PROBABILISTIC RISK ASSESSMENT OF OFFSHORE PRODUCTION PLATFORM BY BAYESIAN NETWORK APPLICATION TO HAZOP AND BOW-TIE STUDIES

A Thesis

by

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ABSTRACT

Successful risk management in an offshore oil and gas production platform requires accurate and up-to-date probability of occurrence of process safety events. Traditional hazard identification and risk assessment techniques such as HAZOP and Bow-tie analysis are the well-accepted methods in the oil and gas industry. However, these methods cannot effectively cope with dynamic operating environments, which continuously affect the estimated probabilities and risks. Factors such as variations in operating conditions, equipment deterioration, and personnel competency affect the safety barriers' performances and consequently alter the probability of occurrence of the process safety events. In the past decade, Bayesian network has gained significant attention in the process safety area because of its ability to include new information. It has been integrated with various traditional risk assessment techniques, including HAZOP and Bow-tie studies, extending their capabilities to consider operational variations and revise the probability of occurrence of the process safety events.

This research applies Bayesian network to HAZOP and Bow-tie studies for a loss of primary containment of high pressure hydrocarbon gas from an export gas compressor system. Eleven process safety indicators such as loss of primary containment and maintenance backlog are integrated into the models to reflect changes in safety barriers' performances. The integration process is realized by aggregating multiple specific

indicators into three element indicators, which are mechanical integrity, operational integrity, and personnel integrity.

The updated probabilities from the developed HAZOP-BN and Bow-tie-BN models are considerably different due to dissimilarity in hazard identification approaches and the BN development process. However, both models provide consistent results with respect to the degree of effect from indicators' input. Therefore, it is prudent for a company to implement the HAZOP-BN or Bow-tie-BN and use process safety indicator data to improve its risk assessment capability. Overtime, probability estimation can be perfected through integration of additional information with the systematic risk assessment method.

DEDICATION

To my parents,

Pornjai Chaiwat and Chalit Chaiwat

To my sister,

Pamanee Chaiwat

To my girlfriend,

Panunya Charoensawadpong

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NOMENCLATURE

API	American Petroleum Institute
BN	Bayesian Network
BTU	British Thermal Unit
CCPS	Center for Chemical Process Safety
CPT	Conditional Probability Table
CSB	Chemical Safety and Hazard Investigation Board
DAG	Directed Acyclic Graph
DORA	Dynamic Operational Risk Assessment
EIA	Energy Information Administration
EIReDA	European Industry Reliability Data Bank
ETA	Event Tree Analysis
FTA	Fault Tree Analysis
GeNIe	Graphical Network Interface
H&MB	Heat and Material Balance
HAZOP	Hazard and Operability
ICI	Imperial Chemical Industries
IOGP	International Association of Oil & Gas Producers
LNG	Liquefied Natural Gas
LOPA	Layer of Protection Analysis
LOPC	Loss of Primary Containment

LTI	Loss Time Injury
MHIDAS	Major Hazard Incident Data Service
MKOPSC	Mary Kay O'Connor Process Safety Center
NDT	Non-destructive Test
OREDA	Offshore Reliability Data
P&ID	Piping and Instrumentation Diagram
PFD	Process Flow Diagram
PICAH	Pressure Indicator Control Alarm High
PM	Preventive Maintenance
PRD	Pressure Relief Device
PSE	Process Safety Event
PSI	Process Safety Indicator
PSV	Pressure Safety Valve
RBI	Risk-based Inspection
RP	Recommended Practice
SCADA	Supervisory Control and Data Acquisition
SCE	Safety Critical Element
SDV	Shut-down Valve
SIS	Safety Instrumented System
TSO	Tight Shut-off
WHP	Wellhead Platform
WOAD	World Offshore Accident Database

TABLE OF CONTENTS

Page

ABSTRACT ii

DEDICATION iv

ACKNOWLEDGEMENTS v

NOMENCLATURE vii

TABLE OF CONTENTS ix

LIST OF FIGURES xi

LIST OF TABLES xiv

1. INTRODUCTION 1

1.1. Background 1
1.2. Problem Statement 11
1.3. Research Objectives 12
1.4. Previous Research at MKOPSC 12
1.5. Organization of this Thesis 14

2. LITERATURE REVIEW 15

2.1. Hazard Identification Techniques 16
2.2. Bayesian Network Application to HAZOP and Bow-tie Studies 23
2.3. Process Safety Indicators 28
2.4. Process Safety Indicators and Bayesian Network 37

3. METHODOLOGY 40

3.1. HAZOP-BN Development 41
3.2. Bow-tie-BN Development 51
3.3. Process Safety Indicators Integration 60
3.4. Prior Probability Definition 63
3.5. Bayesian Network Algorithm 106

4. RESULTS AND DISCUSSIONS 107

4.1. HAZOP-BN Model Results 107
4.2. Bow-tie-BN Model Results 114
4.3. Comparison Between HAZOP-BN and Bow-tie-BN Model 119

5. CONCLUSIONS AND FUTURE WORKS 122

REFERENCES 124

LIST OF FIGURES

Page

Figure 1: Global Energy Production by Sources (Colombano & Colombano, 2015) 2

Figure 2: An Example Offshore Production Facility ("Offshore Production Platform," 2011).. 4

Figure 3: Typical Risk Assessment Techniques in Project Life Cycle............................. 7

Figure 4: The Number of Publications Given Search Terms “Bayesian Network” and “Process Safety” (Without Quote) in the Title, Abstract, or Keywords (Scopus, 2016).. 11

Figure 5: Example Fault Tree for Pressure Tank Rupture Event (Mannan, 2012).......... 18

Figure 6: Example Event Tree for Operator Response to Nuclear Reactor Transient (Mannan, 2012) 20

Figure 7: Simple Representation of a Bow-tie Diagram... 22

Figure 8: Bow-tie (left) and BN (right) model for Gasoline Release Scenario, Reproduced from (Khakzad et al., 2013) 25

Figure 9: Schematic of a Tank System, Reproduced from (Wang et al., 2015).............. 27

Figure 10: Bayesian Network Model for a Tank System Shown in Figure 9, Reproduced from (Wang et al., 2015).. 27

Figure 11: Dynamic BN Construction Mechanism, Reproduced from (Hu et al., 2010) 28

Figure 12: Hierarchical Process for Indicators Aggregation as Defined by Hassan (2010), Reproduced from (H. Pasman & Rogers, 2014)................................. 38

Figure 13: Continuous Bayesian Network with Indicators Integration, Reproduced from (H. Pasman & Rogers, 2014).. 39

Figure 14: Research Methodology.. 41

Figure 15: HAZOP-BN Model Constructed using Information Extracted from a Single HAZOP Entry Shown in Table 3 46

Figure 16: HAZOP-BN Model Illustrating the LOPC Event Caused by Overpressure .. 47

Figure 17: HAZOP-BN Model Illustrating the LOPC Event Caused by Corrosion........ 47

Figure 18: HAZOP-BN Model Illustrating the LOPC Event Caused by Third Party (Ship) Impact 48

Figure 19: HAZOP-BN Model Illustrating the LOPC Event Caused by High Temperature 48

Figure 20: HAZOP-BN Model Illustrating the LOPC Event Caused by Low Temperature Embrittlement 49

Figure 21: HAZOP-BN Model Illustrating the Consequence Developed from the LOPC Event 49

Figure 22: Overview of the HAZOP-BN Model for the LOPC Event 50

Figure 23: Partial Bow-tie Diagram of the LOPC Event Showing Internal Corrosion as a Threat 52

Figure 24: Bow-tie-BN Model Illustrating the LOPC Event with Internal Corrosion as a Threat 53

Figure 25: Bow-tie-BN Model Illustrating the LOPC Event with External Corrosion as a Threat 54

Figure 26: Bow-tie-BN Model Illustrating the LOPC Event with Overpressure as a Threat 54

Figure 27: Bow-tie-BN Model Illustrating the LOPC Event with Leakage from Flanges and Valves as a Threat 55

Figure 28: Bow-tie-BN Model Illustrating the LOPC Event with Mechanical Failure as a Threat 55

Figure 29: Bow-tie-BN Model Illustrating the LOPC Event with Internal Erosion as a Threat 56

Figure 30: Bow-tie-BN Model Illustrating the LOPC Event with Other Threats 57

Figure 31: Bow-tie-BN Model Illustrating the Consequences Developed from the LOPC Event 58

Figure 32: Overview of the Bow-tie-BN Model for the LOPC Event 59

Figure 33: Histogram of the Number of Unplanned Process Shutdown Indicator 70

Figure 34: Histogram of the Number of Unplanned Process Shutdown Indicator and the Gamma Distribution 72

Figure 35: BN Model Illustrating the Aggregation of PSIs into Mechanical Integrity Element 75

Figure 36: BN Model Illustrating the Aggregation of PSIs into Operational Integrity Element 76

Figure 37: BN Model Illustrating the Aggregation of PSIs into Personnel Integrity Element 76

Figure 38: Overview of the HAZOP-BN Model for the LOPC Event with PSIs Integration 78

Figure 39: Overview of the Bow-tie-BN Model for the LOPC Event with PSIs Integration 79

Figure 40: Histogram Illustrating the Number of Unplanned Process Shutdown per Month on the X-Axis and the Probability of Occurrence on the Y-Axis 108

Figure 41: Histogram Illustrating Discretized Distribution for Number of Unplanned Process Shutdown Indicator 108

Figure 42: Initial Probability Distribution of the LOPC Event (Per Month) from the HAZOP-BN Model 110

Figure 43: Posterior Probability of Occurrence of the LOPC Event from HAZOP-BN Model 112

Figure 44: Initial Probability Distribution of the LOPC Event (Per Month) from the Bow-tie-BN Model 115

Figure 45: Posterior Probability of Occurrence of the LOPC Event from Bow-tie-BN Model 117

Figure 46: Posterior Probability of Occurrence of the LOPC Event from HAZOP-BN and Bow-tie-BN Model 120

LIST OF TABLES

Page

Table 1: Typical HAZOP Result Table 28

Table 2: Process Safety Indicators Definition 34

Table 3: Partial HAZOP Result where LOPC of Hydrocarbon Gas Scenario is Identified in the Consequence Column 45

Table 4: Process Safety Indicator Categorization 62

Table 5: Process Safety Indicator Data for Period 1-6 66

Table 6: Process Safety Indicator Data for Period 7-12 67

Table 7: Process Safety Indicator Data for Period 13-18 68

Table 8: Process Safety Indicator Data for Period 19-24 69

Table 9: Prior Distribution Defined for Each Process Safety Indicator.......................... 74

Table 10: Defined Equation for HAZOP-BN Model... 80

Table 11: Defined Equation for Bow-tie-BN Model 93

Table 12: Process Safety Indicators Discretization Results... 109

Table 13: Mean and Standard Deviation of the LOPC Event in HAZOP-BN Model after 10 Trials 111

Table 14: Mean and Standard Deviation of the LOPC Event in Bow-tie-BN Model after 10 Trials 116

1. INTRODUCTION

1.1. Background

Oil and gas industry plays an important part in our daily life. The fossil resources provide not only the energy, but also the raw materials for downstream chemical industry to make consumer products such as construction materials, textiles, medicine, etc. In the energy industry, the world primary energy production[1] increased from 245 quadrillion BTU in 1973 to 518 quadrillion BTU in 2011, or about 2 percent annual growth rate (*Basic petroleum data book, petroleum industry statistics*, 2015). In 2012, the annual oil and gas production of the world accounted for 57% of the total energy production with coal, nuclear, hydroelectric, biofuels, and renewable sources adding to the rest 43% as shown in Figure 1 (Colombano & Colombano, 2015). According to the U.S. Energy Information Administration (EIA), the world consumed 90 million barrels of liquid fuels and 120 trillion cubic feet of natural gas each day in 2012 and it is being projected that both oil and gas will continue to play an important role in the energy industry until 2040 (*International Energy Outlook 2016*, 2016).

Fossil fuels provide numerous benefits, but the process of extracting them from the ground is complex and involves multiple hazards. In general, oil and gas are

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[1] Includes only crude oil, lease condensate, natural gas plant liquids, dry natural gas, coal, hydroelectric, nuclear, geothermal, solar, wind, wood, and waste electric power

produced by drilling into the rock formation until the production zone is reached. In a conventional reservoir, an internal pressure of the reservoir is adequate in delivering the fluid to processing facility on the surface. Over time, these conventional resources are depleted, resulting in the moving of the industry toward enhanced oil recovery and nonconventional resources such as deep water, oil sand, and shale gas. The process to extract these unconventional resources requires complex tools and sophisticated systems to assist hydrocarbons in moving from the porous structure of the rock formation up to the processing facility.

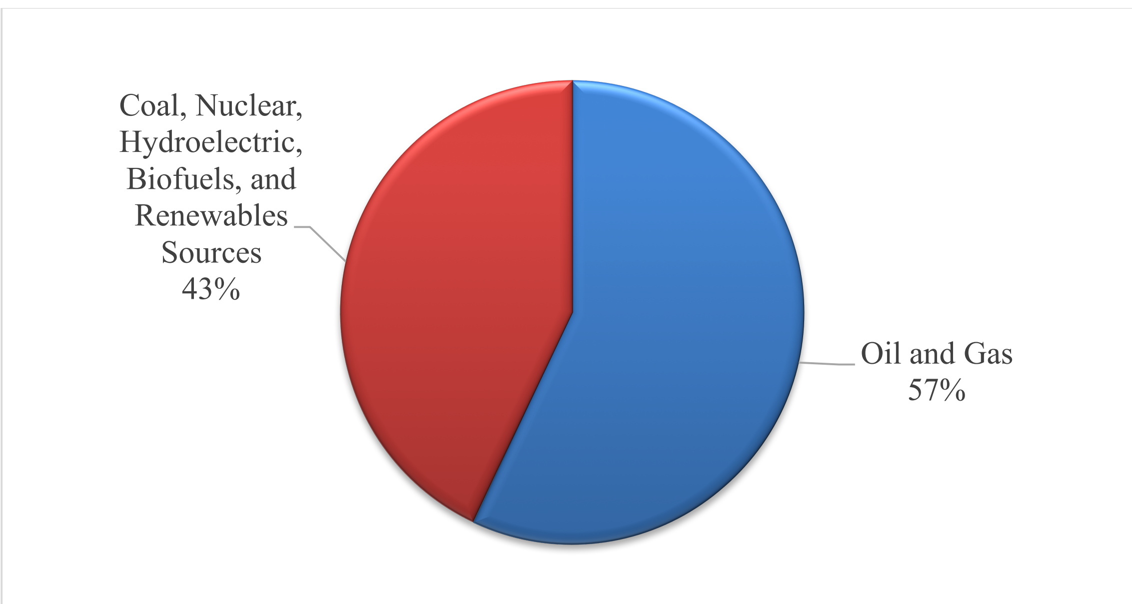

Figure 1: Global Energy Production by Sources (Colombano & Colombano, 2015)

In the U.S., 30% of crude oil and condensate and 10% of natural gas are produced by an offshore section (*Basic petroleum data book, petroleum industry statistics*, 2015). These offshore production facilities tend to have limited space to reduce a capital investment. An example offshore production facility is illustrated in Figure 2. The congested and confined space impacts separation distances between ignition sources and potential areas that may contain flammable materials. As a consequence, offshore facilities may present higher process risks, if not properly managed, from higher explosion overpressure or evacuation impairment. Other hazards associated with oil and gas exploration and production operations include high pressure, high temperature, toxic liquid, toxic gas, working at height, transportation, asphyxiation, and high noise level. These hazards present a significant risk to the operation that could result in personnel injuries, asset damages, and environmental pollutions. Hence, the risk needs to be managed in order to prevent a process safety incident and increase production efficiency.

Figure 2: An Example Offshore Production Facility ("Offshore Production Platform," 2011)

Traditional risk management is performed using hazard or scenario identification methods in order to detect high-risk processes and provide adequate risk reduction measures. HAZOP and Bow-tie methods were introduced in the early 1970s and 1979, respectively, and are well-practiced in the industry today (H. Pasman, 2015a). The HAZOP technique is rigorous and thorough in identifying failure scenarios following a process line on a piping and instrumentation diagram (P&ID). Guidewords are applied to process parameters resulted in a deviation from the design intent for each system of interest. The process is repeated until all the systems are covered. The Bow-tie technique is a combination of fault tree analysis (FTA) and event tree analysis (ETA), where the top event acts as a pivot point, connecting the fault tree and event tree together. Each Bow-tie represents one top event and multiple threats that could lead to that top event are identified and listed on the left side of the top event. Preventive barriers are added or recommended for each threat to inhibit a scenario from developing to the top event. On the right side of the top event is the event tree which displays possible consequences that may occur following the top event. Likewise, mitigation barriers are provided or recommended for each consequence to alleviate or mitigate a consequence once the top event has occurred. Although these techniques are comprehensive in the scenario identification, their strength makes it difficult to re-evaluate and cope with dynamic changes in day-to-day operation such as equipment degradation, weather conditions, and barrier deterioration. Completing a typical HAZOP or Bow-tie workshop for an offshore central processing facility could take several weeks. In addition, the traditional methods do not consider human reliability, safety culture, and near miss data.

Multiple risk assessments are made along the developmental phase of a project and throughout the operational phase of a facility in an attempt to prevent incident as shown in Figure 3. Nonetheless, historical data have shown many process safety incidents in the past. The World Offshore Accident Database (WOAD) listed over 6,000 incidents from 1970 to date (DNV, 2016) in which 553 incidents between 1970 and 2007 resulted in one or more fatalities (IOGP, 2011b). Some of the major offshore incidents are: FPSO P-48 fire in the Campos Basin in 2016 ("Petrobras' FPSO P-48 catches fire," 2016); Abkatun A platform fire in the Gulf of Mexico in 2016 ("Three dead after fire hits Pemex platform again," 2016); Azeri oil rig fire in the Caspian Sea in 2015 (Antidze, 2015); Mumbai High platform fire and explosion in the Arabian Sea in 2005 (Daley, 2013); and Piper Alpha fire and explosion in the North Sea in 1988 (CCPS, 2005). The Major Hazard Incident Data Service (MHIDAS) provided an even higher number for onshore chemical facilities totaling 13,502 incidents between 1970 and 2005 (IOGP, 2011b). The U.S. Chemical Safety Board (CSB), an independent federal agency, investigated 93 industrial chemical incidents and provided more than 784 recommendations. Recently completed investigations include: Macondo blowout and explosion in the Gulf of Mexico in 2010; West Fertilizer explosion and fire in 2013; Caribbean Petroleum Refining tank explosion and fire in 2009; Horsehead Holding Company fatal explosion and fire in 2010; Chevron refinery fire in 2012; Millard Refrigerated Services ammonia release in 2010; and US Ink fire in 2012 (CSB, 2016). The Macondo blowout incident resulted in 11 fatalities and an almost five million barrels of oil spill, which is considered to be the worst oil spill in the U.S. history. The results of CSB investigation indicate that preventive maintenance and emergency response and planning are among the most wanted safety improvements. These barriers have been known by the industry for decades. Thus, it could be deduced that the effectiveness of the existing barriers was not being monitored as they ought to, and therefore, creating weaknesses in the system. James Reason portrayed the safety barriers as slices of Swiss cheese with weaknesses shown as holes in the slices (H. Pasman, 2015a). Multiple holes lined up through layers of protection under implementation could eventually lead to an incident.

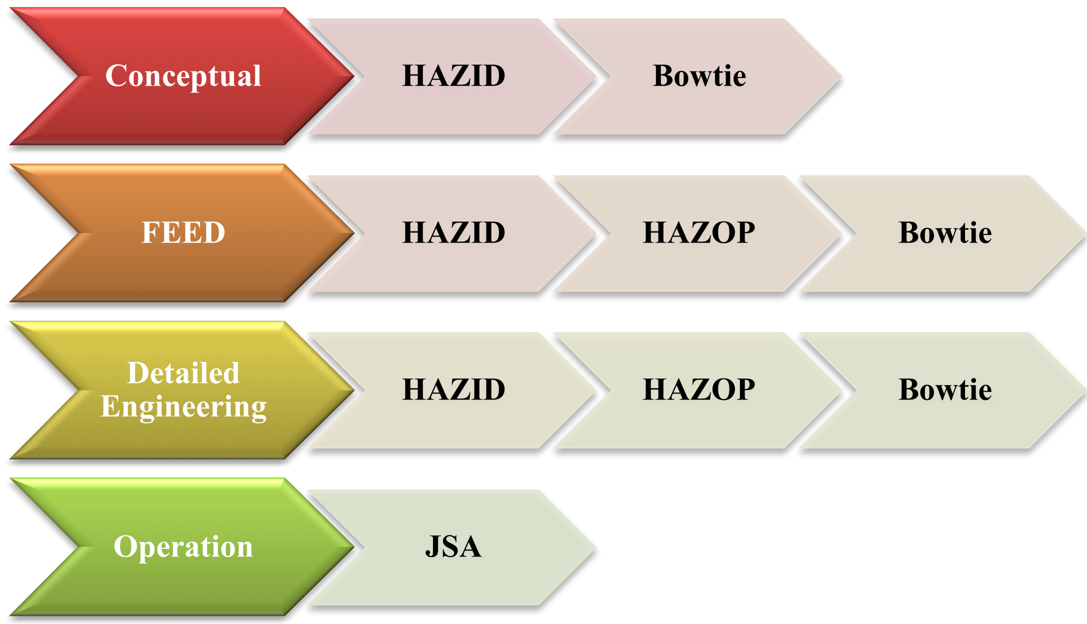

Figure 3: Typical Risk Assessment Techniques in Project Life Cycle

To ensure safety performances of a facility or a company, process safety indicators are also used as a supporting mechanism in process safety management. Works have been done to collect process safety lagging indicators, which are seen as the precursor to process safety incident. However, these lagging indicators are often zero due to low probability of occurrence. Leading indicators have been introduced to address status of the safety barriers. The aims were to improve barriers effectiveness and address any high potential event before it can escalate into major incident. The Center for Chemical Process Safety (CCPS) listed 350 process safety indicators that the operating company can collect to measure its performances (H. Pasman & Rogers, 2014). The International Association of Oil & Gas Producers (IOGP) collects process safety indicators data from more than 30 volunteering companies. The current report provides an analysis to process safety events that are tier 1 and tier 2, which are principally lagging indicators. Benchmarking results are also anonymously reported and a specific company can compare themselves with peers in the industry. Tier 3 and 4 process safety indicators, which are considered as leading indicators, are planned to be included in the future update of the report (IOGP, 2015). Thus far, the information collected serves as key performance indicators, representing the performance level of process safety, and help companies to keep track of their barriers' effectiveness. These indicator data are generally excluded from a probability estimation of possible hazardous scenarios when a quantitative risk analysis is performed. Thus, the calculated risk value may not reflect a true state of an operation.

Bayesian theorem is a statistical process. It is used to calculate conditional probability given information at hand. The theory was independently discovered by Reverend Thomas Bayes in 1763 and Pierre-Simon Laplace in 1812 (Stone, 2013). The simple form of Bayes theorem is shown in Equation 1, where: B is an event of interest; and A is newly observed information. P(A) and P(B) are the probability of event A and event B occurring, respectively. P(A|B) is a probability of event A given event B occurred; whereas P(B|A) is the probability of event B given event A is observed. The formula can be rewritten in probability terms as shown in Equation 2.

Equation 1: Bayes Theorem

$$P(B|A) = \frac{P(A|B)P(B)}{P(A)}$$

Equation 2: Bayes Theorem in Probability Terms (Stone, 2013)

$$Posterior\ probability = \frac{likelihood \times prior\ probability}{marginal\ likelihood}$$

The Bayesian methodology provides a means to incorporate soft evidences or new observations to improve the existing knowledge of an event of interest. Updated equipment conditions, safety critical elements state, or changes in organizational factor can be used as inputs to provide a better estimation of process safety event probability. The benefit of this method is not only a possible dynamic representation of the operational risk of a facility, but also an ability to identify critical contributing causes that lead to a catastrophic incident. Once the causes are identified, corrective measures can be made to reduce the probability of such an event.

Bayesian network (BN) is a graphical representation of stochastic variable nodes and their interrelated cause and effect relationships. It is considered as a subset of the directed acyclic graph (DAG) family. The directed arc or edge (shown as an arrow) originates from the parent node(s) and connected to the child node(s). However, as the arrow does not link back to the parent node(s), the relationship does not form a cycle (an effect cannot be its own cause). Each node signifies the probability of an event of interest occurring, such as dropped object, corrosion, or gas explosion. An arrow connecting any two nodes indicates a causal relationship, such as (a) between corrosion and loss of primary containment, and (b) between failure of platform crane and dropped object. A network can be made for a small corrosion inhibitor pumping unit or even for an entire offshore central processing facility. An application of BN with process safety has shown a rapid interest in the past decade, jumping from three documents in 2005 to 64 documents in 2015, as illustrated in Figure 4. It should be noted that the information was accessed on July 31st, 2016 and therefore might not reflect the total number of publications that might be published in the second half of the year. Many studies provide methodologies to transform traditional risk assessment into a BN to offer the ability to incorporate other factors from equipment and process conditions to human and organizational factors. The common objective of the conversion to BN is to enhance the methods' capability to handle dynamic risks in an operational environment as well as to ensure the effectiveness of barriers in place with an ultimate goal of preventing future process safety incidents. The methodology and the current progress in the dynamic risk assessment and BN applications are discussed in Section 2.

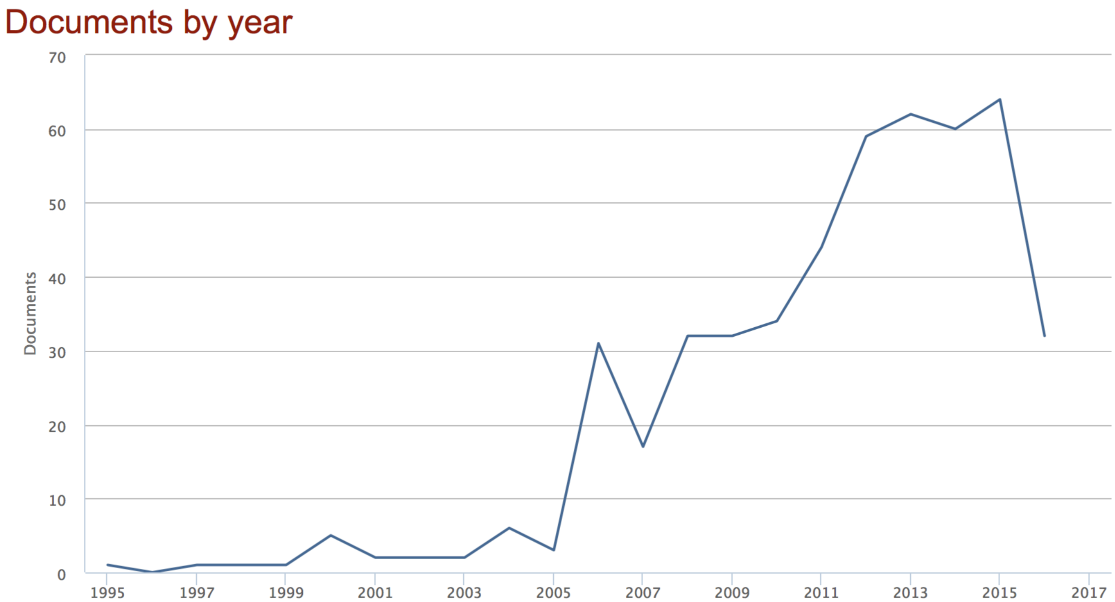

Figure 4: The Number of Publications Given Search Terms “Bayesian Network” and “Process Safety” (Without Quote) in the Title, Abstract, or Keywords (Scopus, 2016)

1.2. Problem Statement

In today’s oil and gas industry, HAZOP and Bow-tie are used as the standard procedures in hazard identification. Bayes theorem has been applied to those methods to enable risk updates using new information. Process safety indicators can be rationally exercised as inputs for a BN method. The current progress demonstrates indicators aggregation to Bow-tie-BN study. However, since the Bow-tie study is developed following other hazard identification studies such as HAZOP, the question is whether HAZOP-BN provides an adequate risk assessment or if Bow-tie-BN is a more preferred pathway. Therefore, it is prudent to determine the procedure that can provide the best solution in predicting a probability of occurrence of process safety events in the future.

