
Pressure impulse	Pa s

Further, under 'Parameters of Simulation and output control', the following parameters were set.

Table A.2: Parameters of Simulation and output control

Parameter	**Value**	**Unit**
Maximum time	45	s
Courant-Friedrich-Levy number based on sound velocity (CFLC)	100	-
Courant-Friedrich-Levy number based on fluid flow velocity (CFLV)	2	-
A parameter that may be used to determine how often data for scalar-time plots are written to the results file during a simulation (MODD)	1	-
A parameter that may be used to determine how often data for field plots are written to file during a simulation (NPLOT)	-1	-
The time interval (in seconds) for field output (DPLOT)	2.5	-

The lower boundaries in X-, Y-, and Z-direction are denoted by XLO, YLO and ZLO respectively, and the upper boundaries likewise by XHI, YHI, ZHI. [22]

Table A.3: Initial Conditions

Parameter	**Value**	**Unit**
Characteristic Velocity	0.1	m s^{-1}
Relative turbulence intensity	0.1	-
Turbulence Length scale	0.01	-
Temperature	20	°C
Ambient Pressure	100000	Pa
Ground height	0	m
Ground Roughness	0.01	m
Reference height	10	m
Canopy height	0	m
Pasquill class	D	-
Ground roughness condition	Rural	-

Table A.4: Parameters of Boundary Conditions

Parameter	**Condition**
XLO	Wind
YLO	Nozzle
ZLO	Wind
YHI	Nozzle
ZLO	Nozzle
ZHI	Nozzle

Table A.5: Gas composition and volume (Volume Fractions)

Species	**Percentage by volume (%)**
Propane	50%
Butane	50%

Table A.6: Details of the Leak

Parameter	**Value**	**Unit**
Type	Jet	-
Position	<6, 5.05, 2.38>	-
Open Sides	+X	-
Duration	180	s
Leak Options	**Value**	**Unit**
Area	0.126	m^2
Mas flow Rate	2.74E+2	kg/s
Velocity	0	ms^{-1}
Relative Turbulence	0.2	

The ignition time was kept at 10 s. The point of ignition was determined using the flammability diagram and initial simulation for dispersion.

Table A.7: Gas monitor region

Property	**Value**
Position	<0, 0, 0>
Size	(28, 12, 8) m