1.3. Research Objectives

The primary goal of this research is to identify the best integrated procedure between HAZOP-BN and Bow-tie-BN to improve quantitative estimations of the process safety incident probability. In order to determine the best procedure, objectives of this research are to: -

- Develop a dynamic Bayesian network based on HAZOP and Bow-tie analysis;
- Devise a method for incorporating multiple process safety leading and lagging indicators as a precursor to a process safety event;
- Propose a new approach to assess risks for an offshore production facility.

1.4. Previous Research at MKOPSC

Dynamic risk assessment is a relatively new field of study; several researches were developed at the Mary Kay O'Connor Process Safety Center (MKOPSC). In 2007, Geun-Woong Yun pioneered Bayesian application for Layer of Protection Analysis (LOPA) using Microsoft Excel to compute the failure data of a LNG importation terminal. A Hazard and Operability (HAZOP) study was conducted to identify possible incident scenarios followed by a LOPA study to quantify the risk level of a facility. Next, generic failure data obtained from the Offshore Reliability Data (OREDA) and the European Industry Reliability Data Bank (EIReDA) were updated with LNG plant specific data using Bayesian-LOPA methodology. One of the recommendations was to incorporate fault tree and event tree analysis to achieve more reliable frequencies of initiating events (Yun, 2007).

Xiaole Yang introduced simulation-based dynamic operational risk assessment (DORA) that can be applied to both the design and operational phase of a facility. During the design period, DORA aids the design of a safety system to achieve as low as reasonably practicable risk level. In the operational phase, cost effective decision making is realized through an optimization of maintenance and inspection intervals. Bayesian updating was applied for reliability information of a system using plant specific or test data. Matlab software was selected for conducting a case study for level control in oil/gas separator. It was recommended that Bayesian application to a complex system is needed while a more sophisticated software may be required (Yang, 2010).

Shubharthi Barua applied BN to FTA for a holdup tank level control failure problem and observed the effect of different maintenance intervals on a probability of failure for components in the system. Prior probabilities from OREDA and CCPS were updated with the maintenance data. However, a discrete model was performed using point values instead of distributions. It is therefore recommended that continuous BN should be considered in the future (Barua, 2012).

1.5. Organization of this Thesis

This thesis is organized into five sections as follows: -

Section 1 provides background information that addresses the importance of fossil fuels in the global energy market. Risk management for the oil and gas industry is briefly discussed followed by the problem statement and research objectives.

Section 2 explores various literatures on hazard identification and risk assessment techniques, Bayesian network and its application to traditional risk assessment, and possible uses of process safety indicators information.

Section 3 describes detailed processes in the development of HAZOP-BN and Bow-tie-BN. List of process safety indicators collected by an energy company and the indicators aggregation method, followed by the prior probability definition procedure for the BN diagrams are explained. BN calculations for the completed model based on information provided by the indicators are included.

Section 4 presents the results obtained from both HAZOP-BN and Bow-tie-BN model. Analysis of the discrepancies between the results are elaborated.

Lastly, Section 5 provides conclusions and recommendations for future works.

2. LITERATURE REVIEW

Managing hazards and risks in oil and gas operations essentially comprised two key steps: 1) hazard identification; and 2) risk assessment and management (F. Khan, Rathnayaka, & Ahmed, 2015). The first step is generally qualitative with the goal of recognizing hazards that could develop into unsafe scenarios. The second step is to manage that hazardous scenario by assessing an associated risk level, which includes evaluating a magnitude of an event and estimating the probability that the event will occur. Following risk assessment, risk management can be performed by reducing the magnitude of a consequence or decreasing a probability of occurrence. A company's risk management framework encompasses multiple layers of hazard identification methods, risk assessment, and process safety management programs. Continuous efforts have been made to prevent and mitigate process safety incidents. However, the process safety incident statistics does not reflect a diminishing trend (F. Khan et al., 2015; H. Pasman, 2015a). In response to mitigate future incidents, a process safety indicator system was established as a precursor to major incidents similar to the practice in an occupational safety area (IOGP, 2011a). The modern process safety research is moving toward methods that can quantitatively incorporate dynamic behaviors of the operations, handle data scarcity, reduce uncertainties, and consider human and organizational aspects. This section provides the introduction to various hazard identification techniques, current progress in the Bayesian network application that enhances risk assessment and management capabilities and dynamically update the prior belief based on additional observations (H. Pasman, 2015b), and the adoption of process safety indicator data into a risk assessment method.

2.1. Hazard Identification Techniques

Many techniques are developed for identifying hazards and risk assessment. The simplest method is a process hazard checklist (Crowl & Louvar, 2011; F. I. Khan & Abbasi, 1998). Checklist questions are prepared in advance based on operation and maintenance history, lessons learned from previous incidents, regulatory or industrial standards requirements, or best practices in the industry (Barua, 2012). Once developed, an operator or a reviewer uses the list to address potential problem areas. The effectiveness of the method depends on the competency of the operator or reviewer implementing the checklist and the comprehensiveness of the checklist questions. The checklist may consist of hundreds or thousands of questions to cover the whole operations of the facility. Nonetheless, it is possible that some hazard scenarios might go unnoticed, thus limiting the applicability of the method to only during the preliminary stage of the project development. Hence, it is not recommended to be used as a replacement for a more complete hazard identification techniques (Crowl & Louvar, 2011; Yang, 2010).

A What-If analysis is a brainstorming session that identifies potential hazardous scenarios by asking questions with “what if …”. The questions are open-ended without specific rules. The method is relatively simple and does not require any specialized technique or a computational tool. The results from the study are qualitative and the method is suitable for only relatively simple scenarios. In addition, the quality of the study greatly relies on the team's experiences (Crowl & Louvar, 2011; F. I. Khan & Abbasi, 1998).

Fault Tree Analysis (FTA) was developed in 1960s by Bell Laboratories and has been widely adopted by the nuclear industry prior to the chemical process industry (Crowl & Louvar, 2011; F. I. Khan & Abbasi, 1998). The method starts with a defined incident or a top event. It uses deductive reasoning to determine intermediate events and basic events failures that can cause an incident or top event. AND-gate and OR-gate connect basic events or intermediate events that are later formed into a tree. A cause-effect concept is utilized in the FTA, enabling logical mapping of the events and understanding of failure mechanism (Rathnayaka, Khan, & Amyotte, 2011). An example fault tree is shown in Figure 5. However, the method has limited ability to accommodate a dynamically changing environment and common cause failures of the events (Barua, 2012).

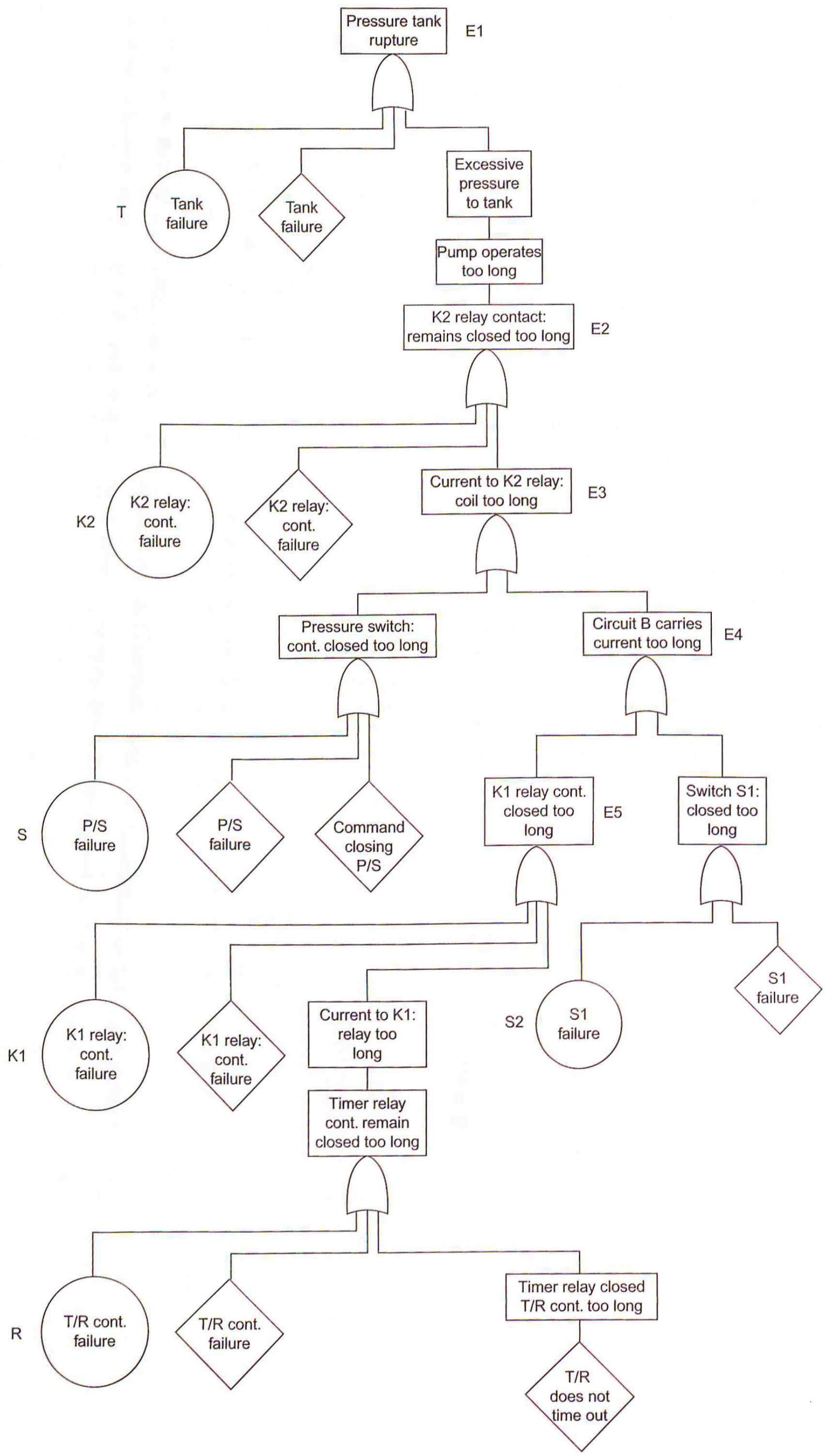

Figure 5: Example Fault Tree for Pressure Tank Rupture Event (Mannan, 2012)

Event Tree Analysis (ETA) was conceived by the U.S. Nuclear Regulatory Commission in 1975 (Barua, 2012). The method is used to explore potential consequences that may arise from an initial incident or event using an inductive reasoning. Potential consequences are branched out of the starting event, forming a tree-like diagram, where each branch represents a specific outcome. Safety systems or barriers are generally listed above the event tree to provide multiple pathways that lead to multiple consequences. If the description of the safety system or barrier is true, the scenario follows the top pathway before continuing to the next safety system or barrier. The probability of an outcome scenario can be calculated using a probability of an initiating event and a probability of success/failure of each safety system or barrier (Crowl & Louvar, 2011; Mannan, 2012). An example event tree is shown in Figure 6. Similar to the FTA, limitation exists in applying ETA methods for modeling a dynamic environment (Bucci et al., 2008).

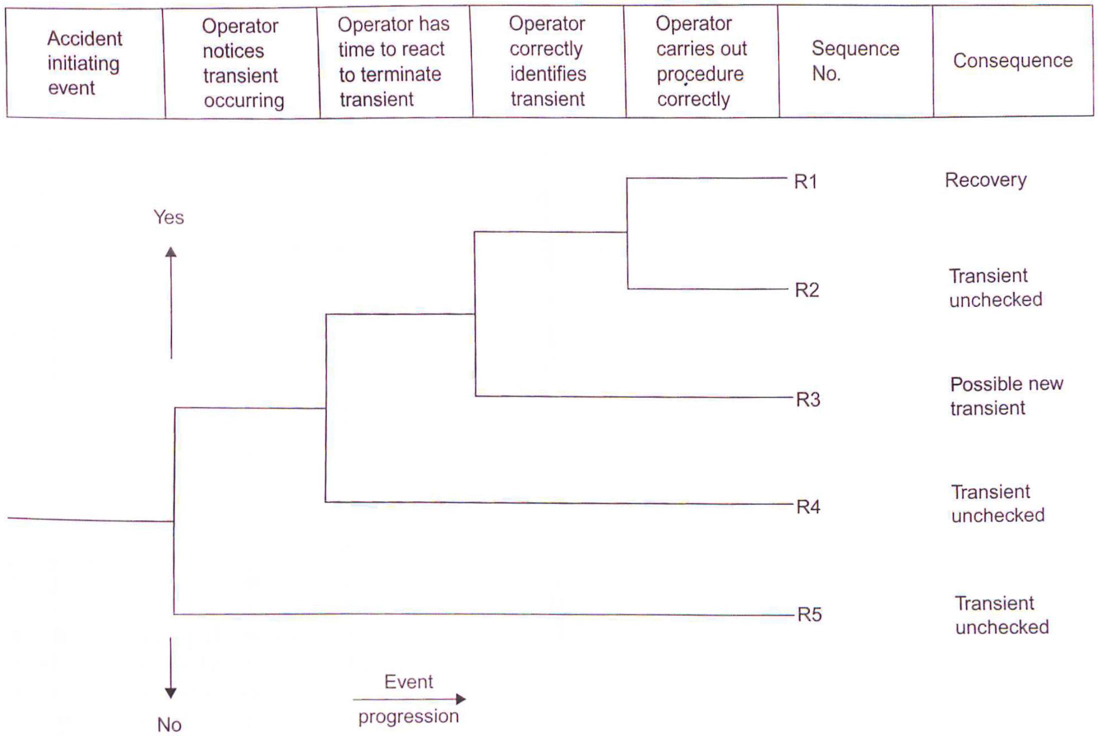

Figure 6: Example Event Tree for Operator Response to Nuclear Reactor Transient (Mannan, 2012)

Bow-tie method was introduced in 1979 at an Imperial Chemical Industries (ICI) training course and was later used by Shell Company in 1990s (H. Pasman, 2015a). A simple Bow-tie is given in Figure 7. It is a merge between the fault tree and the event tree via an event, generally called a "top event" or "critical event". The left side of the Bow-tie is the fault tree, which illustrates various causes, called "threats", that are leading to the top event. The event tree is shown on the right hand side demonstrating possible consequences propagated from the top event. In addition, the Bow-tie diagram also shows safety barriers that can be implemented to avoid the top event from occurring or to alleviate the magnitude of the consequences. Those barriers are referred to as "preventive barriers" and "mitigation barriers", respectively. The preventive and mitigation barriers are also known as a Safety Critical Element (SCE) or a safety critical system, which, upon failure, may lead to the catastrophic incidents. The Bow-tie diagrams are made during a safety case development to manage high-risk scenarios and to prevent them from happening. One of the major advantages of Bow-tie is its graphical representation of pathways of unsafe scenarios that illustrates relationships between threats, preventive barriers, top event, hazard, mitigation barriers, and consequences (Mannan, 2012). Therefore, it is a preferred method in hazard and risk communications to non-technical personnel. In addition to its visualization ability, probability values can be assigned to each event and barrier, enabling a quantitative assessment. The method has been well proven in the process safety analysis as well as the accident risk analysis. However, it still suffered the same limitation as FTA and ETA in dynamic risk assessment (Khakzad, Khan, & Amyotte, 2012).

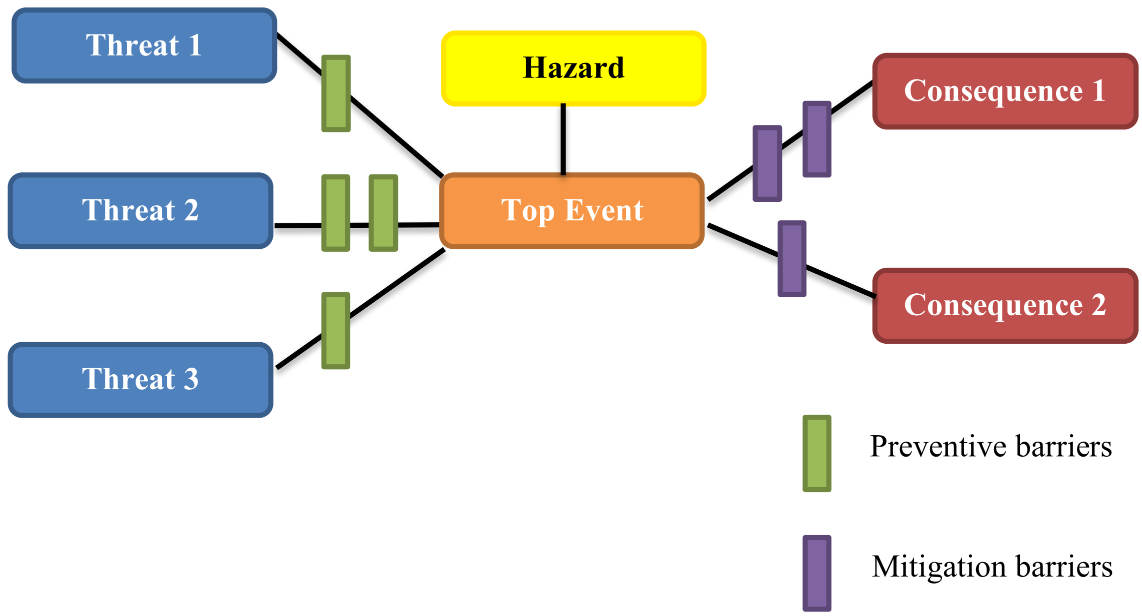

Figure 7: Simple Representation of a Bow-tie Diagram

Another well-established and accepted method is a Hazard and Operability (HAZOP) study, which was also developed by the ICI in 1974 (F. I. Khan & Abbasi, 1998). The study was conducted by a multi-disciplinary team from design engineers to operators to review and identify possible deviations from a defined design intent. HAZOP documentations include, but are not limited to, Process Flow Diagrams (PFDs), Piping and Instrumentation Diagrams (P&IDs), Heat and Material Balances (H&MBs), standard operating procedures, and equipment specifications (Crowl & Louvar, 2011). Guidewords are applied to process parameters to form possible deviations. Brainstorming is performed for each applicable deviation to examine the documents and identify possible causes and describe potential consequences. Safeguards are sought for each hazardous scenario while a recommendation is made where insufficient safeguards are observed. Due to its systematic and thoroughness of the process in identifying hazardous operations, it is the most successful method in process hazard assessment (F. Khan et al., 2015; H. Pasman, 2015a; H. J. Pasman, Knegtering, & Rogers, 2013). Nonetheless, it suffered from a limitation to consider spatial features, and extensive time and manpower commitment to execute the method (Barua, 2012; F. I. Khan & Abbasi, 1998).

2.2. Bayesian Network Application to HAZOP and Bow-tie Studies

Bayesian method is widely used in artificial intelligence for a deep learning and a machine learning application (F. Khan et al., 2015). It is also applied in the medical, psychology, and reliability fields. Recently, Bayesian method has been used in the search for the flight MH370 incident that occurred in 2014 (Davey, Gordon, Holland, Rutten, & Williams, 2016). In the past decade, this method has gained drastic attentions in process safety discipline and was mentioned in 491 documents (Scopus, 2016). Weber et al. (2012) studied 200 articles related to Bayesian network (BN) application to dependability, risk analysis, and maintenance subject. They found that 26% fall under the risk analysis category (Weber, Medina-Oliva, Simon, & Iung, 2012). Bayes' rule or Bayes' theorem is a rigorous method that takes into account previous experiences or additional information to estimate the probability of an event. Cause and effect relationships are crucial in developing a BN. Events of interest are depicted by a node in BN; whereas directed arc or edge (shown as an arrow) originates from one node (parent node, cause node) to another node (child node, effect node). BNs are direct acyclic graphs (DAGs) because an effect cannot be its own cause but can cause other effects (H. Pasman, 2015b).

For continuous variables, the form of Bayes' theorem is shown in Equation 3, where $f(\theta|t)$ is the posterior probability density function for a continuous random variable θ given continuous variable t. $l(t|\theta)$ is the likelihood function based on sample data t, and $h(\theta)$ is the prior probability density function for the variable θ.

Equation 3: Bayes Theorem for Continuous Variables

$$f(\theta|t) = \frac{l(t|\theta)h(\theta)}{\int_{-\infty}^{\infty} l(t|\theta)h(\theta)d\theta}$$

The traditional risk assessment methods described in Section 2.1 are effective in hazard identification and risk assessment. However, not all methods are suitable for BN application. The checklist and what-if analysis are fairly simple and are not applicable for a complex and dynamic risk assessment. Therefore, they will not be considered further in this study. The FTA and ETA provide a logical mapping of cause and effect relationships in hazardous scenarios and are rational options for BN development. Bow-tie analysis encompasses both FTA and ETA in its study and provides a better overview of the scenarios. Hence, it is prudent to select Bow-tie as a preferred method for BN application. Khakzad et al. (2012) applied Bayes' theorem to update the fault tree and event tree in the Bow-tie diagram with new observations or information, enabling dynamic risk analysis for the facility (Khakzad et al., 2012). Later, in 2013, they performed Bayesian network analysis using probability updating and probability adapting method to Bowtie-BN (see Figure 8). The first method is used to calculate the posterior probability when a certain event is observed, i.e. $P(x_i|Q)$. In the latter method, posterior probability is calculated when a certain event has occurred "n" times, i.e. $P(x_i|Q=n)$. It was shown that the probability adapting method is preferable to dynamically assess risks because the prior probability is updated using new observations (Khakzad, Khan, & Amyotte, 2013). Application of BN with Bow-tie analysis is also performed for offshore drilling operation by using accident precursors in risk updating (Abimbola, Khan, & Khakzad, 2014).

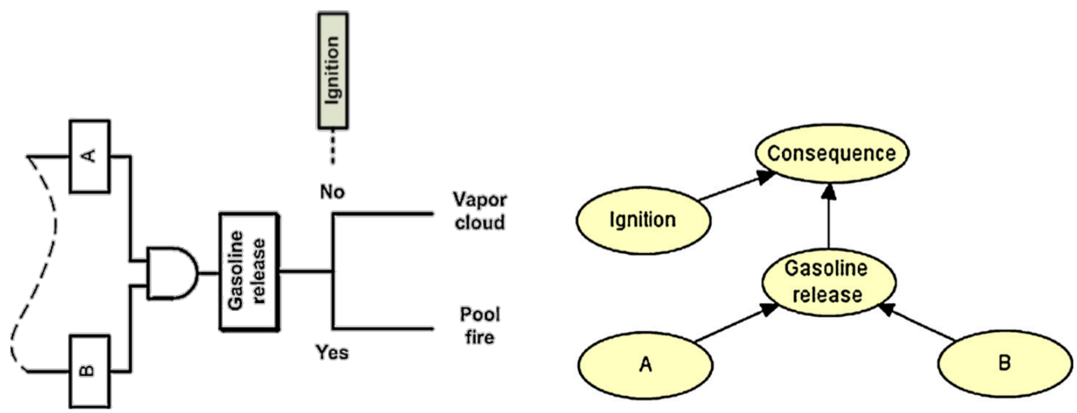

Figure 8: Bow-tie (left) and BN (right) model for Gasoline Release Scenario, Reproduced from (Khakzad et al., 2013)

HAZOP study is one of the industry-standard methods for risk assessment due to its comprehensiveness, as mentioned previously. However, the results of the analysis are not presented in a form of DAG, instead, they are presented in a form of table summarizing parameters, guidewords, causes, consequences, safeguards, and recommendations (see Table 1). Therefore, additional steps are required to extract hazardous scenarios from a specific node in order to construct a BN. A node in HAZOP study represents a subsystem under consideration and normally starts from a shutdown valve or a piping specification break upstream of a system or equipment to another shutdown valve or another piping specification break downstream of that system or equipment. Wang et al. (2015) demonstrated an early warning capability of the HAZOP-based BN. A case study for a tank system is given and shown in Figure 9 and Figure 10 (Wang, Khan, & Ahmed, 2015). Hu et al. (2010) developed an integrated method based on the HAZOP study and the dynamic BN. The process of converting HAZOP into BN is shown in Figure 11. Observable variables from the supervisory control and data acquisition (SCADA) are used to update a condition of a plant and provide a pre-warning alarm for proactive maintenance. The method can also prioritize possible causes of an unsafe scenario, assisting field engineers to find the most likely explanation. Consequently, catastrophic incidents can be avoided as soon as possible (Hu, Zhang, Ma, & Liang, 2010).

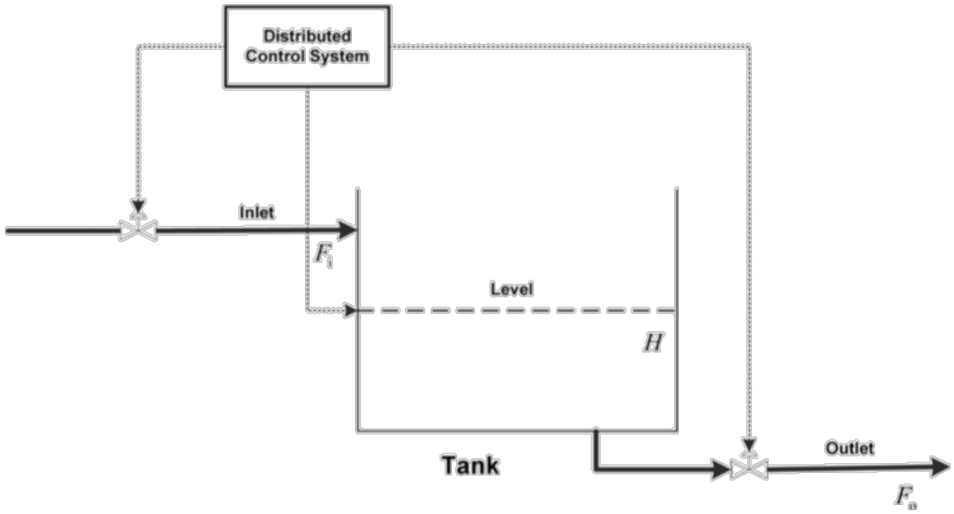

Figure 9: Schematic of a Tank System, Reproduced from (Wang et al., 2015)

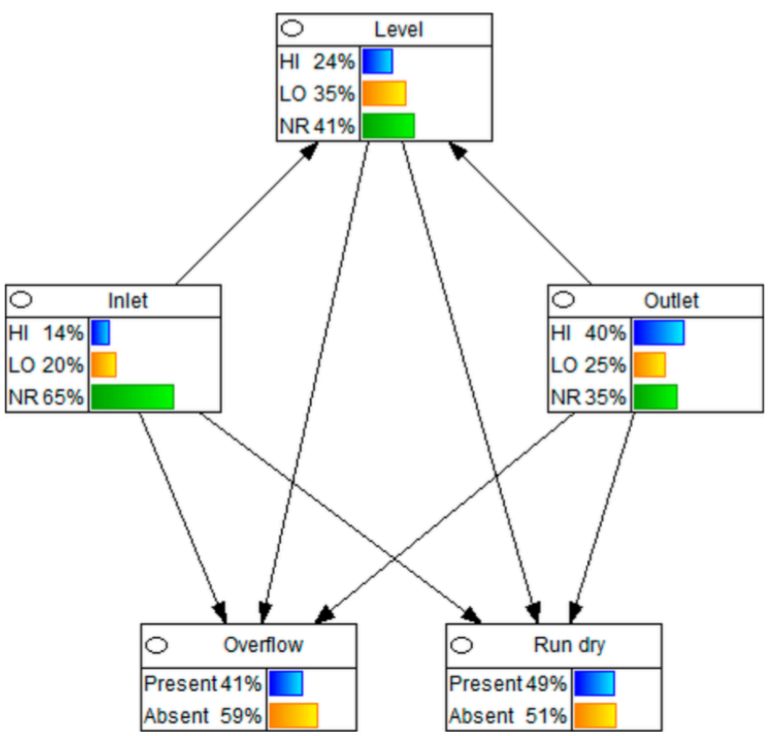

Figure 10: Bayesian Network Model for a Tank System Shown in Figure 9, Reproduced from (Wang et al., 2015)

Table 1: Typical HAZOP Result Table

Parameters	Guidewords	Causes	Consequences	Safeguards	Recommendations

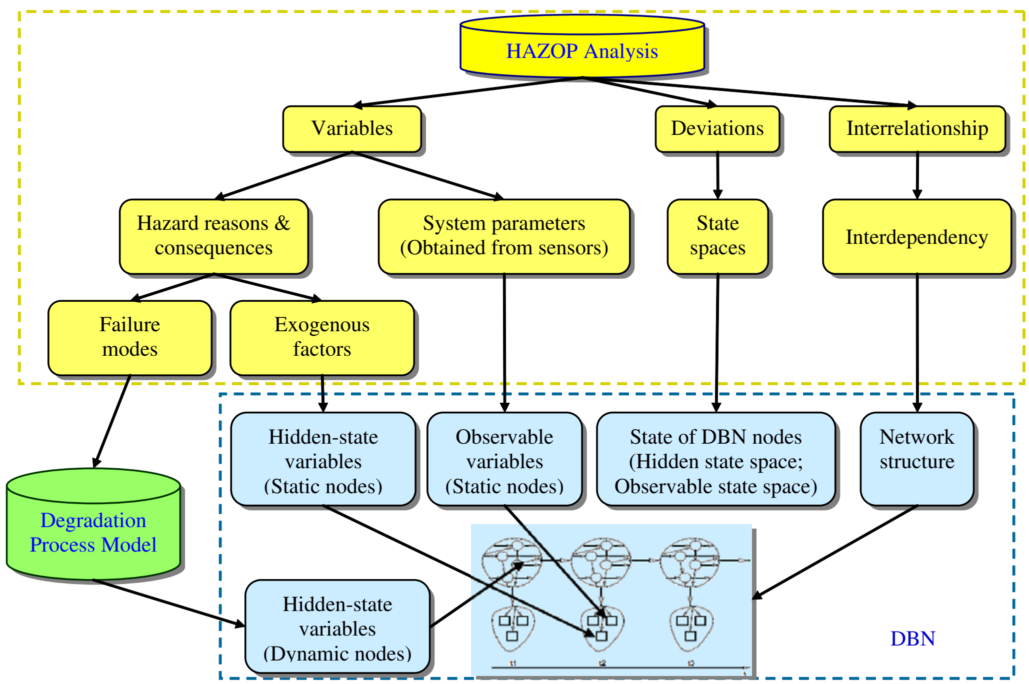

Figure 11: Dynamic BN Construction Mechanism, Reproduced from (Hu et al., 2010)

2.3. Process Safety Indicators

Process safety indicators (PSIs) are established to reinforce the risk control in process facilities. The indicators reflect performance levels of risk barriers in the process safety area, which deals with a prevention and control of loss of containment of hazardous materials or energy. Many organizations have issued guidelines or standards related to PSIs, such as the American Petroleum Institute (API) standard on "Process Safety Performance Indicators for the Refining and Petrochemical Industries (RP 754)" (API, 2016), the Center for Chemical Process Safety (CCPS)'s "Guideline for Process Safety Metrics" (CCPS, 2010), and the International Association of Oil & Gas Producers (IOGP)'s report on "Process Safety – Recommended Practice on Key Performance Indicators" (IOGP, 2011a). The CCPS guideline provides an extensive list of 350 indicators to embrace its 20 process safety management system elements. In addition, the Master thesis done by Hassan presents 279 asset integrity indicators for three pillars of asset integrity, which are mechanical integrity, operational integrity, and personnel integrity (M. J. Hassan, 2011). Mendeloff et al. (2013) analyzed data collecting from the industry based on the first edition of API RP 754. They found that major firms have already collected data beyond standard's requirements. The study concluded that PSIs might help increasing an awareness in process safety comparing with the well-established-and-regulated occupational safety indicators (Mendeloff, Han, Fleishman-Mayer, & Vesely, 2013).

Following API RP 754 and IOGP 456, a 4-tier approach is devised for PSIs to collect not only major incidents, which are relatively rare, but also the more frequent and lower consequence events. A tier 1 represents the most lagging indicators group while the tier 4 is the most leading group. Definitions of each tier are provided in API document (API, 2016) and are reproduced in below for clear understanding.

"A Tier 1 Process Safety Event (T-1 PSE) is a loss of primary containment (LOPC) with the greatest consequence. A T-1 PSE is an unplanned or uncontrolled release of any material, including non-toxic and nonflammable materials (e.g. steam, hot water, nitrogen, compressed carbon dioxide or compressed air), from a process that results in one or more of the consequences listed below;

- *An employee, contractor or subcontractor "days away from work" injury and/or fatality.*
- *A hospital admission and/or fatality of a third-party.*
- *An officially declared community evacuation or community shelter-in-place including precautionary community evacuation or community shelter-in-place.*
- *A fire or explosion damage greater than or equal to $100,000 of direct cost.*
- *An engineered pressure relief (e.g. PRD, SIS, or manually initiated emergency depressure) discharge, of a quantity greater than or equal to the threshold quantities in any one-hour period, to atmosphere whether directly or via a downstream destructive device that results in one or more of the following four consequences:*
    - *rainout;*
    - *discharge to a potentially unsafe location;*
    - *an on-site shelter-in-place or on-site evacuation, excluding precautionary on-site shelter-in-place or on-site evacuation;*

- *public protective measures (e.g. road closure) including precautionary public protective measures.*

- *An upset emission from a permitted or regulated source, of a quantity greater than or equal to the threshold quantities in any one-hour period, that results in one or more of the following four consequences:*
    - *rainout;*
    - *discharge to a potentially unsafe location;*
    - *an on-site shelter-in-place or on-site evacuation, excluding precautionary on-site shelter-in-place or on-site evacuation;*
    - *public protective measures (e.g. road closure) including precautionary public protective measures.*
- *A release of material greater than or equal to the threshold quantities in any one-hour period.*

A Tier 2 Process Safety Event (T-2 PSE) is a LOPC with lesser consequence. A T-2 PSE is an unplanned or uncontrolled release of any material, including non-toxic and non-flammable materials (e.g. steam, hot water, nitrogen, compressed carbon dioxide, or compressed air), from a process that results in one or more of the consequences listed below and is not reported as a Tier 1 PSE.

- *An employee, contractor or subcontractor recordable injury.*
- *A fire or explosion damage greater than or equal to $2500 of direct cost.*

NOTE: Some companies rather than performing a detailed estimate use a simple rule-of-thumb to determine if the direct cost exceeded $2500: If the damage requires repair, then the direct cost is often at least $2500.

- *An engineered pressure relief (PRD, SIS, or manually initiated emergency depressure) device discharge, of a quantity greater than or equal to the threshold quantities in any one-hour period, to atmosphere whether directly or via a downstream destructive device that results in one or more of the following four consequences:*
    - *rainout;*
    - *discharge to a potentially unsafe location;*
    - *an on-site shelter-in-place or on-site evacuation excluding precautionary on-site shelter-in-place or on-site evacuation;*
    - *public protective measures (e.g. road closure);*
    - *including precautionary public protective measures.*
- *An upset emission from a permitted or regulated source, of a quantity greater than or equal to the threshold quantities in any one-hour period, that results in one or more of the following four consequences:*
    - *rainout;*
    - *discharge to a potentially unsafe location;*
    - *an on-site shelter-in-place or on-site evacuation, excluding precautionary on-site shelter-in-place or on-site evacuation;*

    - *public protective measures (e.g. road closure) including precautionary public protective measures.*
- *A release of material greater than or equal to the threshold quantities in any one-hour period.*

A Tier 3 PSE typically represents a challenge to the barrier system that progressed along the path to harm, but is stopped short of a Tier 1 or Tier 2 PSE consequence. Indicators at this level provide an additional opportunity to identify and correct weaknesses within the barrier system.

Tier 4 indicators typically represent performance of individual components of the barrier system and are comprised of operating discipline and management system performance. Indicators at this level provide an opportunity to identify and correct isolated system weaknesses. Tier 4 indicators are indicative of process safety system weaknesses that may contribute to future Tier 1 or Tier 2 PSEs. In that sense, Tier 4 indicators may identify opportunities for both learning and systems improvement. Tier 4 indicators are too facility-specific for benchmarking or developing industry applicable criteria. They are intended for internal company use and for local (facility) reporting."

In this study, 11 PSIs are considered based on available data obtained from an energy company. Tier 1 and tier 2 PSIs are lagging indicators, which resulted in a considerable impact, and tier 3 and tier 4 PSIs are leading indicators, which comprised near misses, unsafe conditions, or failures of safety barriers. These leading indicators provide evidence to the barriers' health and the effectiveness of major incident prevention of a facility or an organization. Detailed definitions of the 11 PSIs are given in Table 2.

Table 2: Process Safety Indicators Definition

Indicator	Definition
Number of tier 1 LOPC	Number of LOPC events that conformed to T-1 PSE definition provided in API RP 754.
Number of tier 2 LOPC	Number of LOPC events that conformed to T-2 PSE definition provided in API RP 754.

Table 2 Continued

Indicator	Definition
Number of tier 3 LOPC	Number of LOPC events that results in one or more of the consequences listed below: • fire or explosion; • action to prevent or limit the consequence of a potential fire or explosion; • has a potential to cause fatality or major injury • a continuous release of gas or 2 phases flow at a rate greater than 1 kg/hour; • a discrete release of gas or 2 phases flow with a total mass greater than 0.1 kg; • a continuous release of liquid at a rate greater than 5 kg/day; • a discrete release of liquid with a total mass greater than 5 kg.
Number of failure on test or demand of SCE	Any failure of SCE related to process safety during test or in-situ demand.
Percentage of SCE backlog	Percentage of SCE that fall behind maintenance schedule.

Table 2 Continued

Indicator	Definition
Number of unplanned process shutdown	Number of unplanned shutdowns of process units, initiated either manually or automatically.
Number of emergency blowdown	Number of emergency blowdowns of process units, initiated either manually or automatically.
Number of tier 4 LOPC	Number of LOPC events that are below defined criteria for tier 3 LOPC.
Percentage of contractor companies with approved safety plan	Number of contracts with approved safety plan compared to total number of contracts in execution on site.
Ratio of planned/unplanned maintenance	Ratio of hours spent on planned/unplanned maintenance activities.
Number of deviation on SCE in place	Number of deviations (derogations) presented at the time of reporting.

2.4. Process Safety Indicators and Bayesian Network

Process safety indicators are implemented as a part of a company's process safety management system, providing feedbacks to continuously improve system performance. One of the objectives is to reduce the LOPC number to zero, similar to the occupational safety's goal of zero fatality or zero loss time injury (LTI). However, a chance of occurrence of a process safety event is much lower than that of the occupational safety, which makes the trend examination for a process safety event misleading or inconclusive. Indicators themselves may also demonstrate erratic or random trend due to many possible contributing factors involved (H. Pasman & Rogers, 2014). The number of barriers presented in an oil and gas operating facility can easily reach several hundreds or thousands, which can result in the same amount of indicators set up to measure their performances. This is beyond the capability of human to straightforwardly comprehend their implication or to grasp the overview of the situation. Therefore, the indicators aggregation method was proposed to rationally combined multiple indicators into few and apprehensible elements. Hassan (2011) presented an analytical hierarchy process that grouped 279 specific leading and lagging indicators into three key element indicators as shown in Figure 12 (M. J. Hassan, 2011). However, the work did not use the indicators' information to update the risk assessment. Pasman & Rogers (2014) adopted and applied Hassan's framework to the Bow-tie analysis for an offshore process facility. Figure 13 demonstrates the causal relationships between the indicators and various elements in the BN model. Therefore, changes in the key element indicators' value can impact a probability of occurrence of a hazardous event, which eventually influence a cost of incident if monetary amounts are assigned to each consequence outcome (H. Pasman & Rogers, 2014).

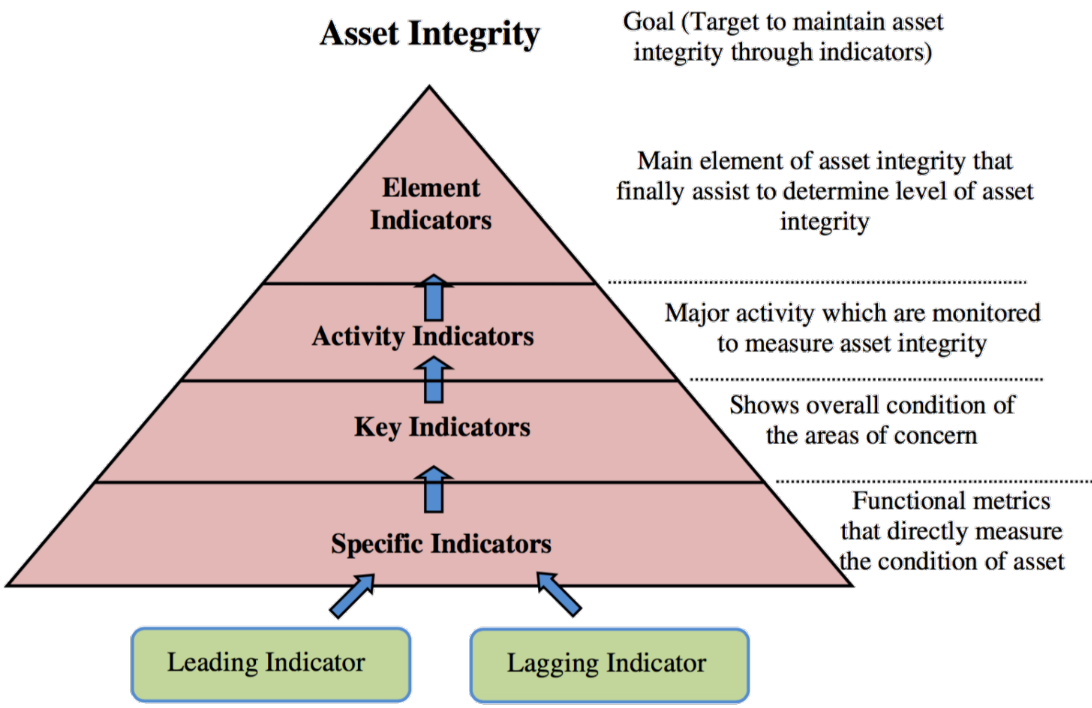

Figure 12: Hierarchical Process for Indicators Aggregation as Defined by Hassan (2010), Reproduced from (H. Pasman & Rogers, 2014)

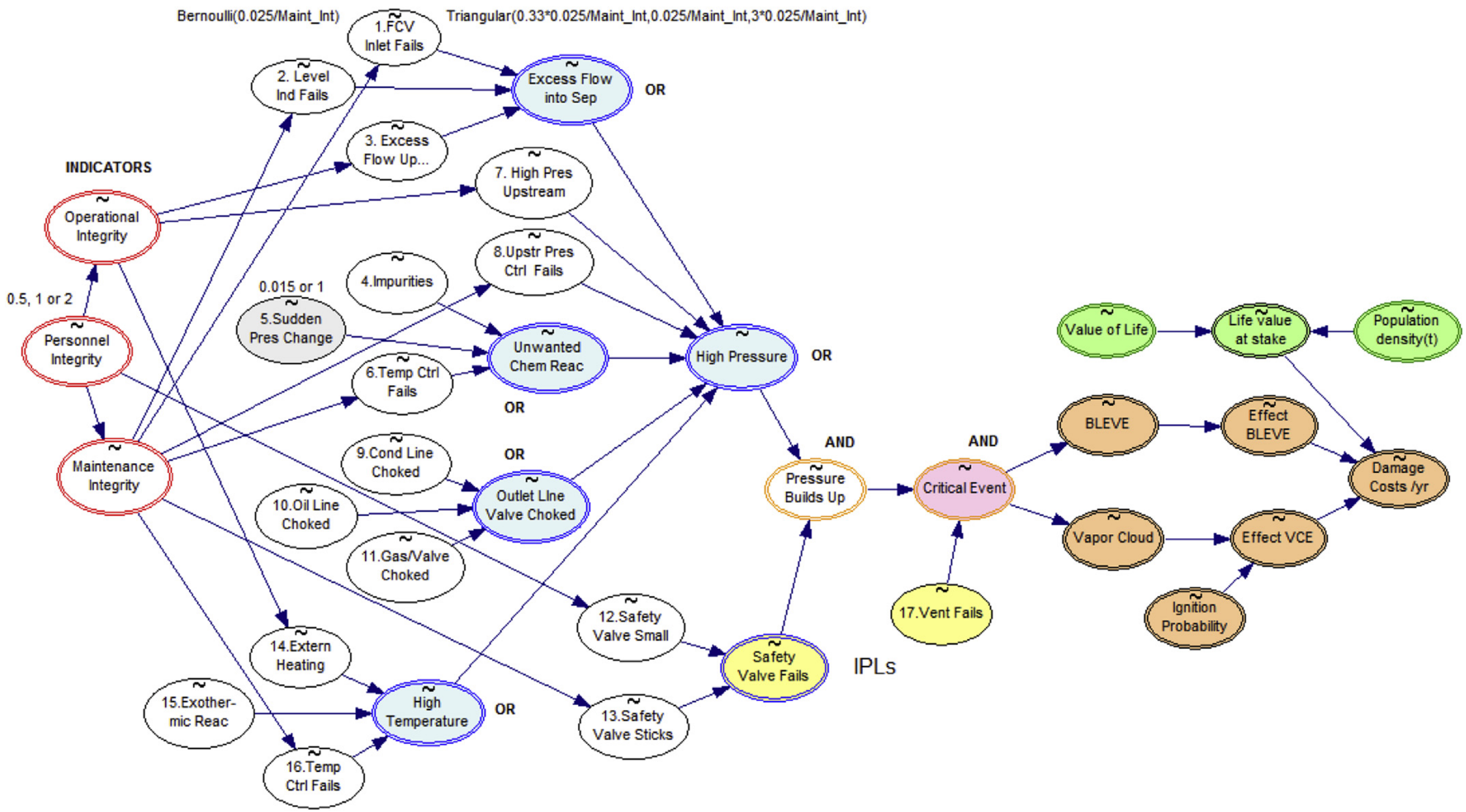

Figure 13: Continuous Bayesian Network with Indicators Integration, Reproduced from (H. Pasman & Rogers, 2014)

3. METHODOLOGY

The research methodology is divided into 4 main parts; BN development, prior probability definition, process safety indicators integration, and posterior probability calculation. The overall process is summarized as shown in Figure 14. The BN development based on information from HAZOP or Bow-tie study is explained in Section 3.1 and 3.2, respectively. Section 3.3 provides the PSI integration method. Section 3.4 elaborates the method used in defining prior probabilities for event nodes as well as PSI nodes. Lastly, BN algorithm for calculation of posterior probability is specified in Section 3.5.

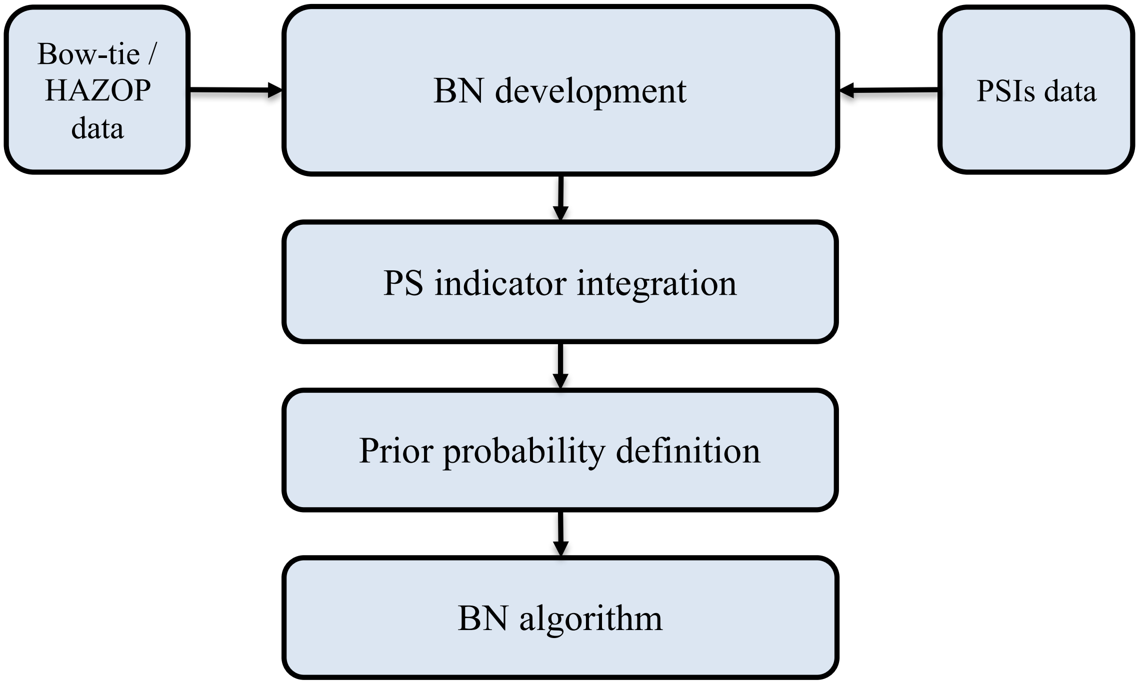

Figure 14: Research Methodology

3.1. HAZOP-BN Development

The study begins with a completed HAZOP report obtained from an energy company. The HAZOP study was conducted for an entire offshore production platform by a team of expert in an oil and gas industry. Thus, it is considered to be well-founded and rational to be directly adopted for this research. However, it is not feasible to consider the whole report because there were more than 25 nodes and over 400 pages of HAZOP results, which may consist of unconnected scenarios. Thus, the scope of this research is limited to the loss of primary containment (LOPC) of high pressure hydrocarbon gas from an export gas compressor scenario.

The export gas compressor system consists of mainly the compressor units, which compress gas from around 750 psi to 1,900 psig, and sale gas metering, which measure a quantity of gas sale before exporting to onshore gas separation facilities. The construction of the BN starts with identification of the LOPC scenario from the study. Subsequence consequences, such as fire and explosion, causes, and safeguards, were collected and defined separately from the LOPC node. Each node is then connected to each other where causal relationships can be identified. In this step, most causal relationships between causes and consequences can be easily identified. However, a detailed fault tree analysis may be required to determine dependency between each safeguard, e.g. where two safeguards need to fail simultaneously for a cause to develop into a subsequent event. Then, safeguards were extracted from each entry of the HAZOP study and directly applied to each cause, but not to the LOPC event, since they moderate the probability of occurrence of the immediate or intermediate cause rather than the LOPC.

There are two main types of BN; a discrete type, and a continuous type. The discrete type BN is suitable for discrete variables where finite set of states or conditions can be defined and their probability can be described by one value. For example: 1) compressor's states are set as either in failure or working condition; or 2) ratios of a preventive/corrective maintenance are set as high, medium, or low. When two nodes are causally linked, a crisp probability value is assigned to each state of a parent node. For a child node, a conditional probability table (CPT) is created where conditional probability value is required. The size of the CPT grows exponentially with the number of connecting parents and their states, and the number of state of the child node. For instance, a child node with two states, e.g. available or not available, that has three parent nodes, which also having two states, will have the CPT size of 2^3 x 2 = 16, where each box requires a probability value. If a child node has seven parent nodes instead of three, the CPT size becomes 2^7 x 2 = 256. This can be impractical if the parent node has several states or when multiple parent nodes are connected to a single child node. Continuous type BN software allows distribution functions as inputs, treats each node as continuous variable, and defines the probability value using a continuous distribution or equation. The evaluation is convoluting the parent distribution with the child one through, e.g. a Monte-Carlo solver or in another software, by so-called, dynamic discretization. Hence, it is preferred when large number of causal relationships linked to a single node is expected and where a system under consideration encompassed complex interrelationships. In addition, continuous distribution allows incorporation of uncertainties in probability values collected from day-to-day operations either from a different in machine or imperfect data collection process, thus more realistic results can be obtained.

Partial HAZOP result of the export gas compressor node is presented in Table 3. Following the steps described earlier, continuous type BN can be constructed. A LOPC event is created as a starting point. From the HAZOP study, an overpressure scenario is found to be an immediate cause of the LOPC. This overpressure is further caused by high pressure upstream of the compressor system, which occurs due to compressor trips. Preventive maintenance (PM) helps avoiding compressor trips or failure. Two dissimilar check valves downstream of the inlet shut-down valve (SDV) and the inlet SDV tight shut-off (TSO) are considered as the safeguarding barriers for the high pressure node. Fully rated compressor suction system, pressure indicator control alarm high (PICAH), compressor blowdown, and pressure safety valve for upstream system are counted as safeguard against overpressure. A directed arc originates from the cause node (parent node) and connects to the effect node (child node). The constructed BN from this HAZOP entry is shown in Figure 15. GeNIe software version 2.1 is used for the BN development and calculation. Blue-colored nodes represent events of interest, whereas pink-colored nodes represent safeguards or barriers.

Table 3: Partial HAZOP Result where LOPC of Hydrocarbon Gas Scenario is Identified in the Consequence Column

Parameters	Guide-words	Causes	Consequences	Safeguards
Flow	No	Export Gas Compressor trips/fails	Potential for back-flow of high pressure gas from Export Gas Suction Scrubber to Raffinate Header, causing high pressure and possible overpressure of the upstream system	- PM program for Compressors in line with Vendor recommendations - Suction side of Compressor is fully rated for discharge conditions - Inlet SDV closes on Compressor trip/shutdown, valve is TSO - Two dissimilar check valves downstream of the inlet SDV - Export Gas Compressor system will blowdown in an event of trip/shutdown over a period of several minutes - PICAH on Raffinate Header, with relief to HP Flare - PSV for Raffinate Gas Header upstream of the Compressor system

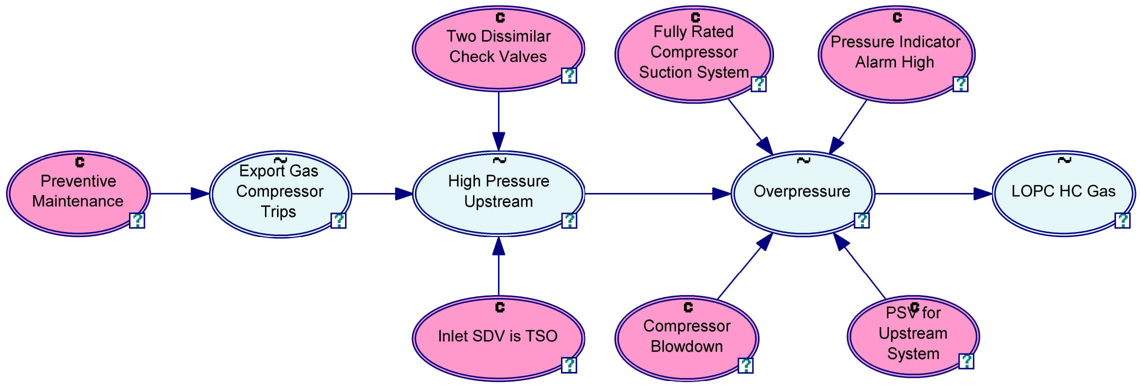

Figure 15: HAZOP-BN Model Constructed using Information Extracted from a Single HAZOP Entry Shown in Table 3

Following the same steps, all entries from the export gas compressor HAZOP node were analyzed. Figure 16 to Figure 20 demonstrate different causes of the LOPC event. It should be noted that the LOPC HC gas node is duplicated in all of the figures to allow an ease of understanding. Figure 21 shows the consequence of the LOPC event. The overview of the HAZOP-BN model for the LOPC event is shown in Figure 22.

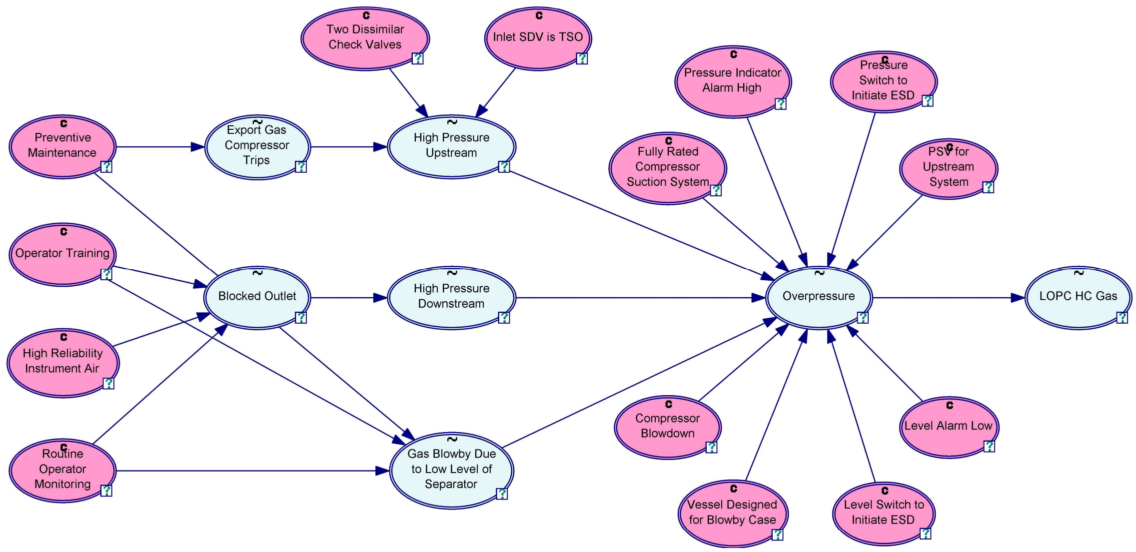

Figure 16: HAZOP-BN Model Illustrating the LOPC Event Caused by Overpressure

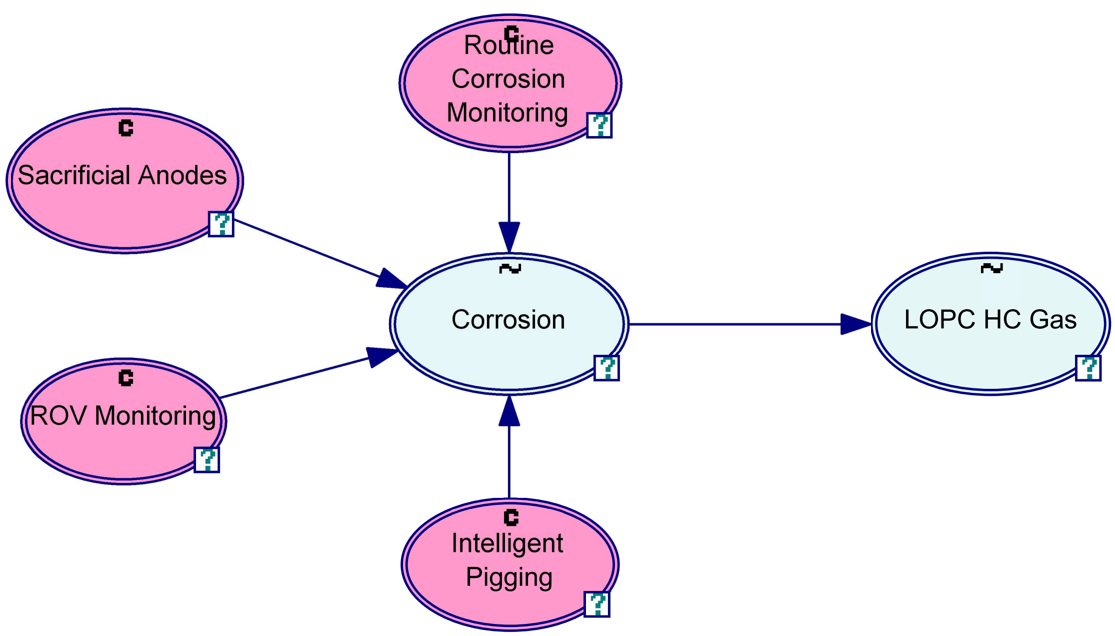

Figure 17: HAZOP-BN Model Illustrating the LOPC Event Caused by Corrosion

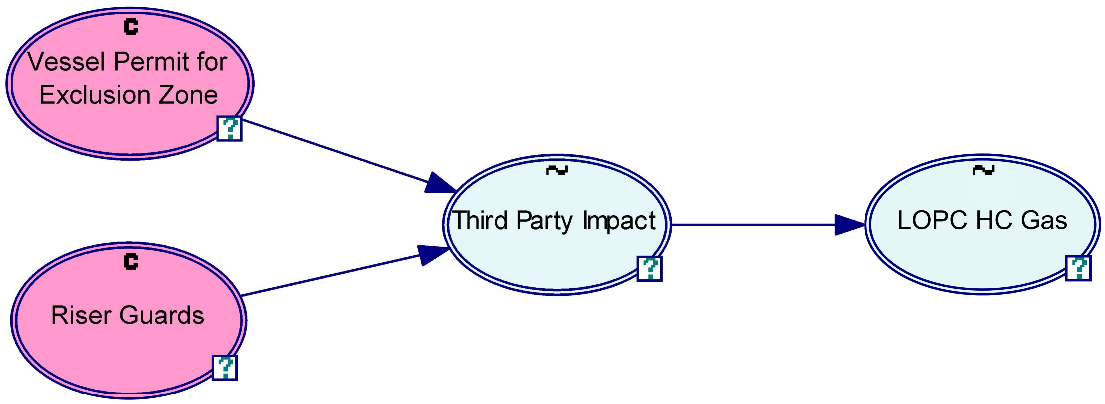

Figure 18: HAZOP-BN Model Illustrating the LOPC Event Caused by Third Party (Ship) Impact

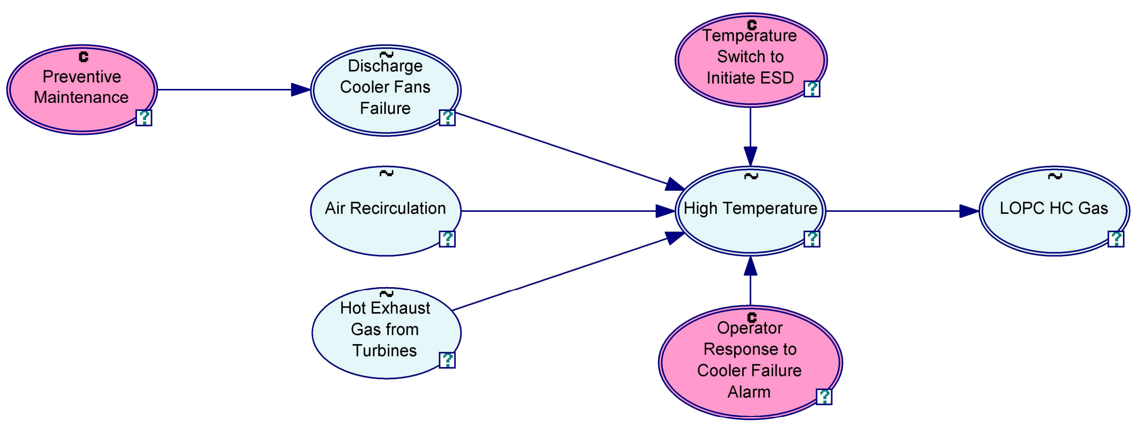

Figure 19: HAZOP-BN Model Illustrating the LOPC Event Caused by High Temperature

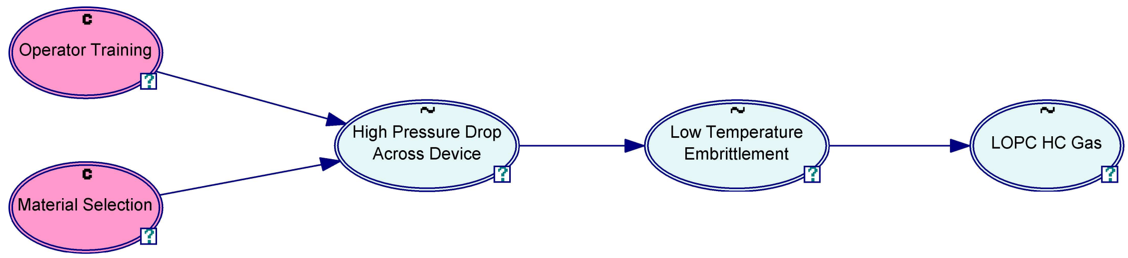

Figure 20: HAZOP-BN Model Illustrating the LOPC Event Caused by Low Temperature Embrittlement

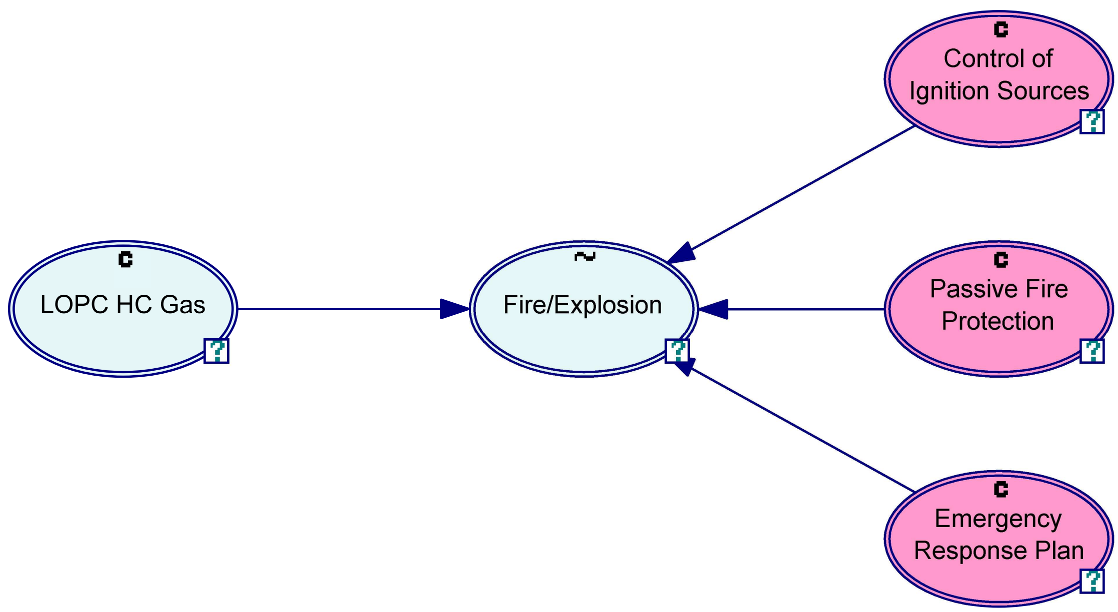

Figure 21: HAZOP-BN Model Illustrating the Consequence Developed from the LOPC Event

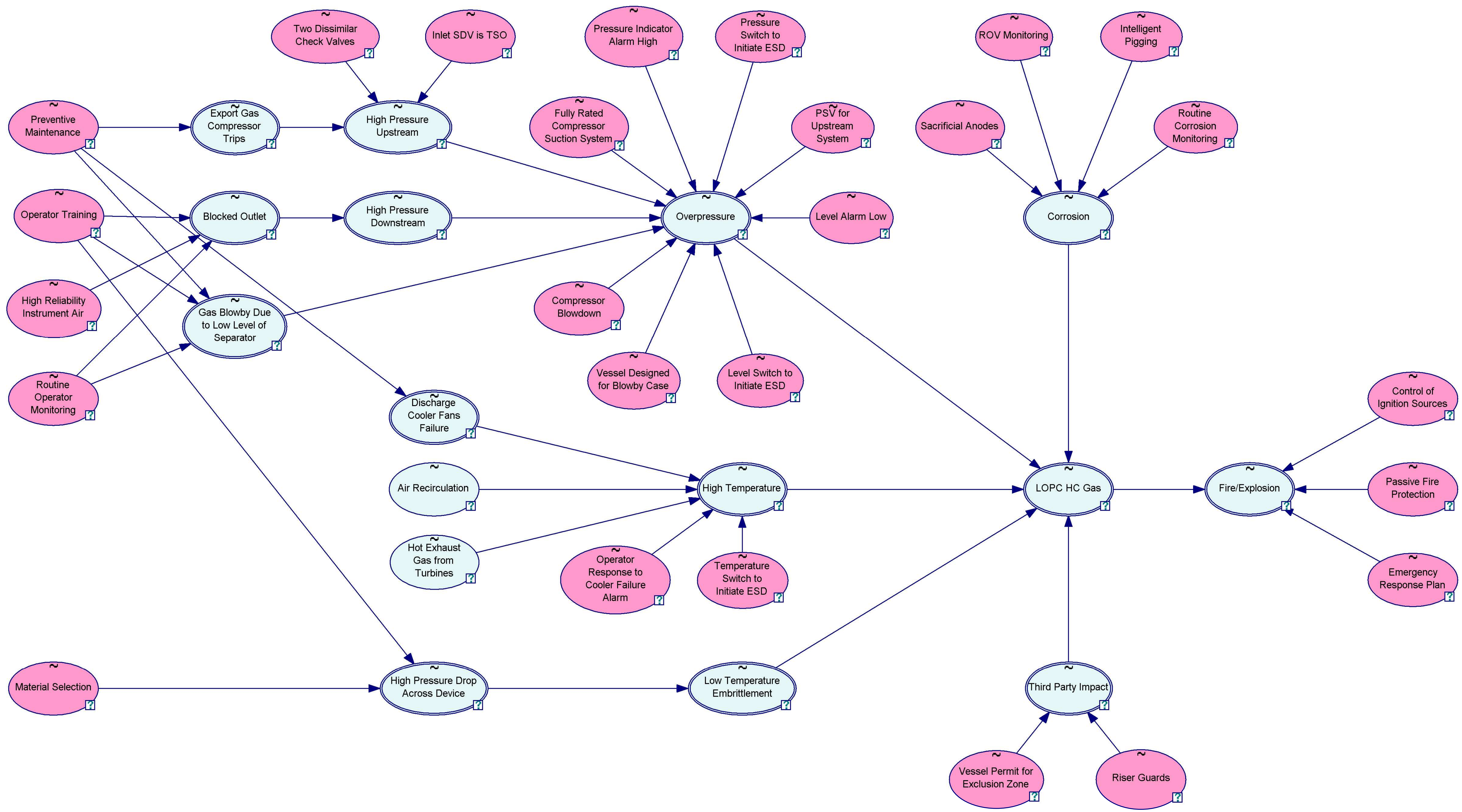

Figure 22: Overview of the HAZOP-BN Model for the LOPC Event

3.2. Bow-tie-BN Development

Bow-tie-BN development is slightly different from the HAZOP-BN. Even though a pictorial representation of a Bow-tie diagram and a Bayesian network are very similar, the development of Bow-tie-BN has its own challenges. Similar to the HAZOP study, the Bow-tie study was obtained from an energy company. It was conducted for an entire offshore production platform by a team of experts. Therefore, it is directly adopted for this research. However, only a LOPC of hydrocarbon gas Bow-tie was selected from the Bow-tie study out of 15 Bow-tie diagrams in total, which is considered to be adequate for this research. The Bow-tie diagram provides threats, top event, consequences, and safeguards for each threat and consequence. In addition, escalation factors are also developed in the original Bow-tie study. These escalation factors are failure scenarios that can impair a specific barrier, which can also be considered as a threat. Barriers to prevent the escalation factor from impairing the main barrier are shown on the line that connects between the escalation factor and the main barrier. The escalation factors are excluded from this study to simplify the model. The threats, top event, consequences, and safeguards nodes from the Bow-tie study can be directly adopted into the BN. The connection between each of the nodes is defined using cause-and-effect analysis. Each threat is connected to the top event, i.e., LOPC, while the barriers are directly linked to the threats, not to the top event. A detailed fault tree analysis may be required where the failure of a single safeguard does not necessarily lead to a threat from developing into the top event. Continuous type BN is used because of the same rationale given earlier in Section 3.1. The model is made with GeNIe software version 2.1.

Figure 23 presents part of the Bow-tie diagram for the LOPC event. Internal corrosion is shown as a threat that leads to LOPC event. In between, four barriers, which are: routine non-destructive test (NDT) based on risk-based inspection (RBI) approach; corrosion inhibitor injection on remote wellhead platform (WHP); intelligent pigging; and corrosion monitoring, are identified. The BN model can be developed as shown in Figure 24, where blue-colored nodes represent events of interest; whereas pink-colored nodes represent safeguards or barriers.

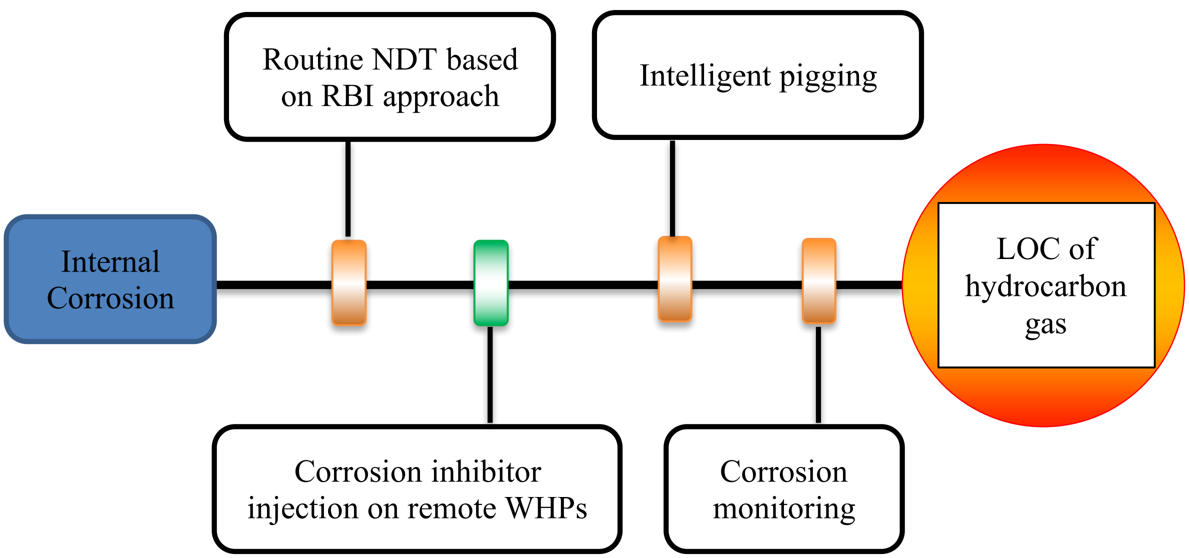

Figure 23: Partial Bow-tie Diagram of the LOPC Event Showing Internal Corrosion as a Threat

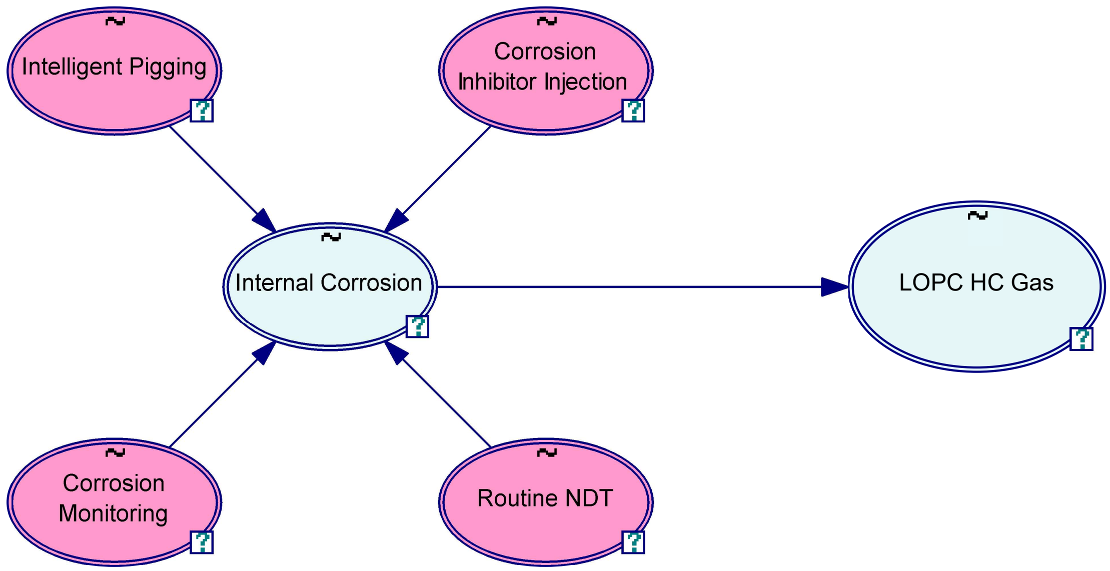

Figure 24: Bow-tie-BN Model Illustrating the LOPC Event with Internal Corrosion as a Threat

The entire Bow-tie diagram was converted into BN following the same method as the internal corrosion threat shown above. Figure 25 to Figure 30 magnify each threat of the LOPC event, except for internal corrosion threat, which is already shown in Figure 24. Again, it should be noted that the LOPC HC gas node is duplicated in all of the figures to allow an ease of understanding. Figure 31 shows the consequence of the LOPC event. The overview of the Bow-tie-BN model for the LOPC event is shown in Figure 32.

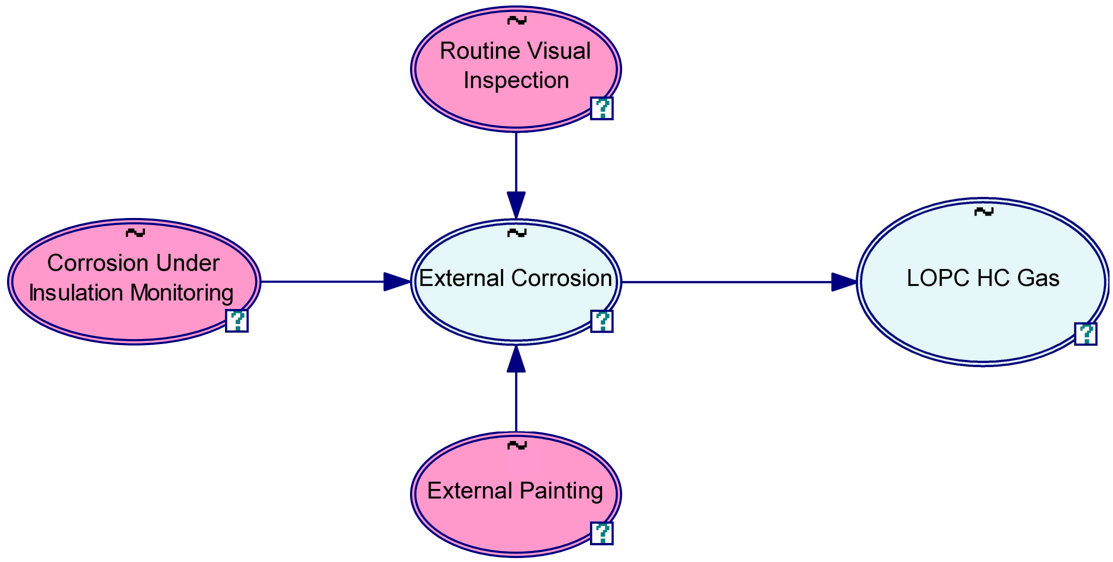

Figure 25: Bow-tie-BN Model Illustrating the LOPC Event with External Corrosion as a Threat

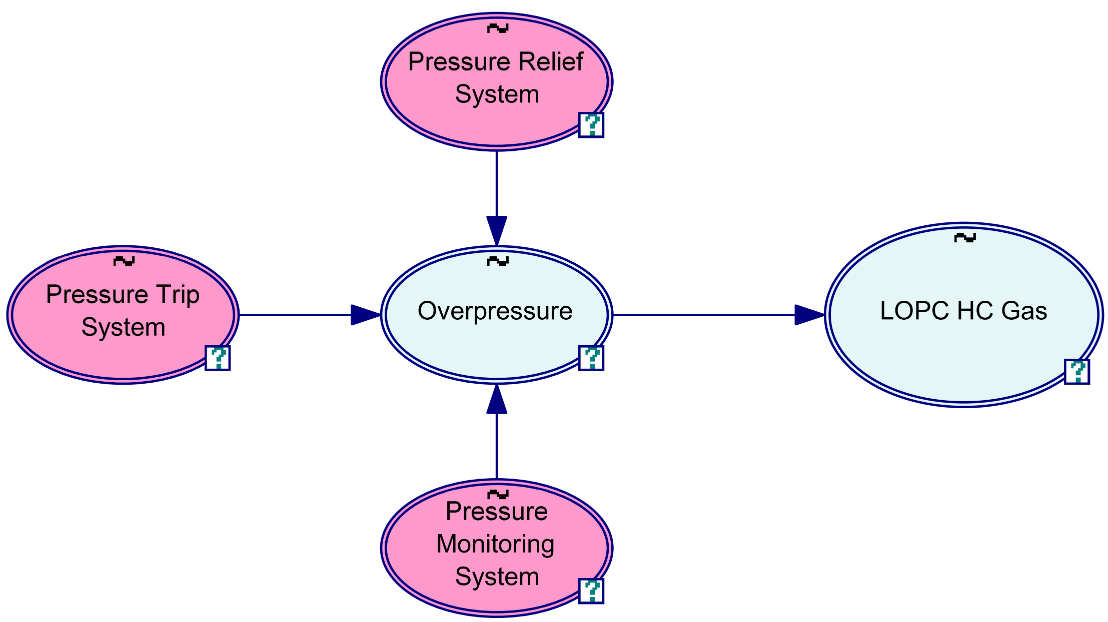

Figure 26: Bow-tie-BN Model Illustrating the LOPC Event with Overpressure as a Threat

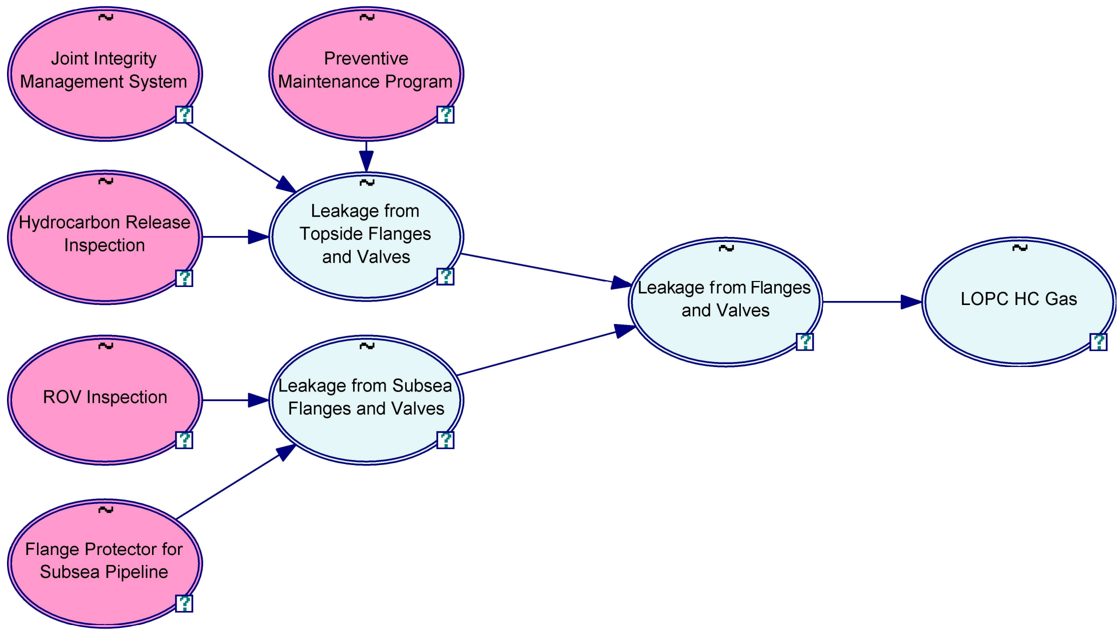

Figure 27: Bow-tie-BN Model Illustrating the LOPC Event with Leakage from Flanges and Valves as a Threat

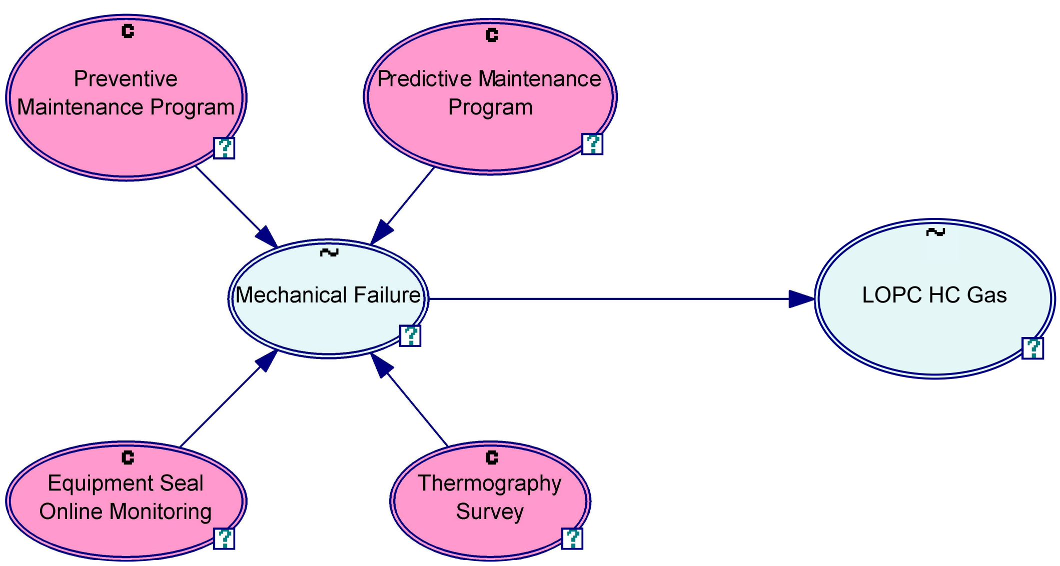

Figure 28: Bow-tie-BN Model Illustrating the LOPC Event with Mechanical Failure as a Threat

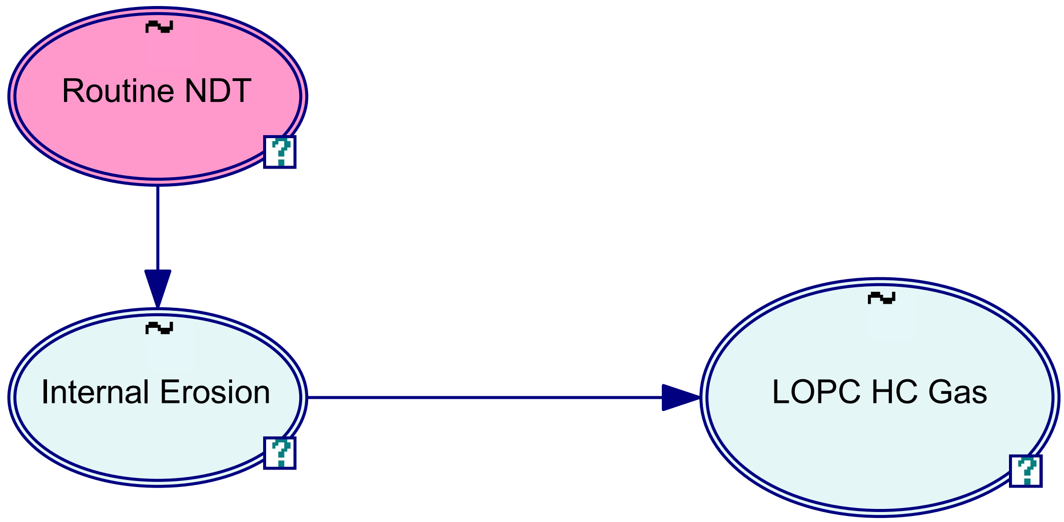

Figure 29: Bow-tie-BN Model Illustrating the LOPC Event with Internal Erosion as a Threat

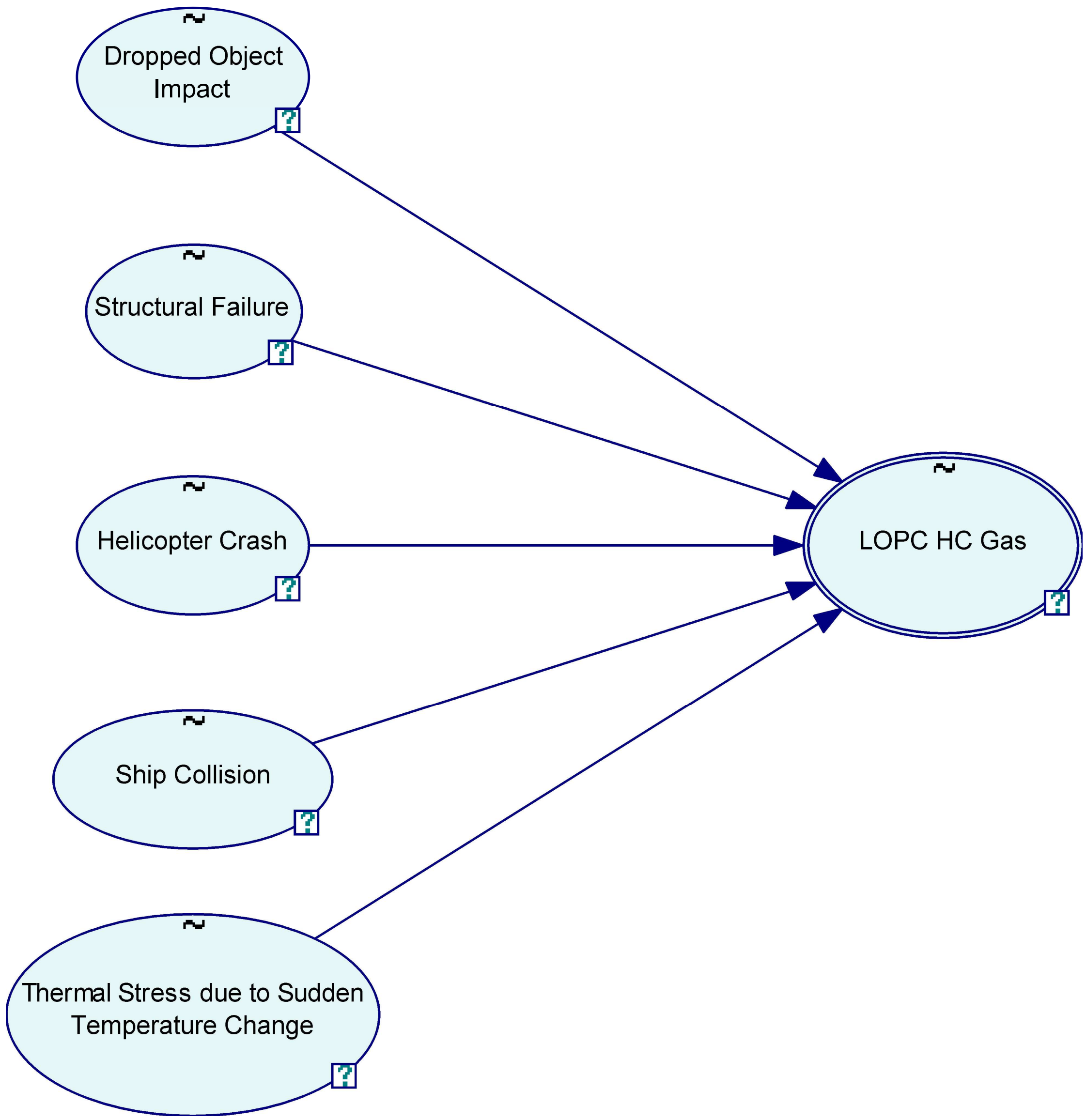

Figure 30: Bow-tie-BN Model Illustrating the LOPC Event with Other Threats

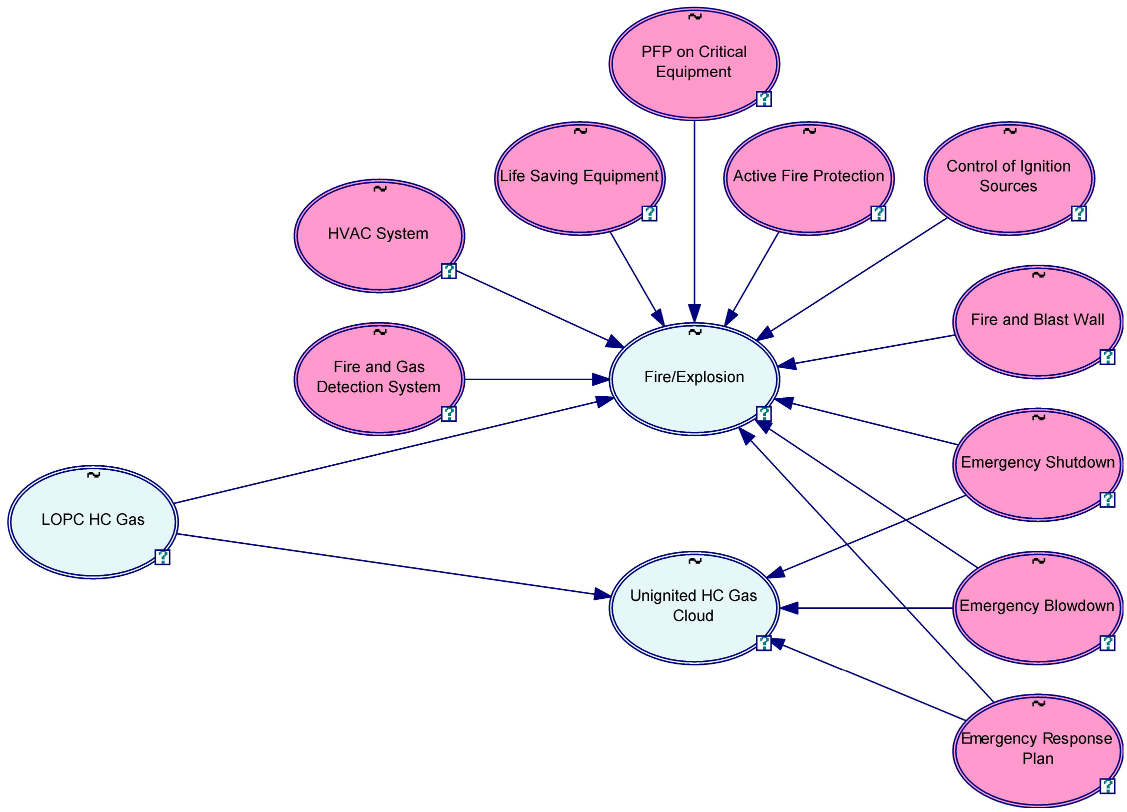

Figure 31: Bow-tie-BN Model Illustrating the Consequences Developed from the LOPC Event

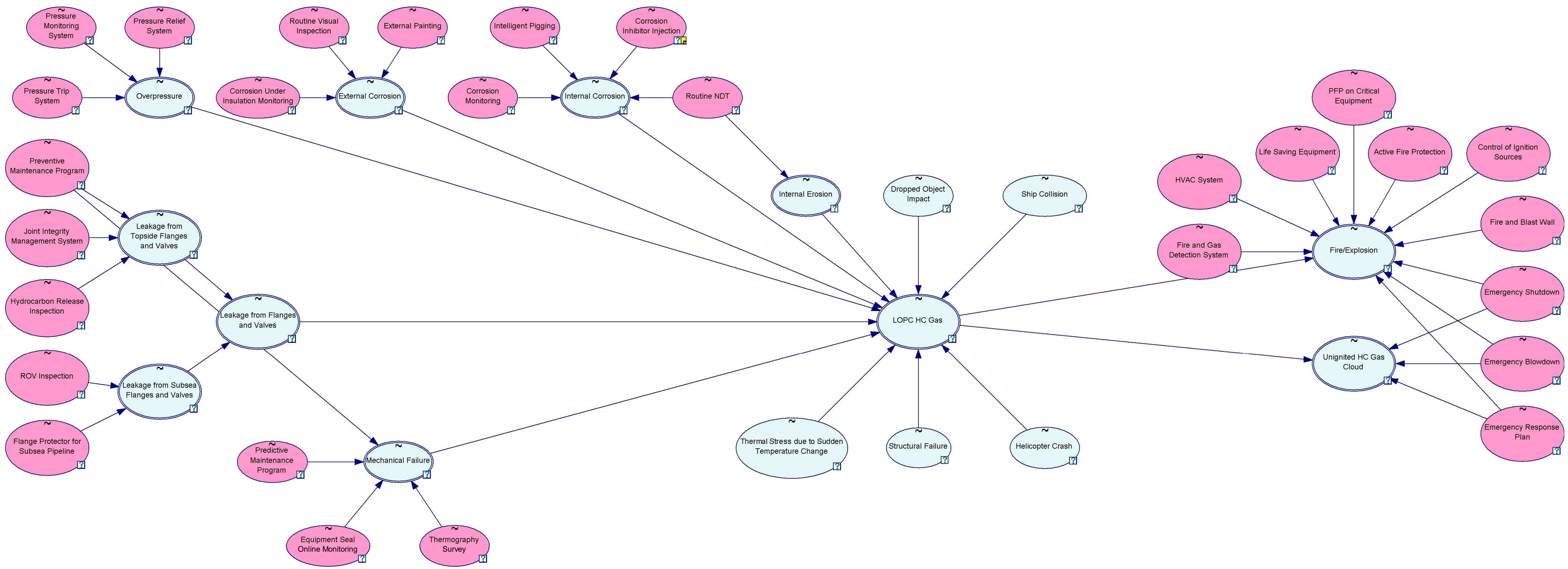

Figure 32: Overview of the Bow-tie-BN Model for the LOPC Event

3.3. Process Safety Indicators Integration

Process safety indicators provide additional observations that refine the probability estimation of an event. Conceptually, the indicators measure the effectiveness or performance of the barrier or safeguard, and can represent as a factor added to the reliability of the barrier or safeguard. However, not all indicators are available for each of the barriers, as some activities are performed without collecting data as key performance indicators. The barriers can be categorized into three types, which are hardware, liveware, and software. Thus, an aggregation approach (M. J. Hassan, 2011; H. Pasman & Rogers, 2014) is adopted where the indicators are also grouped into three categories that match with the types of barriers. These groups of PSIs are mechanical integrity, operational integrity, and personnel integrity. Mechanical integrity impacts the effectiveness of the plant barriers or safeguards, which are physical or passive, such as pressure relief system, fire/blast wall, or painting. Operational integrity affects the procedural barriers, safeguards, or systems that require activation of safety system, such as a pressure trip system or a preventive maintenance program. Lastly, a personnel integrity group influences the probability of success of people barriers or safeguards such as a routine visual inspection and a thermography survey. By aggregating process safety indicators into three groups, causal links between the same types of barrier-indicator pairs can be done. Additionally, connecting three aggregated indicators to the top event is made to represent the causal impact from all barriers to the probability of occurrence of the top event.

In this study, 11 process safety indicators are used for updating of the probability of a LOPC event. A hierarchical framework for asset integrity proposed by Hassan & Khan was adopted (J. Hassan & Khan, 2012). The 11 indicators were individually compared to 279 indicators listed in Hassan's thesis (M. J. Hassan, 2011) and categorized into mechanical integrity, operational integrity, or personnel integrity. All indicators fit into Hassan's classification framework except for tier 1 LOPC, tier 2 LOPC, tier 3 LOPC, and tier 4 LOPC, as these were not normally considered as an asset integrity indicator. Nonetheless, these LOPC indicators reflect a deterioration in all aspects of the asset integrity. Therefore, they are considered to be a part of all integrity types. Table 4 summarized the classification of the process safety indicators.

As mentioned earlier, process safety indicators are used in the performance measurement of various barriers and safeguards installed on the platform. Each type of the indicator has a direct correlation with the same type of barrier/safeguard. In addition to the direct influence on the barriers/safeguards in place, the process safety integrity is also perceived as a precursor to the process safety event, which in this case is a LOPC.

Table 4: Process Safety Indicator Categorization

Process Safety Indicator	Process Safety Integrity		
	Mechanical Integrity	Operational Integrity	Personnel Integrity
Number of tier 1 LOPC	√	√	√
Number of tier 2 LOPC	√	√	√
Number of tier 3 LOPC	√	√	√
Number of failure on test or demand of SCE	√		
Percentage of SCE backlog	√		
Number of unplanned process shutdown		√	
Number of emergency blowdown		√	
Number of tier 4 LOPC	√	√	√
Percentage of contractor companies with approved safety plan			√
Ratio of planned/unplanned maintenance	√		
Number of deviation on SCE in place		√	√

3.4. Prior Probability Definition

The Bayesian network constructed from previous steps provides backbone of the diagram. Next, prior probability values are input into each node. For a purpose of developing a network for the quantitative analysis of different hazard identification methods, several assumptions were made to allow the analysis to be performed without having a burden in collecting myriad amount of real-time operating data. The same set of assumptions is applied to both HAZOP-BN and Bow-tie-BN models for consistency. Basis of the model is also outlined below: -

- Time period of the study is considered to be one month;
- The process safety indicator data is reported on a monthly basis, which is consistent with the time boundary of the model;
- The rate of occurrence of any basic event is assumed to be one time per month. For example, overpressure scenario is assumed to have prior probability of 1 time per month. This prior probability is considered as a demand rate, which will be moderated further by the probability of failure on demand of the barriers or safeguards. Exceptions are made where the basic event does not have barriers or safeguards installed. In such cases, it is assumed that the rate of occurrence is Triangular(Min, Mode, Max) = Triangular(0.01/3, 0.01, 0.01x3);
- Barriers and safeguards are categorized into three groups: hardware; software; and liveware;

- The probability of failure of barriers or safeguards is considered to be the probability of failure on demand of that specific equipment or system. Each type of barriers/safeguards group has the following probability of failure on demand value;
    - Hardware (equipment or passive system): 0.01;
    - Software (procedural control or active system): 0.01;
    - Liveware (human barrier): 0.1.
- A triangular distribution is used to incorporate uncertainties in the point value given above. Thus, the following probability of failure on demand is obtained;
    - Hardware (equipment or passive system): Triangular(Min, Mode, Max) = Triangular(0.01/3, 0.01, 0.01x3);
    - Software (procedural control or active system): Triangular(Min, Mode, Max) = Triangular(0.01/3, 0.01, 0.01x3);
    - Liveware (human barrier): Triangular(Min, Mode, Max) = Triangular(0.1/3, 0.1, 0.1x3).

For PSIs, additional steps are required to convert the basic information obtained from an energy company into the prior probabilities. Raw data are collected for each month of operation. Then, it is normalized by 100,000 man-hours to obtain the rate of occurrence based on hours of operation. This is done to avoid potential mistakes of a prediction when there are uncommon operations such as construction projects that happen in a particular month. Exceptions are made for percentage of SCE backlog, percentage of contractor with approved safety plan, ratio of planned/unplanned maintenance, and number of deviation on SCE in place. This is due to the nature of the indicators which does not conform to the basis of man-hour. Normalized data are given in Table 5 to Table 8.

Table 5: Process Safety Indicator Data for Period 1-6

Process Safety Indicator	**Period / Process Safety Indicator Rate Per 100,000 Man-Hours**					
	1	**2**	**3**	**4**	**5**	**6**
Number of tier 1 LOPC	0.00	0.00	0.00	0.00	0.00	0.00
Number of tier 2 LOPC	0.00	0.00	0.00	0.00	0.00	0.00
Number of tier 3 LOPC	0.00	0.92	1.42	0.00	4.25	1.43
Number of failure on test or demand of SCE	0.00	0.00	2.83	9.70	14.2	9.98
Percentage of SCE backlog	0.00	0.00	0.00	0.00	0.00	0.00
Number of unplanned process shutdown	0.93	1.83	2.83	4.16	2.84	4.28
Number of emergency blowdown	0.00	0.00	0.00	0.00	1.42	0.00
Number of tier 4 LOPC	0.93	2.75	1.42	5.54	5.67	4.28
Percentage of contractor companies with approved safety plan	100	100	100	100	100	100
Ratio of planned/unplanned maintenance	3.04	1.74	2.04	2.88	3.34	1.47
Number of deviation on SCE in place	20	7	18	7	7	6

Table 6: Process Safety Indicator Data for Period 7-12

Process Safety Indicator	**Period / Process Safety Indicator Rate Per 100,000 Man-Hours**					
	7	**8**	**9**	**10**	**11**	**12**
Number of tier 1 LOPC	0.00	0.00	0.00	0.00	0.00	0.00
Number of tier 2 LOPC	0.00	0.00	0.00	0.00	0.00	0.00
Number of tier 3 LOPC	0.00	0.00	0.00	0.46	1.88	0.00
Number of failure on test or demand of SCE	1.38	4.50	3.12	2.75	3.13	2.56
Percentage of SCE backlog	0.00	0.00	0.00	0.00	0.00	0.00
Number of unplanned process shutdown	6.91	13.5	1.25	2.75	1.25	6.39
Number of emergency blowdown	1.38	0.00	0.00	1.38	0.00	2.56
Number of tier 4 LOPC	5.53	6.01	1.87	1.84	2.51	5.11
Percentage of contractor companies with approved safety plan	100	100	100	100	100	100
Ratio of planned/unplanned maintenance	1.87	2.83	1.89	7.36	3.04	4.07
Number of deviation on SCE in place	1	1	6	1	7	7

Table 7: Process Safety Indicator Data for Period 13-18

Process Safety Indicator	**Period / Process Safety Indicator Rate Per 100,000 Man-Hours**					
	13	**14**	**15**	**16**	**17**	**18**
Number of tier 1 LOPC	0.00	0.00	0.00	0.00	0.00	0.00
Number of tier 2 LOPC	0.00	0.00	0.00	0.00	0.00	0.94
Number of tier 3 LOPC	0.00	0.00	0.00	0.00	0.00	0.00
Number of failure on test or demand of SCE	4.12	0.87	1.26	1.45	4.28	0.94
Percentage of SCE backlog	0.00	0.00	0.00	0.00	0.00	0.00
Number of unplanned process shutdown	6.18	0.00	1.68	1.45	0.86	2.82
Number of emergency blowdown	2.06	0.00	0.00	1.45	0.86	1.88
Number of tier 4 LOPC	3.09	2.62	0.84	3.62	4.28	2.82
Percentage of contractor companies with approved safety plan	100	0.00	0.00	0.00	0.00	0.00
Ratio of planned/unplanned maintenance	2.14	2.59	1.78	1.90	2.19	2.15
Number of deviation on SCE in place	9	0	18	7	4	2

Table 8: Process Safety Indicator Data for Period 19-24

Process Safety Indicator	**Period / Process Safety Indicator Rate Per 100,000 Man-Hours**					
	19	**20**	**21**	**22**	**23**	**24**
Number of tier 1 LOPC	0.00	0.00	0.00	0.00	0.00	0.00
Number of tier 2 LOPC	0.00	0.00	0.00	0.00	0.00	0.00
Number of tier 3 LOPC	0.00	0.00	0.00	0.00	0.00	0.00
Number of failure on test or demand of SCE	0.91	9.62	0.00	2.24	2.66	0.00
Percentage of SCE backlog	0.00	1.82	1.16	0.00	0.00	0.00
Number of unplanned process shutdown	0.91	0.00	0.68	0.00	0.89	5.82
Number of emergency blowdown	0.00	0.00	0.00	0.00	0.00	3.49
Number of tier 4 LOPC	0.91	0.60	0.68	6.71	0.89	3.49
Percentage of contractor companies with approved safety plan	0.00	0.00	0.00	0.00	0.00	0.00
Ratio of planned/unplanned maintenance	2.31	2.07	5.09	4.53	4.56	1.20
Number of deviation on SCE in place	2	7	4	1	5	5

Then, for each indicator, a histogram was made to visualize the shape of the distribution. Sturges' rule is applied for calculating the number of bin for the histogram. Since there are 24 data for 24 months reporting period, the total number of bin is six. Figure 33 demonstrates the histogram that was made for the number of unplanned process shutdown indicator.

Equation 4: Sturges' Formula

$$Number\ of\ bin = \lceil \log_2(number\ of\ data) \rceil + 1$$

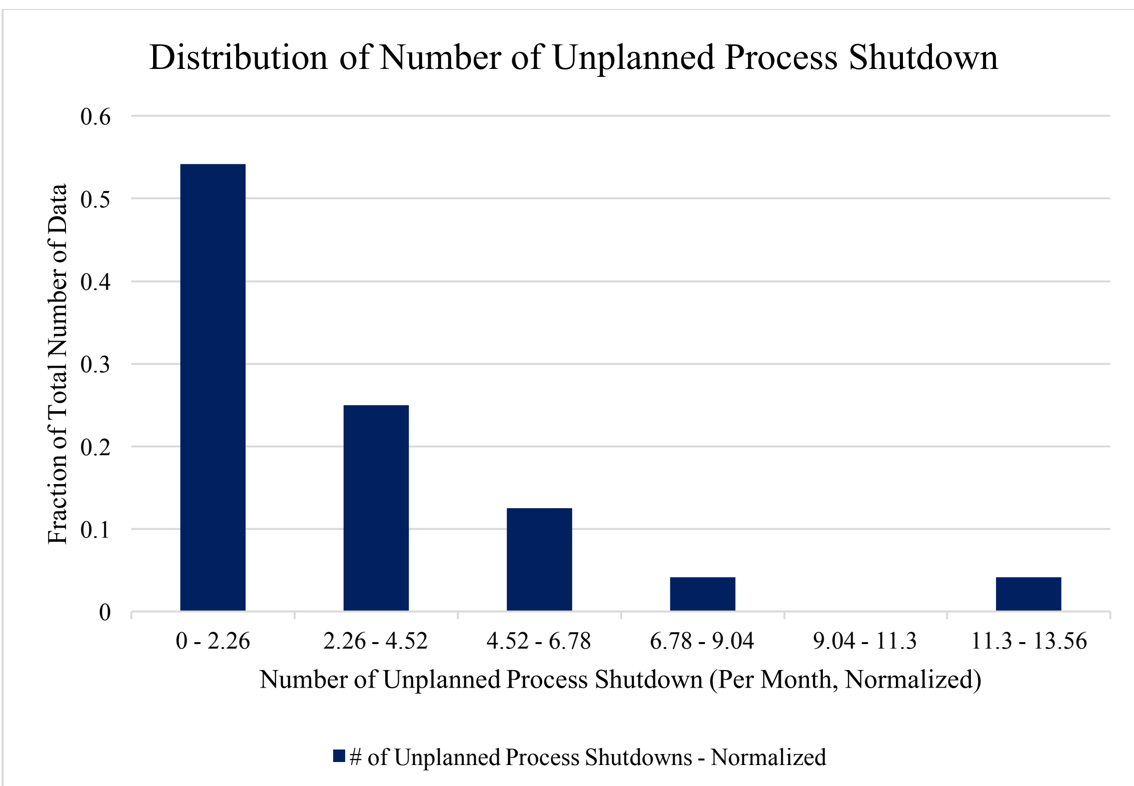

Figure 33: Histogram of the Number of Unplanned Process Shutdown Indicator

After the histogram was made, a specific distribution was sought by mapping multiple distribution types to the histogram. Four types of distribution comprised of Exponential distribution, Gamma distribution, Weibull distribution, and Uniform distribution were pre-selected due to the characteristics of the histograms. Probability density functions for each of the distribution are given in Equation 5 to Equation 7. The sum of error squared method is performed for each type of distribution against the actual data. The distribution type that has the least value of the sum of error squared is selected. The analysis is done using Microsoft Excel 2016. The representative distribution for the number of unplanned process shutdown indicator is shown in Figure 34.

Equation 5: Exponential(λ) Probability Density Function

$$f(x;\ \lambda) = \lambda e^{-\lambda x}$$

Equation 6: Gamma(α, β) Probability Density Function

$$f(x;\ \alpha, \beta) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-\frac{x}{\beta}}$$

Equation 7: Weibull(α, β) Probability Density Function

$$f(x;\ \alpha, \beta) = \frac{\alpha}{\beta^{\alpha}} x^{\alpha-1} e^{-\left(\frac{x}{\beta}\right)^{\alpha}}$$

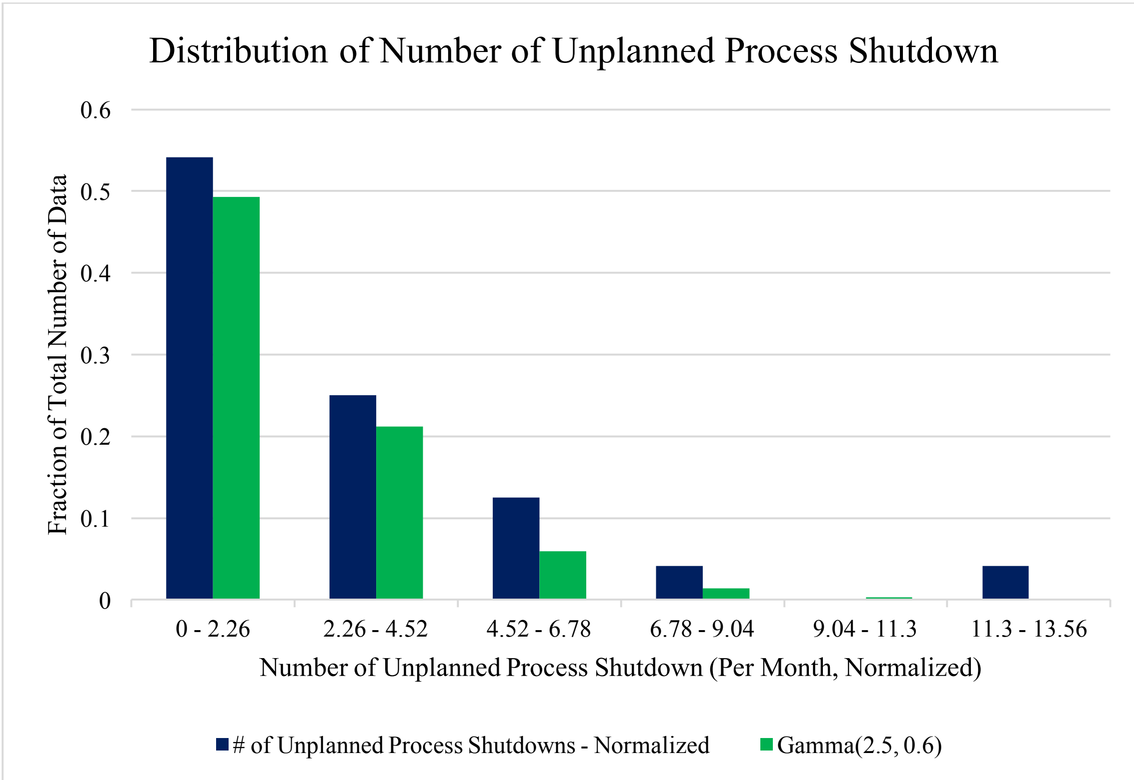

Figure 34: Histogram of the Number of Unplanned Process Shutdown Indicator and the Gamma Distribution

The histograms were made for all indicators except for tier 1 LOPC and tier 2 LOPC. From Table 5 to Table 8, it can be observed that tier 1 LOPC indicator data are nil for all months and only one data appears for tier 2 LOPC on the 18^{th} month. This is due to the low probability of occurrence for a large scale release in a single facility. Therefore, industrial-wide generic data are obtained from IOGP, which collected data from over 30 companies. The rate of tier 1 and tier 2 LOPC were reported as 2.23 and 5.43 times per 100,000 man-hours, respectively (IOGP, 2015). Thus, the prior probability for tier 1 LOPC and tier 2 LOPC were assumed to be Triangular(2.23/3, 2.23, 2.23x3) and Triangular(5.43/3, 5.43, 5.43x3), respectively. Table 9 summarizes the prior distribution defined for each process safety indicator.

In order to proceed to the next step of the study, the prior distributions of these PSIs are discretized into three classes; high, medium, and low. Each class is assigned with a point value as detailed below. It should be noted that these values are arbitrarily set for the purpose of the study and do not reflect the real effect on the barriers' performances, which should be studied further in the future.

- "High" class is assigned with the value of 1, i.e. representing strong performance and, consequently, would not alter the probability of failure on demand of the barrier/safeguard. The PSI values that exceed the mean plus 1 standard deviation are categorized into this class;
- "Medium" class is assigned with the value of 0.9, i.e. representing average performance. The PSI values that are between the mean and 1 standard deviation are categorized into this class;
- "Low" class is assigned with the value of 0.5, i.e. representing poor performance. The PSI values that are below the mean minus 1 standard deviation are categorized into this class.

Table 9: Prior Distribution Defined for Each Process Safety Indicator

Process Safety Indicator	Representative Prior Distribution
Number of tier 1 LOPC	Triangular(2.23/3, 2.23, 2.23x3)
Number of tier 2 LOPC	Triangular(5.43/3, 5.43, 5.43x3)
Number of tier 3 LOPC	Gamma(0.5, 0.5)
Number of failure on test or demand of SCE	Weibull(2.5, 2)
Percentage of SCE backlog	Gamma(0.2, 0.3)
Number of unplanned process shutdown	Gamma(2.5, 0.6)
Number of emergency blowdown	Weibull(0.5, 0.12)
Number of tier 4 LOPC	Weibull(0.85, 2.5)
Percentage of contractor companies with approved safety plan	Uniform
Ratio of planned/unplanned maintenance	Weibull(1.8, 1.7)
Number of deviation on SCE in place	Exponential(0.3)

An indicators aggregation step is executed by adding up the value of specific indicators and dividing by the number of the indicator in the group to obtain the value between 0 and 1. For example, mechanical integrity group consists of seven process safety indicators. If six of the indicators are categorized in "high" class and one is in "low" class, then the mechanical integrity value is calculated as $\frac{(1)(6)+(0.9)(0)+(0.5)(1)}{7} = 0.9286$. The BN model for the PSI aggregation is shown in Figure 35 to Figure 37.

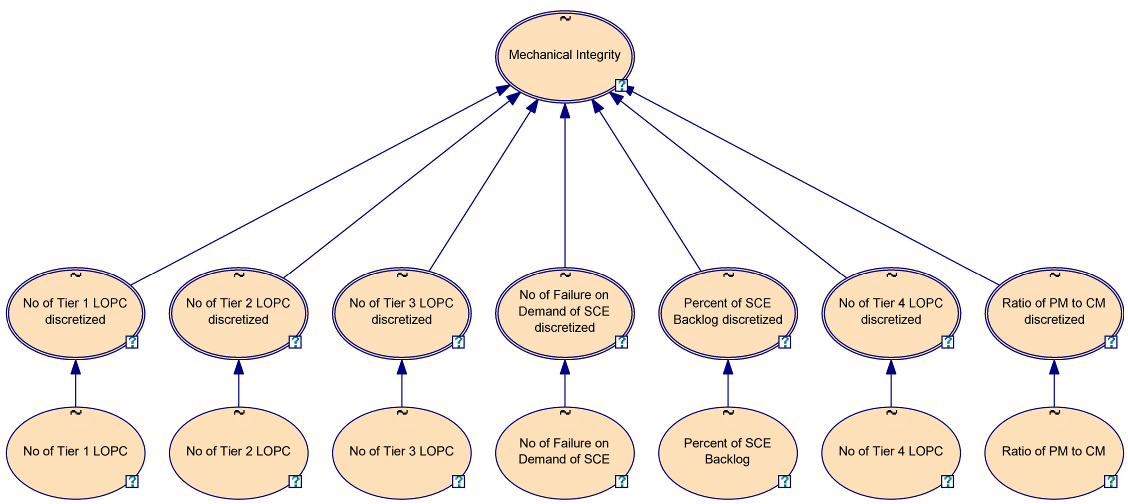

Figure 35: BN Model Illustrating the Aggregation of PSIs into Mechanical Integrity Element

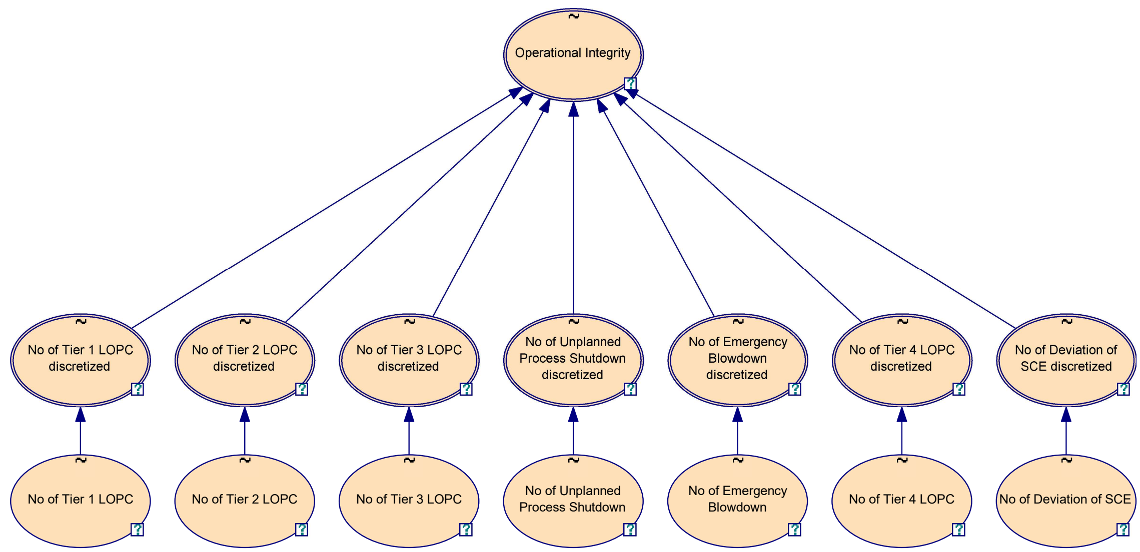

Figure 36: BN Model Illustrating the Aggregation of PSIs into Operational Integrity Element

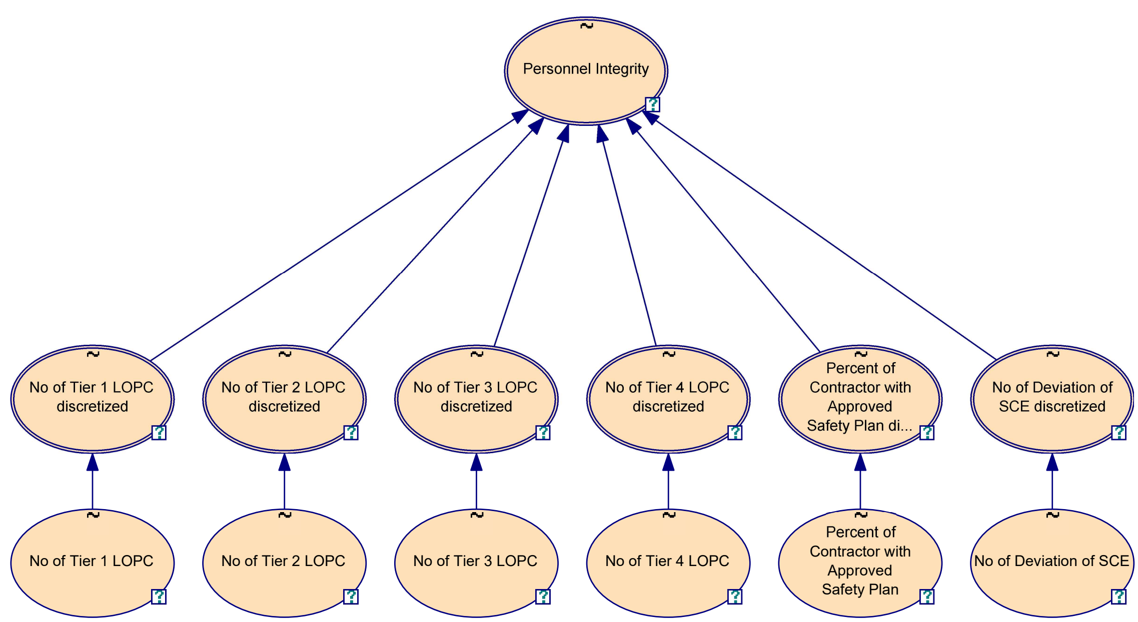

Figure 37: BN Model Illustrating the Aggregation of PSIs into Personnel Integrity Element

The calculated mechanical integrity, operational integrity, and personnel integrity are integrated into the BN by dividing the probability of failure on demand of the barrier by the computed value. For example, the pressure relief system barrier from the Bow-tie-BN model has the probability of failure on demand of Triangular(0.01/3, 0.01, 0.01x3). The barrier is categorized as a hardware barrier. If the mechanical integrity is 0.5, that means the modified probability of failure on demand for the barrier will be doubled.

To calculate the modified probability of failure on demand for the LOPC event, the mechanical integrity, operational integrity, and personnel integrity were combined using weight factor of 0.4, 0.34, and 0.26, respectively. These weight factor values are obtained from Hassan's study (M. J. Hassan, 2011). Then, this number is applied as a denominator for the LOPC node. When combine with the arbitrary number defined for each of the integrities, it can be projected that low integrity level will double the probability of occurrence of LOPC, and medium, and high integrity will result in about 10%, and 0% increase in the probability value, respectively.

Figure 38 and Figure 39 represent the overall HAZOP-BN and Bow-tie-BN model, respectively. Defined equation for each of the node in the model is elaborated in Table 10 and Table 11.

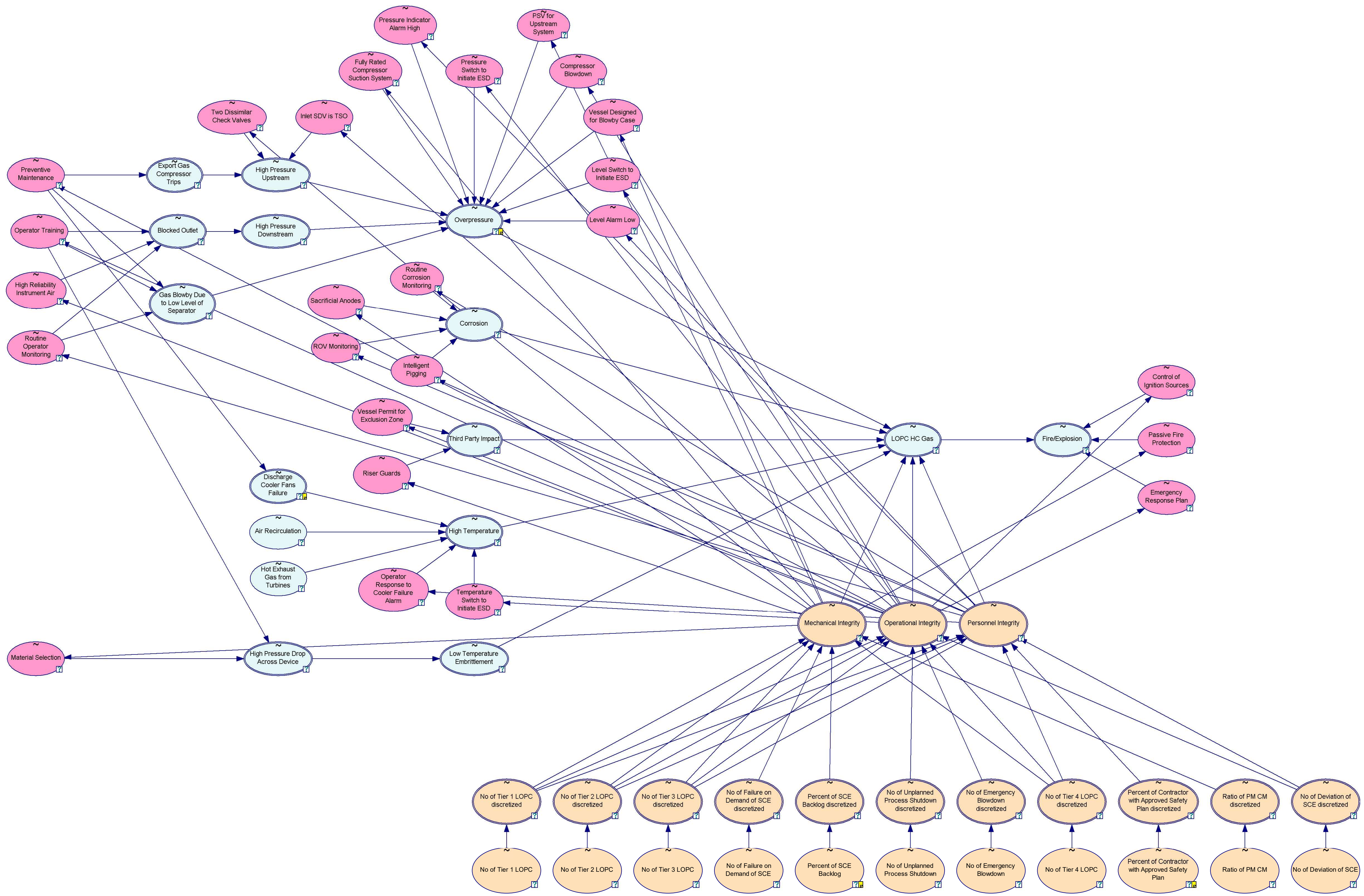

Figure 38: Overview of the HAZOP-BN Model for the LOPC Event with PSIs Integration

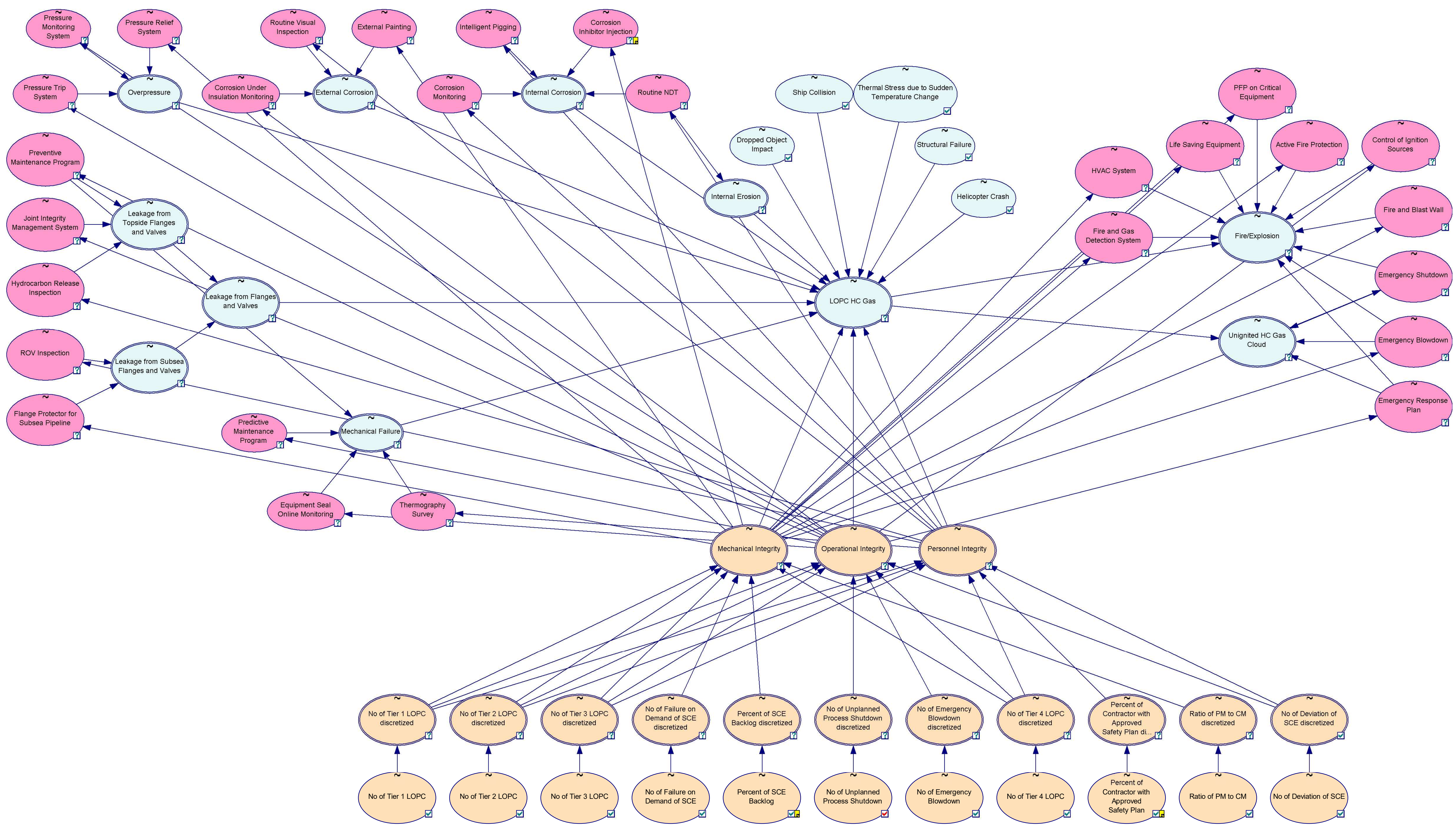

Figure 39: Overview of the Bow-tie-BN Model for the LOPC Event with PSIs Integration

Table 10: Defined Equation for HAZOP-BN Model

Node	Type	Defined Equation
Air Recirculation	Event	Air_Recirculation = Triangular(0.01/3, 0.01, 0.01*3)
Blocked Outlet	Event	Blocked_Outlet = 1 - (1 - High_Reliability_Instrument_Air) * (1 - Operator_Training * Routine_Operator_Monitoring)
Compressor Blowdown	Software Barrier	Compressor_Blowdown = Triangular(0.01/3, 0.01, 0.01*3) / Operational_Integrity
Control of Ignition Sources	Software Barrier	Control_of_Ignition_Sources = Triangular(0.01/3, 0.01, 0.01*3) / Operational_Integrity
Corrosion	Event	Corrosion = Sacrificial_Anodes * (1 - (1 - Routine_Corrosion_Monitoring) * (1 - ROV_Monitoring) * (1 - Intelligent_Pigging))
Discharge Cooler Fans Failure	Event	Discharge_Cooler_Fans_Failure = Preventive_Maintenance
Emergency Response Plan	Software Barrier	Emergency_Response_Plan = Triangular(0.01/3, 0.01, 0.01*3) / Operational_Integrity
Export Gas Compressor Trips	Event	Export_Gas_Compressor_Trips = Preventive_Maintenance

Table 10 Continued

Node	Type	Defined Equation
Fire/Explosion	Event	Fire_Explosion = LOPC_HC_Gas * Control_of_Ignition_Sources * Passive_Fire_Protection * Emergency_Response_Plan
Fully Rated Compressor Suction System	Hardware Barrier	Fully_Rated_Compressor_Suction_System = Triangular(0.01/3, 0.01, 0.01*3) / Mechanical_Integrity
Gas Blowby Due to Low Level of Separator	Event	Gas_Blowby_Due_to_Low_Level_of_Separator = Operator_Training * (1 - (1 - Preventive_Maintenance) * (1 - Routine_Operator_Monitoring))
High Pressure Downstream	Event	High_Pressure_Downstream = Blocked_Outlet
High Pressure Drop Across Device	Event	High_Pressure_Drop_Across_Device = 1 - (1 - Operator_Training) * (1 - Material_Selection)
High Pressure Upstream	Event	High_Pressure_Upstream = Export_Gas_Compressor_Trips * Two_Dissimilar_Check_Valves * Inlet_SDV_is_TSO

Table 10 Continued

Node	Type	Defined Equation
High Reliability Instrument Air	Software Barrier	High_Reliability_Instrument_Air = Triangular(0.01/3, 0.01, 0.01*3) / Operational_Integrity
High Temperature	Event	High_Temperature = (1 - (1 - Discharge_Cooler_Fans_Failure) * (1 - Air_Recirculation) * (1 - Hot_Exhaust_Gas_from_Turbines)) * Operator_Response_to_Cooler_Failure_Alarm * Temperature_Switch_to_Initiate_ESD
Hot Exhaust Gas from Turbines	Event	Hot_Exhaust_Gas_from_Turbines = Triangular(0.01/3, 0.01, 0.01*3)
Inlet SDV is TSO	Software Barrier	Inlet_SDV_is_TSO = Triangular(0.01/3, 0.01, 0.01*3) / Operational_Integrity
Intelligent Pigging	Liveware Barrier	Intelligent_Pigging = Triangular(0.1/3, 0.1, 0.1*3) / Personnel_Integrity

Table 10 Continued

Node	Type	Defined Equation
LOPC HC Gas	Event	LOPC_HC_Gas = (1 - (1 - Overpressure) * (1 - Corrosion) * (1 - Third_Party_Impact) * (1 - High_Temperature) * (1 - Low_Temperature_Embrittlement)) / (0.4 * Mechanical_Integrity + 0.34 * Operational_Integrity + 0.26 * Personnel_Integrity)
Level Alarm Low	Liveware Barrier	Level_Alarm_Low = Triangular(0.1/3, 0.1, 0.1*3) / Personnel_Integrity
Level Switch to Initiate ESD	Software Barrier	Level_Switch_to_Initiate_ESD = Triangular(0.01/3, 0.01, 0.01*3) / Operational_Integrity
Low Temperature Embrittlement	Event	Low_Temperature_Embrittlement = High_Pressure_Drop_Across_Device
Material Selection	Hardware Barrier	Material_Selection = Triangular(0.01/3, 0.01, 0.01*3) / Mechanical_Integrity

Table 10 Continued

Node	Type	Defined Equation
Mechanical Integrity	Element Indicator	Mechanical_Integrity = (No_of_Tier_1_LOPC_discretized + No_of_Tier_2_LOPC_discretized + No_of_Tier_3_LOPC_discretized + No_of_Failure_on_Demand_of_SCE_discretized + Percent_of_SCE_Backlog_discretized + No_of_Tier_4_LOPC_discretized + Ratio_of_PM_CM_discretized) / 7
No of Deviation of SCE	Specific Indicator	No_of_Deviation_of_SCE = Exponential(0.3)
No of Deviation of SCE discretized	Specific Indicator	No_of_Deviation_of_SCE_discretized = If(No_of_Deviation_of_SCE < 0.1, 1, If(No_of_Deviation_of_SCE < 6.67, 0.9, 0.5))
No of Emergency Blowdown	Specific Indicator	No_of_Emergency_Blowdown = Weibull(0.5, 0.12)
No of Emergency Blowdown discretized	Specific Indicator	No_of_Emergency_Blowdown_discretized = If(No_of_Emergency_Blowdown < 0.01, 1, If(No_of_Emergency_Blowdown < 0.78, 0.9, 0.5))

Table 10 Continued

Node	Type	Defined Equation
No of Failure on Demand of SCE	Specific Indicator	No_of_Failure_on_Demand_of_SCE = Weibull(2.5, 2)
No of Failure on Demand of SCE discretized	Specific Indicator	No_of_Failure_on_Demand_of_SCE_discretized = If(No_of_Failure_on_Demand_of_SCE < 1.02, 1, If(No_of_Failure_on_Demand_of_SCE < 2.53, 0.9, 0.5))
No of Tier 1 LOPC	Specific Indicator	No_of_Tier_1_LOPC = Triangular(0.7444, 2.2333, 6.7)
No of Tier 1 LOPC discretized	Specific Indicator	No_of_Tier_1_LOPC_discretized = If(No_of_Tier_1_LOPC < 1.96, 1, If(No_of_Tier_1_LOPC < 4.49, 0.9, 0.5))
No of Tier 2 LOPC	Specific Indicator	No_of_Tier_2_LOPC = Triangular(1.8111, 5.4333, 16.3)
No of Tier 2 LOPC discretized	Specific Indicator	No_of_Tier_2_LOPC_discretized = If(No_of_Tier_2_LOPC < 4.77, 1, If(No_of_Tier_2_LOPC < 10.93, 0.9, 0.5))
No of Tier 3 LOPC	Specific Indicator	No_of_Tier_3_LOPC = Gamma(0.5, 0.5)

Table 10 Continued

Node	Type	Defined Equation
No of Tier 3 LOPC discretized	Specific Indicator	No_of_Tier_3_LOPC_discretized = If(No_of_Tier_3_LOPC < 0.01, 1, If(No_of_Tier_3_LOPC < 0.6, 0.9, 0.5))
No of Tier 4 LOPC	Specific Indicator	No_of_Tier_4_LOPC = Weibull(0.85, 2.5)
No of Tier 4 LOPC discretized	Specific Indicator	No_of_Tier_4_LOPC_discretized = If(No_of_Tier_4_LOPC < 0.1, 1, If(No_of_Tier_4_LOPC < 5.93, 0.9, 0.5))
No of Unplanned Process Shutdown	Specific Indicator	No_of_Unplanned_Process_Shutdown = Gamma(2.5, 0.6)
No of Unplanned Process Shutdown discretized	Specific Indicator	No_of_Unplanned_Process_Shutdown_discretized = If(No_of_Unplanned_Process_Shutdown < 0.55, 1, If(No_of_Unplanned_Process_Shutdown < 2.45, 0.9, 0.5))

Table 10 Continued

Node	Type	Defined Equation
Operational Integrity	Element Indicator	Operational_Integrity = (No_of_Tier_1_LOPC_discretized + No_of_Tier_2_LOPC_discretized + No_of_Tier_3_LOPC_discretized + No_of_Unplanned_Process_Shutdown_discretized + No_of_Emergency_Blowdown_discretized + No_of_Tier_4_LOPC_discretized + No_of_Deviation_of_SCE_discretized) / 7
Operator Response to Cooler Failure Alarm	Liveware Barrier	Operator_Response_to_Cooler_Failure_Alarm = Triangular(0.1/3, 0.1, 0.1*3) / Personnel_Integrity
Operator Training	Software Barrier	Operator_Training = Triangular(0.01/3, 0.01, 0.01*3) / Operational_Integrity

Table 10 Continued

Node	Type	Defined Equation
Overpressure	Event	Overpressure = 1 - (1 - High_Pressure_Upstream * Pressure_Indicator_Alarm_High * Fully_Rated_Compressor_Suction_System * Compressor_Blowdown * PSV_for_Upstream_System) * (1 - High_Pressure_Downstream * Fully_Rated_Compressor_Suction_System * Pressure_Switch_to_Initiate_ESD) * (1 - Gas_Blowby_Due_to_Low_Level_of_Separator * Vessel_Designed_for_Blowby_Case * Pressure_Switch_to_Initiate_ESD * Level_Switch_to_Initiate_ESD * Level_Alarm_Low)
PSV for Upstream System	Hardware Barrier	PSV_for_Upstream_System = Triangular(0.01/3, 0.01, 0.01*3) / Mechanical_Integrity
Passive Fire Protection	Hardware Barrier	Passive_Fire_Protection = Triangular(0.01/3, 0.01, 0.01*3) / Mechanical_Integrity

Table 10 Continued

Node	Type	Defined Equation
Percent of Contractor with Approved Safety Plan	Specific Indicator	Percent_of_Contractor_with_Approved_Safety_Plan = Uniform(0, 100)
Percent of Contractor with Approved Safety Plan discretized	Specific Indicator	Percent_of_Contractor_with_Approved_Safety_Plan_discretized = If((100 - Percent_of_Contractor_with_Approved_Safety_Plan) / 100 < 0.21, 1, If((100 - Percent_of_Contractor_with_Approved_Safety_Plan) / 100 < 0.8, 0.9, 0.5))
Percent of SCE Backlog	Specific Indicator	Percent_of_SCE_Backlog = Gamma(0.2, 0.3)
Percent of SCE Backlog discretized	Specific Indicator	Percent_of_SCE_Backlog_discretized = If(Percent_of_SCE_Backlog < 0.001, 1, If(Percent_of_SCE_Backlog < 0.19, 0.9, 0.5))

Table 10 Continued

Node	Type	Defined Equation
Personnel Integrity	Element Indicator	Personnel_Integrity = (No_of_Tier_1_LOPC_discretized + No_of_Tier_2_LOPC_discretized + No_of_Tier_3_LOPC_discretized + No_of_Tier_4_LOPC_discretized + Percent_of_Contractor_with_Approved_Safety_Plan_discretized + No_of_Deviation_of_SCE_discretized) / 6
Pressure Indicator Alarm High	Liveware Barrier	Pressure_Indicator_Alarm_High = Triangular(0.1/3, 0.1, 0.1*3) / Personnel_Integrity
Pressure Switch to Initiate ESD	Software Barrier	Pressure_Switch_to_Initiate_ESD = Triangular(0.01/3, 0.01, 0.01*3) / Operational_Integrity
Preventive Maintenance	Software Barrier	Preventive_Maintenance = Triangular(0.01/3, 0.01, 0.01*3) / Operational_Integrity
ROV Monitoring	Liveware Barrier	ROV_Monitoring = Triangular(0.1/3, 0.1, 0.1*3) / Personnel_Integrity
Ratio of PM CM	Specific Indicator	Ratio_of_PM_CM = Weibull(1.8, 1.7)

Table 10 Continued

Node	Type	Defined Equation
Ratio of PM CM discretized	Specific Indicator	Ratio_of_PM_CM_discretized = If(Ratio_of_PM_CM > 2.38, 1, If(Ratio_of_PM_CM > 0.64, 0.9, 0.5))
Riser Guards	Hardware Barrier	Riser_Guards = Triangular(0.01/3, 0.01, 0.01*3) / Mechanical_Integrity
Routine Corrosion Monitoring	Liveware Barrier	Routine_Corrosion_Monitoring = Triangular(0.1/3, 0.1, 0.1*3) / Personnel_Integrity
Routine Operator Monitoring	Liveware Barrier	Routine_Operator_Monitoring = Triangular(0.1/3, 0.1, 0.1*3) / Personnel_Integrity
Sacrificial Anodes	Hardware Barrier	Sacrificial_Anodes = Triangular(0.01/3, 0.01, 0.01*3) / Mechanical_Integrity
Temperature Switch to Initiate ESD	Software Barrier	Temperature_Switch_to_Initiate_ESD = Triangular(0.01/3, 0.01, 0.01*3) / Operational_Integrity
Third Party Impact	Event	Third_Party_Impact = Riser_Guards * Vessel_Permit_for_Exclusion_Zone
Two Dissimilar Check Valves	Hardware Barrier	Two_Dissimilar_Check_Valves = Triangular(0.01/3, 0.01, 0.01*3) * Triangular(0.01/3, 0.01, 0.01*3) / Mechanical_Integrity

Table 10 Continued

Node	Type	Defined Equation
Vessel Designed for Blowby Case	Hardware Barrier	Vessel_Designed_for_Blowby_Case = Triangular(0.01/3, 0.01, 0.01*3) / Mechanical_Integrity
Vessel Permit for Exclusion Zone	Software Barrier	Vessel_Permit_for_Exclusion_Zone = Triangular(0.01/3, 0.01, 0.01*3) / Operational_Integrity

Table 11: Defined Equation for Bow-tie-BN Model

Node	Type	Defined Equation
Active Fire Protection	Hardware Barrier	Active_Fire_Protection = Triangular(0.01/3, 0.01, 0.01*3) / Mechanical_Integrity
Control of Ignition Sources	Software Barrier	Control_of_Ignition_Sources = Triangular(0.01/3, 0.01, 0.01*3) / Operational_Integrity
Corrosion Inhibitor Injection	Hardware Barrier	Corrosion_Inhibitor_Injection = Triangular(0.01/3, 0.01, 0.01*3) / Mechanical_Integrity
Corrosion Monitoring	Liveware Barrier	Corrosion_Monitoring = Triangular(0.1/3, 0.1, 0.1*3) / Personnel_Integrity
Corrosion Under Insulation Monitoring	Software Barrier	Corrosion_Under_Insulation_Monitoring = Triangular(0.01/3, 0.01, 0.01*3) / Operational_Integrity
Dropped Object Impact	Event	Dropped_Object_Impact = Triangular(0.01/3, 0.01, 0.01*3)
Emergency Blowdown	Hardware Barrier	Emergency_Blowdown = Triangular(0.01/3, 0.01, 0.01*3) / Mechanical_Integrity
Emergency Response Plan	Software Barrier	Emergency_Response_Plan = Triangular(0.01/3, 0.01, 0.01*3) / Operational_Integrity
Emergency Shutdown	Hardware Barrier	Emergency_Shutdown = Triangular(0.01/3, 0.01, 0.01*3) / Mechanical_Integrity

Table 11 Continued

Node	Type	Defined Equation
Equipment Seal Online Monitoring	Software Barrier	Equipment_Seal_Online_Monitoring = Triangular(0.01/3, 0.01, 0.01*3) / Operational_Integrity
External Corrosion	Event	External_Corrosion = External_Painting * (1 - (1 - Routine_Visual_Inspection) * (1 - Corrosion_Under_Insulation_Monitoring))
External Painting	Hardware Barrier	External_Painting = Triangular(0.01/3, 0.01, 0.01*3) / Mechanical_Integrity
Fire and Blast Wall	Hardware Barrier	Fire_and_Blast_Wall = Triangular(0.01/3, 0.01, 0.01*3) / Mechanical_Integrity
Fire and Gas Detection System	Hardware Barrier	Fire_and_Gas_Detection_System = Triangular(0.01/3, 0.01, 0.01*3) / Mechanical_Integrity

Table 11 Continued

Node	Type	Defined Equation
Fire/Explosion	Event	Fire_Explosion = LOPC_HC_Gas * Fire_and_Blast_Wall * Control_of_Ignition_Sources * Active_Fire_Protection * Emergency_Shutdown * Emergency_Blowdown * Emergency_Response_Plan * PFP_on_Critical_Equipment * Life_Saving_Equipment * HVAC_System * Fire_and_Gas_Detection_System
Flange Protector for Subsea Pipeline	Hardware Barrier	Flange_Protector_for_Subsea_Pipeline = Triangular(0.01/3, 0.01, 0.01*3) / Mechanical_Integrity
HVAC System	Hardware Barrier	HVAC_System = Triangular(0.01/3, 0.01, 0.01*3) / Mechanical_Integrity
Helicopter Crash	Event	Helicopter_Crash = Triangular(0.01/3, 0.01, 0.01*3)
Hydrocarbon Release Inspection	Liveware Barrier	Hydrocarbon_Release_Inspection = Triangular(0.1/3, 0.1, 0.1*3) / Personnel_Integrity
Intelligent Pigging	Liveware Barrier	Intelligent_Pigging = Triangular(0.1/3, 0.1, 0.1*3) / Personnel_Integrity

Table 11 Continued

Node	Type	Defined Equation
Internal Corrosion	Event	Internal_Corrosion = (1 - (1 - Intelligent_Pigging) * (1 - Corrosion_Monitoring) * (1 - Routine_NDT)) * Corrosion_Inhibitor_Injection
Internal Erosion	Event	Internal_Erosion = Routine_NDT
Joint Integrity Management System	Software Barrier	Joint_Integrity_Management_System = Triangular(0.01/3, 0.01, 0.01*3) / Operational_Integrity
LOPC HC Gas	Event	LOPC_HC_Gas = (1 - (1 - Internal_Corrosion) * (1 - External_Corrosion) * (1 - Overpressure) * (1 - Leakage_from_Flanges_and_Valves) * (1 - Mechanical_Failure) * (1 - Internal_Erosion) * (1 - Dropped_Object_Impact) * (1 - Structural_Failure) * (1 - Helicopter_Crash) * (1 - Ship_Collision) * (1 - Thermal_Stress_due_to_Sudden_Temperature_Change)) / (0.4 * Mechanical_Integrity + 0.34 * Operational_Integrity + 0.26 * Personnel_Integrity)
Leakage from Flanges and Valves	Event	Leakage_from_Flanges_and_Valves = 1 - (1 - Leakage_from_Subsea_Flanges_and_Valves) * (1 - Leakage_from_Topside_Flanges_and_Valves)

Table 11 Continued

Node	Type	Defined Equation
Leakage from Subsea Flanges and Valves	Event	Leakage_from_Subsea_Flanges_and_Valves = ROV_Inspection * Flange_Protector_for_Subsea_Pipeline
Leakage from Topside Flanges and Valves	Event	Leakage_from_Topside_Flanges_and_Valves = 1 - (1 - Preventive_Maintenance_Program * Joint_Integrity_Management_System) * (1 - Preventive_Maintenance_Program * Hydrocarbon_Release_Inspection) * (1 - Joint_Integrity_Management_System * Hydrocarbon_Release_Inspection)
Life Saving Equipment	Hardware Barrier	Life_Saving_Equipment = Triangular(0.01/3, 0.01, 0.01*3) / Mechanical_Integrity

Table 11 Continued

Node	Type	Defined Equation
Mechanical Failure	Event	Mechanical_Failure = 1 - (1 - Preventive_Maintenance_Program * Predictive_Maintenance_Program) * (1 - Preventive_Maintenance_Program * Equipment_Seal_Online_Monitoring) * (1 - Preventive_Maintenance_Program * Thermography_Survey) * (1 - Predictive_Maintenance_Program * Equipment_Seal_Online_Monitoring) * (1 - Predictive_Maintenance_Program * Thermography_Survey) * (1 - Equipment_Seal_Online_Monitoring * Thermography_Survey)

Table 11 Continued

Node	Type	Defined Equation
Mechanical Integrity	Element Indicator	Mechanical_Integrity = (No_of_Tier_1_LOPC_discretized + No_of_Tier_2_LOPC_discretized + No_of_Tier_3_LOPC_discretized + No_of_Failure_on_Demand_of_SCE_discretized + Percent_of_SCE_Backlog_discretized + No_of_Tier_4_LOPC_discretized + Ratio_of_PM_to_CM_discretized) / 7
No of Deviation of SCE	Specific Indicator	No_of_Deviation_of_SCE = Exponential(0.3)
No of Deviation of SCE discretized	Specific Indicator	No_of_Deviation_of_SCE_discretized = If(No_of_Deviation_of_SCE < 0.1, 1 , If(No_of_Deviation_of_SCE < 6.67, 0.9, 0.5))
No of Emergency Blowdown	Specific Indicator	No_of_Emergency_Blowdown = Weibull(0.5, 0.12)
No of Emergency Blowdown discretized	Specific Indicator	No_of_Emergency_Blowdown_discretized = If(No_of_Emergency_Blowdown < 0.01, 1, If(No_of_Emergency_Blowdown < 0.78, 0.9, 0.5))

Table 11 Continued

Node	Type	Defined Equation
No of Failure on Demand of SCE	Specific Indicator	No_of_Failure_on_Demand_of_SCE = Weibull(2.5, 2)
No of Failure on Demand of SCE discretized	Specific Indicator	No_of_Failure_on_Demand_of_SCE_discretized = If(No_of_Failure_on_Demand_of_SCE < 1.02, 1, If(No_of_Failure_on_Demand_of_SCE < 2.53, 0.9, 0.5))
No of Tier 1 LOPC	Specific Indicator	No_of_Tier_1_LOPC = Triangular(0.7444, 2.2333, 6.7)
No of Tier 1 LOPC discretized	Specific Indicator	No_of_Tier_1_LOPC_discretized = If(No_of_Tier_1_LOPC < 1.96, 1, If(No_of_Tier_1_LOPC < 4.49, 0.9, 0.5))
No of Tier 2 LOPC	Specific Indicator	No_of_Tier_2_LOPC = Triangular(1.8111, 5.4333, 16.3)
No of Tier 2 LOPC discretized	Specific Indicator	No_of_Tier_2_LOPC_discretized = If(No_of_Tier_2_LOPC < 4.77, 1, If(No_of_Tier_2_LOPC < 10.93, 0.9, 0.5))
No of Tier 3 LOPC	Specific Indicator	No_of_Tier_3_LOPC = Gamma(0.5, 0.5)

Table 11 Continued

Node	Type	Defined Equation
No of Tier 3 LOPC discretized	Specific Indicator	No_of_Tier_3_LOPC_discretized = If(No_of_Tier_3_LOPC < 0.01, 1, If(No_of_Tier_3_LOPC < 0.6, 0.9, 0.5))
No of Tier 4 LOPC	Specific Indicator	No_of_Tier_4_LOPC = Weibull(0.85, 2.5)
No of Tier 4 LOPC discretized	Specific Indicator	No_of_Tier_4_LOPC_discretized = If(No_of_Tier_4_LOPC < 0.1, 1, If(No_of_Tier_4_LOPC < 5.93, 0.9, 0.5))
No of Unplanned Process Shutdown	Specific Indicator	No_of_Unplanned_Process_Shutdown = Gamma(2.5, 0.6)
No of Unplanned Process Shutdown discretized	Specific Indicator	No_of_Unplanned_Process_Shutdown_discretized = If(No_of_Unplanned_Process_Shutdown < 0.55, 1, If(No_of_Unplanned_Process_Shutdown < 2.45, 0.9, 0.5))

Table 11 Continued

Node	Type	Defined Equation
Operational Integrity	Element Indicator	Operational_Integrity = (No_of_Tier_1_LOPC_discretized + No_of_Tier_2_LOPC_discretized + No_of_Tier_3_LOPC_discretized + No_of_Unplanned_Process_Shutdown_discretized + No_of_Emergency_Blowdown_discretized + No_of_Tier_4_LOPC_discretized + No_of_Deviation_of_SCE_discretized) / 7
Overpressure	Event	Overpressure = Pressure_Relief_System * Pressure_Monitoring_System * Pressure_Trip_System
PFP on Critical Equipment	Hardware Barrier	PFP_on_Critical_Equipment = Triangular(0.01/3, 0.01, 0.01*3) / Mechanical_Integrity
Percent of Contractor with Approved Safety Plan	Specific Indicator	Percent_of_Contractor_with_Approved_Safety_Plan = Uniform(0, 100)

Table 11 Continued

Node	Type	Defined Equation
Percent of Contractor with Approved Safety Plan discretized	Specific Indicator	Percent_of_Contractor_with_Approved_Safety_Plan_discretized = If((100 - Percent_of_Contractor_with_Approved_Safety_Plan) / 100 < 0.21, 1, If((100 - Percent_of_Contractor_with_Approved_Safety_Plan) / 100 < 0.8, 0.9, 0.5))
Percent of SCE Backlog	Specific Indicator	Percent_of_SCE_Backlog = Gamma(0.2, 0.3)
Percent of SCE Backlog discretized	Specific Indicator	Percent_of_SCE_Backlog_discretized = If(Percent_of_SCE_Backlog < 0.001, 1, If(Percent_of_SCE_Backlog < 0.19, 0.9, 0.5))
Personnel Integrity	Element Indicator	Personnel_Integrity = (No_of_Tier_1_LOPC_discretized + No_of_Tier_2_LOPC_discretized + No_of_Tier_3_LOPC_discretized + No_of_Tier_4_LOPC_discretized + Percent_of_Contractor_with_Approved_Safety_Plan_discretized + No_of_Deviation_of_SCE_discretized) / 6

Table 11 Continued

Node	Type	Defined Equation
Predictive Maintenance Program	Software Barrier	Predictive_Maintenance_Program = Triangular(0.01/3, 0.01, 0.01*3) / Operational_Integrity
Pressure Monitoring System	Software Barrier	Pressure_Monitoring_System = Triangular(0.01/3, 0.01, 0.01*3) / Operational_Integrity
Pressure Relief System	Hardware Barrier	Pressure_Relief_System = Triangular(0.01/3, 0.01, 0.01*3) / Mechanical_Integrity
Pressure Trip System	Software Barrier	Pressure_Trip_System = Triangular(0.01/3, 0.01, 0.01*3) / Operational_Integrity
Preventive Maintenance Program	Software Barrier	Preventive_Maintenance_Program = Triangular(0.01/3, 0.01, 0.01*3 / Operational_Integrity
ROV Inspection	Liveware Barrier	ROV_Inspection = Triangular(0.1/3, 0.1, 0.1*3) / Personnel_Integrity
Ratio of PM to CM	Specific Indicator	Ratio_of_PM_to_CM = Weibull(1.8, 1.7)
Ratio of PM to CM discretized	Specific Indicator	Ratio_of_PM_to_CM_discretized = If(Ratio_of_PM_to_CM > 2.38, 1, If(Ratio_of_PM_to_CM > 0.64, 0.9, 0.5))

Table 11 Continued

Node	Type	Defined Equation
Routine NDT	Liveware Barrier	Routine_NDT = Triangular(0.1/3, 0.1, 0.1*3) / Personnel_Integrity
Routine Visual Inspection	Liveware Barrier	Routine_Visual_Inspection = Triangular(0.1/3, 0.1, 0.1*3) / Personnel_Integrity
Ship Collision	Event	Ship_Collision = Triangular(0.01/3, 0.01, 0.01*3)
Structural Failure	Event	Structural_Failure = Triangular(0.01/3, 0.01, 0.01*3)
Thermal Stress due to Sudden Temperature Change	Event	Thermal_Stress_due_to_Sudden_Temperature _Change = Triangular(0.01/3, 0.01, 0.01*3)
Thermography Survey	Liveware Barrier	Thermography_Survey = Triangular(0.1/3, 0.1, 0.1*3) / Personnel_Integrity
Unignited HC Gas Cloud	Event	Unignited_HC_Gas_Cloud = LOPC_HC_Gas * Emergency_Shutdown * Emergency_Blowdown * Emergency_Response_Plan

3.5. Bayesian Network Algorithm

Bayesian network calculations are performed using GeNIe V.2.1. The software was developed by the Decision Systems Laboratory, University of Pittsburgh in 1994, but is now owned by BayesFusion, LLC. As the constructed BN models are continuous type, the Monte Carlo simulation technique is adopted where 10,000 samplings are generated for each node. Hybrid Likelihood Weighing algorithm is selected by default in the software. The algorithm weighted each sample by the likelihood of evidence given the partial sample generated. It is considered to be superior than Logic Sampling method in case with observed evidence (*GeNIe Modeler*).

4. RESULTS AND DISCUSSIONS

Bayesian Networks (BNs) for LOPC of hydrocarbon gas scenario are developed following the methodology elaborated in Section 3. The first BN is constructed based on information provided by the HAZOP study from an energy company. The results from the HAZOP-BN model and their analyses are presented in Section 4.1. The second BN is developed from the Bow-tie study, which was also provided by an energy company. The results from the Bow-tie-BN model and their analysis are given in Section 4.2.

4.1. HAZOP-BN Model Results

The HAZOP-BN model is made with the GeNIe software. The structure of the model is as illustrated in Figure 38 in Section 3.4. Prior distribution is defined for each and every node in the model according to the type of the node. A complete list of equations inputted into the model is given in Table 10. For process safety indicators, prior distributions are calculated from the data gathered during 24 months from an energy company. A histogram of the number of unplanned process shutdown indicator simulated from the software is shown in Figure 40. Discretized distribution of this indicator is given in Figure 41. Approximately 70 percent of the indicator values are categorized as medium integrity whereas the rest of the values are equally categorized as low and high integrity, respectively. The mean integrity value for the indicator is approximately 0.85. The process is repeated for all other indicators. Statistical values for all indicators are given in Table 12.

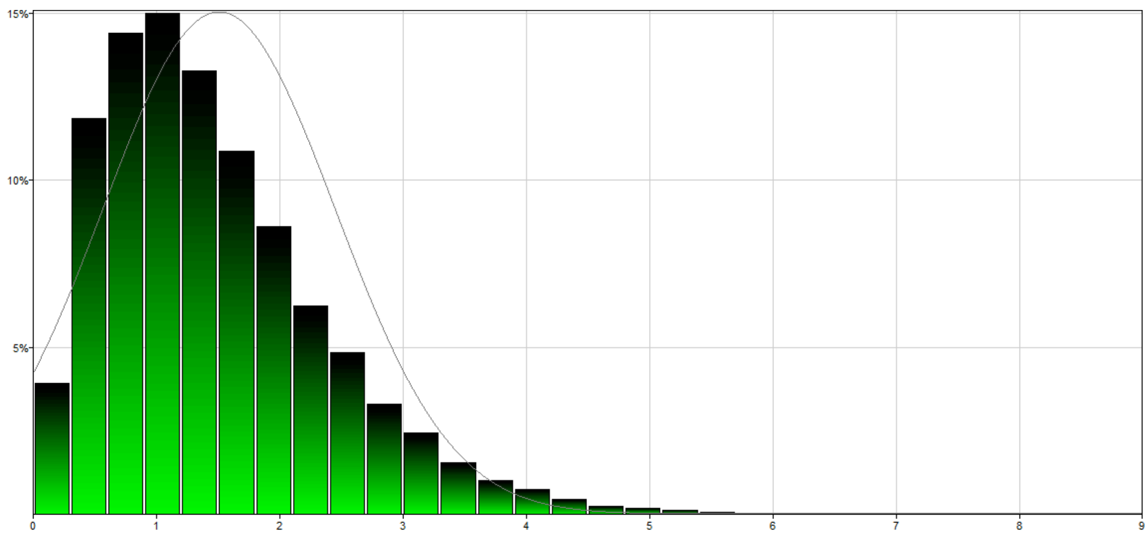

Figure 40: Histogram Illustrating the Number of Unplanned Process Shutdown per Month on the X-Axis and the Probability of Occurrence on the Y-Axis

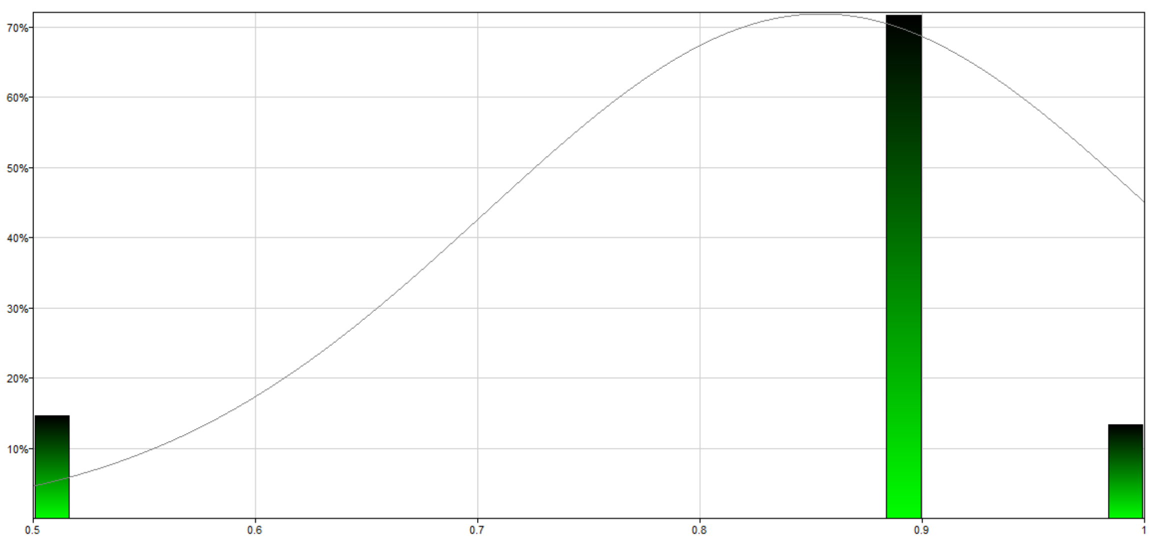

Figure 41: Histogram Illustrating Discretized Distribution for Number of Unplanned Process Shutdown Indicator

Table 12: Process Safety Indicators Discretization Results

Process Safety Indicator	Statistical Value After Discretization	
	Mean	Standard Deviation
Number of tier 1 LOPC	0.8465	0.1652
Number of tier 2 LOPC	0.8432	0.1666
Number of tier 3 LOPC	0.8655	0.1428
Number of failure on test or demand of SCE	0.8508	0.1604
Percentage of SCE backlog	0.8980	0.1348
Number of unplanned process shutdown	0.8545	0.1513
Number of emergency blowdown	0.8939	0.1229
Number of tier 4 LOPC	0.8557	0.1374
Percentage of contractor companies with approved safety plan	0.8413	0.1747
Ratio of planned/unplanned maintenance	0.8541	0.1556
Number of deviation on SCE in place	0.8493	0.1389

The initial probability of occurrence of the LOPC of hydrocarbon gas is computed using discretized PSIs data mentioned earlier. The distribution of the initial probability is illustrated in Figure 42. Approximation to normal distribution is performed by the software and shown as a grey line overlapped onto the histogram. The shape of the LOPC histogram resembles the Triangular distribution of the prior distribution of the barrier nodes. However, a tendency to normal distribution is observed because of the differences in prior distribution values and because there are many nodes presented in the model.

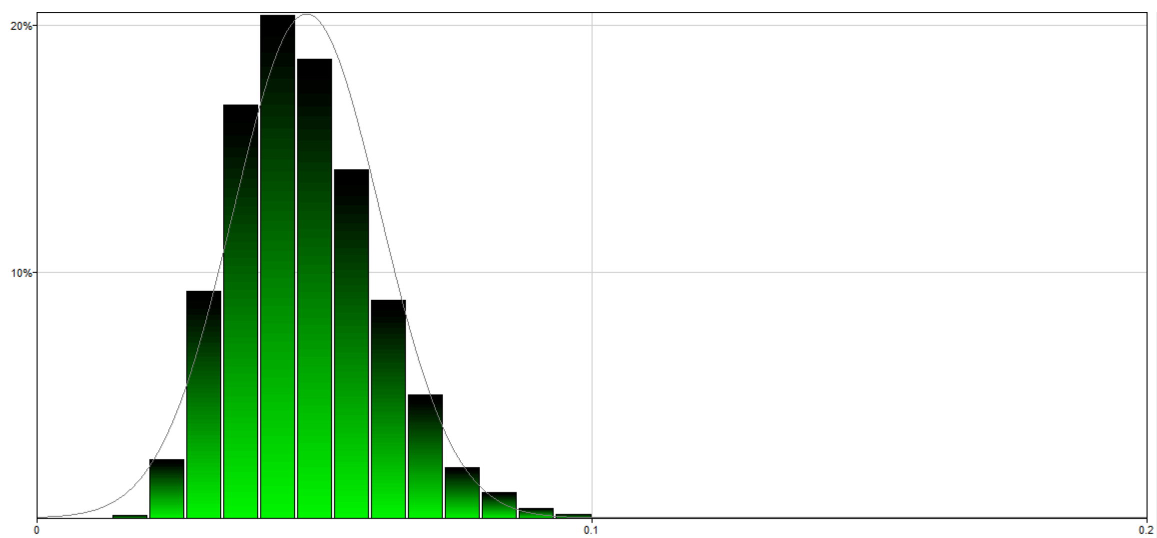

Figure 42: Initial Probability Distribution of the LOPC Event (Per Month) from the HAZOP-BN Model

The computed probability of the LOPC event ranges from 0.0152 to 0.1368 with the mean value of 0.0483, which denotes the number of occurrence of LOPC event in one month. It suggests that the LOPC event can be expected every 21 months based on the mean value. However, this figure should be analyzed with caution because many of the inputs are assumed values. Plant specific data should be collected and inputted into the model for a proper prediction and further use. Where plant specific data are not available, industry specific data may be used.

The consistency of the software calculation is evaluated by performing multiple simulations with the same inputs. Table 13 shows the record for the mean and standard deviation values of initial probability of occurrence for the LOPC event for 10 trials. It shows that the mean values range from 0.0480 to 0.0484. Thus, around 1 percent aleatory uncertainty is expected from the software. This value is relatively small compared to the calculated standard deviation. Thus, the uncertainty from software sampling algorithm is reasonably acceptable.

Table 13: Mean and Standard Deviation of the LOPC Event in HAZOP-BN Model after 10 Trials

Item	**Trial**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Mean	0.0483	0.0482	0.0481	0.0482	0.0480	0.0482	0.0481	0.0484	0.0482	0.0481
SD	0.0133	0.0132	0.0131	0.0131	0.0133	0.0134	0.0133	0.0133	0.0133	0.0134

The posterior probabilities of LOPC event is calculated by providing specific indicator data from Table 5 to Table 8 as observation (or evidence) in the BN software. The GeNIe software equipped with a temporal plate function, which performs the calculation in a time step manner. However, this function is not available for continuous type BN. Therefore, the process is performed manually and repeated for 24 months. The results are extracted from the software to Microsoft Excel and shown in Figure 43.

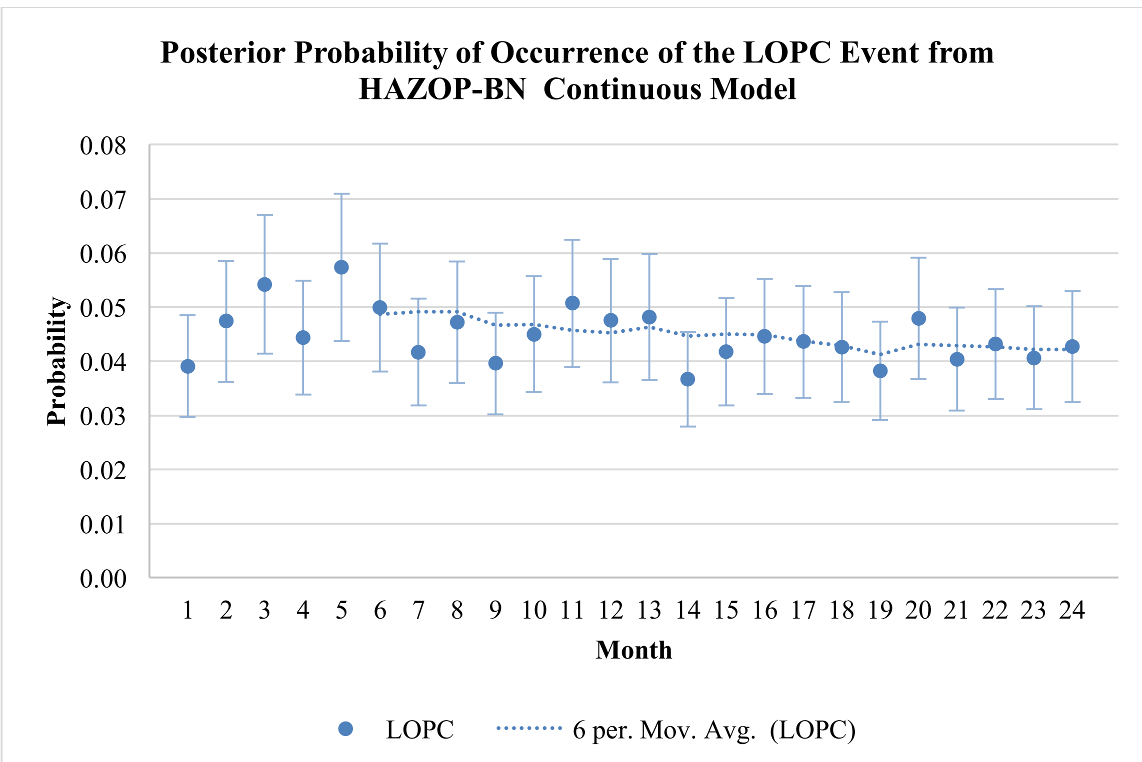

Figure 43: Posterior Probability of Occurrence of the LOPC Event from HAZOP-BN Model

The estimated mean values of an occurrence of the LOPC event are between 0.0367 and 0.0574 times per month. The bracket extending from the dot represents one standard deviation from the mean value. By comparison, these values are not vastly different, mostly within one standard deviation from the previous month estimates. However, it should be noted that only changes in the PSI integrity level are taken into account. In real world operations, changing in number of occurrence of basic events such as overpressure and high temperature can be expected from month to month. Incorporating those changes into the BN model would yield more accurate estimation of the occurrence of the LOPC event.

To observe a trend of the LOPC event, a six-month moving average is made and shown as a dotted line in Figure 43. It can be seen that the occurrence of LOPC is slightly decreasing, which means that the energy company has managed to reduce the process safety risk during the data collection period.

In the developed model, the LOPC event is possible if any of its causes are true. There are five causes identified from the HAZOP study: overpressure, corrosion, third party impact, high temperature, and low temperature embrittlement. Although the exact contribution cannot be determined due to a complexity of the interrelationships in the model, the BN model allows identification of the most likely contributing factor by observing the probability of occurrence value from each cause node. The low temperature embrittlement is found to be the most likely contributing factor because of its minimal number of barriers in place and its fault tree structure. The software is equipped with sensitivity analysis function that can quantitatively categorize the degree of influence of the target node, e.g., the LOPC event node, and thus the most likely contributing factor can be quickly identified. However, this function only works with the discrete type BN only. Nonetheless, the main focus here is that the BN model supports the analysis of the major contributors, either manually or automatically, so that incident prevention actions can be performed to reduce the likelihood of the top event.

4.2. Bow-tie-BN Model Results

The Bow-tie-BN model is made with the GeNIe software. The structure of the model is illustrated in Figure 39 in Section 3.4. Prior distribution was defined for each and every node in the model according to the type of the node. A complete list of equations input into the model is given in Table 11. For process safety indicators, the same inputs as the HAZOP-BN model were used. Discretization is performed in the same manner and incorporated into the Bow-tie-BN model.

The initial probability of occurrence of the LOPC of hydrocarbon gas is computed using the discretized PSIs data mentioned earlier. The distribution of the initial probability is illustrated in Figure 44. Approximation to normal distribution is performed by the software and shown as a grey line overlapping with the histogram. Similar to the analysis for HAZOP-BN model, the shape of the LOPC histogram from Bow-tie-BN model resembles the Triangular distribution of the prior distribution of the barrier nodes.

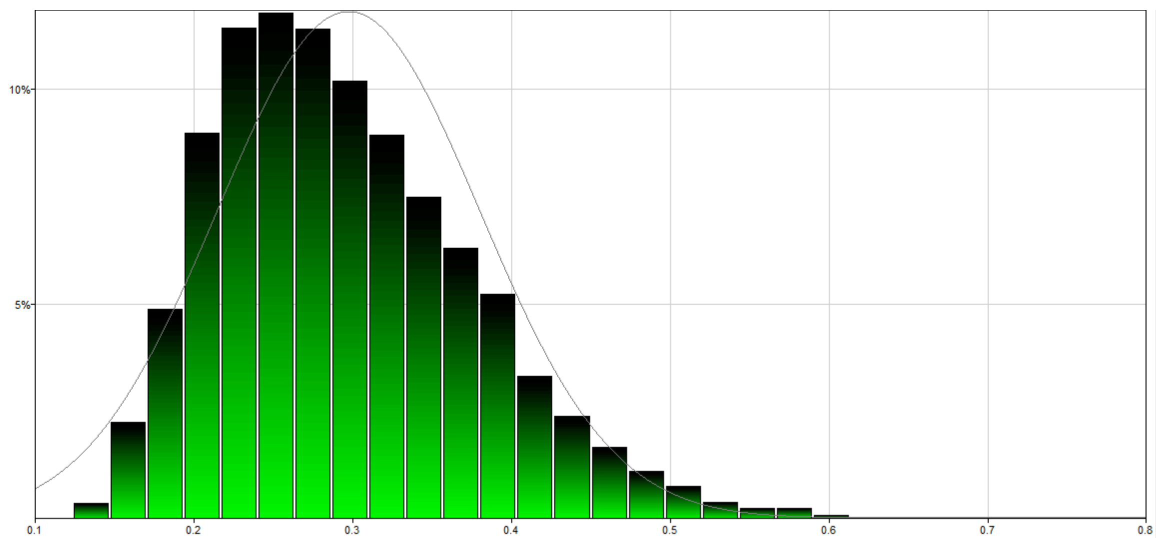

Figure 44: Initial Probability Distribution of the LOPC Event (Per Month) from the Bow-tie-BN Model

The computed probability of LOPC event ranges from 0.1280 to 0.7560 with the mean value of 0.2966, which denotes the number of occurrence of the LOPC event in one month. It suggests that the LOPC event can be expected every three months based on the mean value. However, this figure should be analyzed with caution because many of the inputs are assumed values. Plant specific data should be collected and inputted into the model for proper prediction and further use. Where plant specific data are not available, industry specific data may be used instead. This analysis is in-line with the one performed for the HAZOP-BN model in the previous section.

From Figure 29, it shows that the internal erosion cause has only one barrier installed, which is a routine NDT. The barrier is categorized as a liveware, which has the probability of failure on demand of Triangular(0.1/3, 0.1, 0.1x3). The mean value of the internal erosion event is calculated as 0.1714, which is significantly large compared to the mean value of the LOPC event of 0.2966. Therefore, with the assumption that one internal erosion occurred in a month, the shape of the distribution shown in Figure 44 is influenced by the shape of this routine NDT barrier.

The consistency of the software calculation is evaluated by performing multiple simulations with the same inputs. Table 14 shows the record for the mean and standard deviation values of initial probability of occurrence for the LOPC event for 10 trials. It shows that the mean values range from 0.2947 to 0.2968. Thus, around 1 percent aleatory uncertainty is expected from the software. This value is relatively small compared to the calculated standard deviation. Thus, the uncertainty from the software sampling algorithm is reasonably acceptable.

Table 14: Mean and Standard Deviation of the LOPC Event in Bow-tie-BN Model after 10 Trials

Item	**Trial**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Mean	0.2966	0.2959	0.2949	0.2956	0.2966	0.2968	0.2961	0.2962	0.2947	0.2957
SD	0.0831	0.0817	0.0823	0.0807	0.0827	0.0831	0.0831	0.0830	0.0825	0.0812

The posterior probabilities of the LOPC event is calculated by providing specific indicator data from Table 5 to Table 8 as an observation (or an evidence) in the BN software. The temporal plate function in GeNIe software is not available for a continuous type BN as explained in Section 4.1. Therefore, the process is performed manually and repeated for the 24 months. The results are extracted from the software to Microsoft Excel and shown in Figure 45.

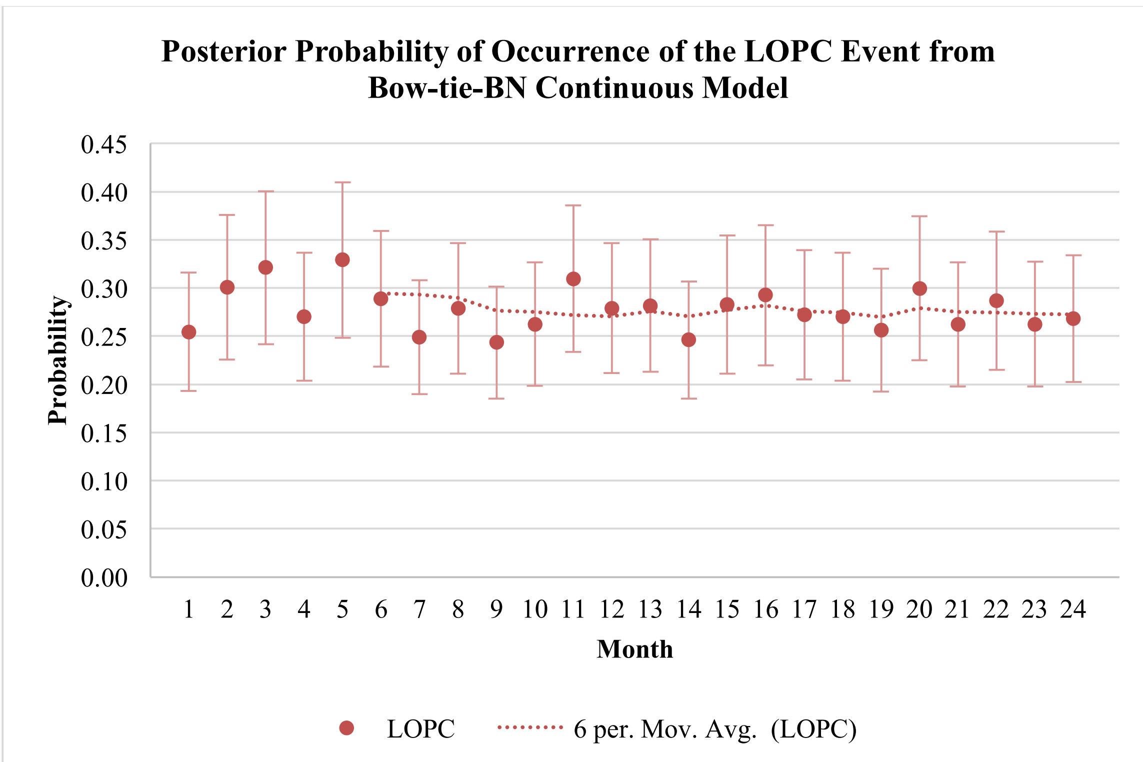

Figure 45: Posterior Probability of Occurrence of the LOPC Event from Bow-tie-BN Model

The estimated mean values of occurrence of the LOPC event are between 0.2433 and 0.3292 times per month. The bracket extending from a dot represents one standard deviation from the mean value. By comparison, these values are not vastly different, mostly within one standard deviation from the previous month's estimates. However, it should be noted here, same as the HAZOP-BN model, that only changes in the PSI integrity level are taken into account. In real world operation, changes in number of occurrence of basic events such as internal corrosion or dropped object impact would be changing from month to month. Incorporating those changes into the BN model would yield more accurate estimations of the occurrence of the LOPC event.

To observe a trend in the estimated probability of occurrence of the LOPC event, a six-month moving average is made and shown as a dotted line in Figure 45. It can be seen that the occurrence of LOPC is slightly decreasing and almost leveled in the second 12-month period.

There are 11 causes identified in the Bow-tie study that lead to the LOPC event: internal corrosion, external corrosion, overpressure, leakage from flanges and valves, mechanical failure, internal erosion, dropped object impact, structural failure, helicopter crash, ship collision, and thermal stress due to sudden temperature change. The LOPC event is possible if any of it causes is true. Identification of the most likely contributing factor is manually performed by observing the probability of occurrence value for each of the cause. As mentioned earlier, the internal erosion is found to be the most likely contributing factor because it has only one barrier linked to it. However, it may not be the case if real data is used, since the cause with few barriers could mean that they have a very low probability of occurrence per month in the beginning. Thus, each cause of the LOPC event should be thoroughly inspected to identify which cause has the largest contribution to the top event.

4.3. Comparison Between HAZOP-BN and Bow-tie-BN Model

The predicted probability of occurrence of the LOPC event from both HAZOP-BN and Bow-tie-BN model are shown in Figure 46. The blue color represents the result from the HAZOP-BN and is to be read with the left axis. The red color represents the result from the Bow-tie-BN and is to be read with the right axis. Even though the BNs were constructed based on different studies, the results are considerably in line with each other. The standard deviation brackets extend from the mean value point also have approximately the same length. The numerical analysis is performed. It indicates that the standard deviation value is approximately 25 percent of the mean value for both HAZOP-BN and Bow-tie-BN.

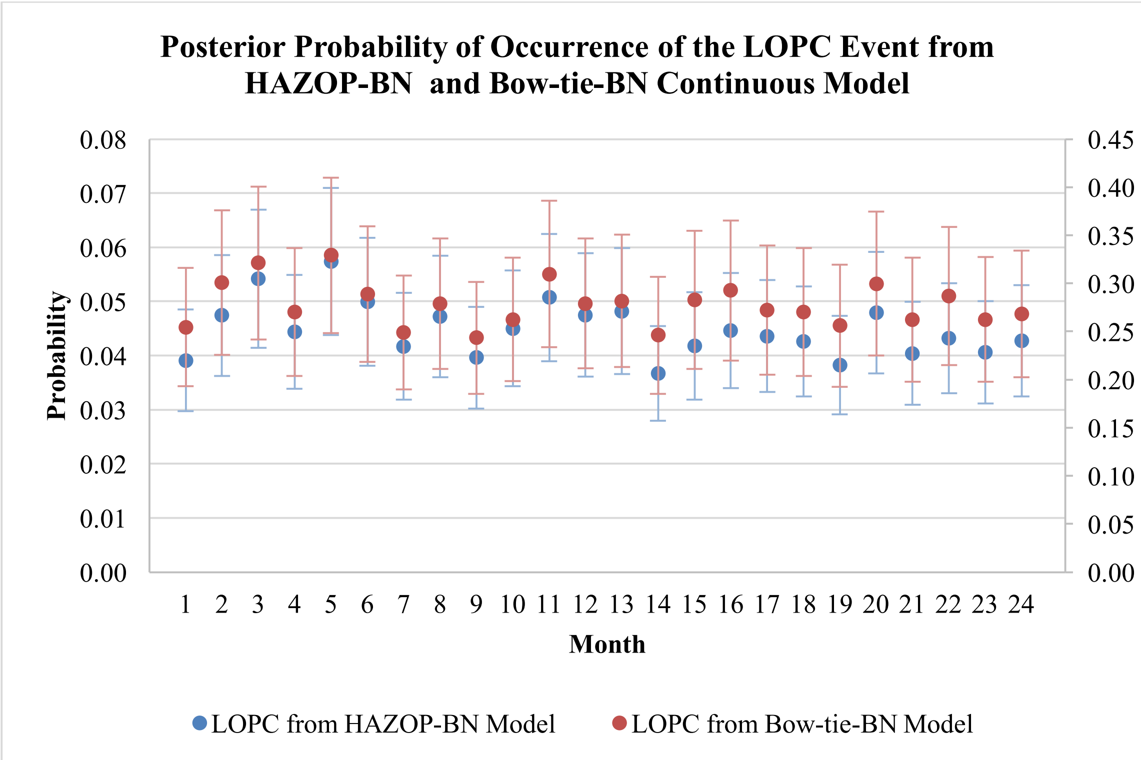

Figure 46: Posterior Probability of Occurrence of the LOPC Event from HAZOP-BN and Bow-tie-BN Model

Examining the absolute mean value obtained from both models, the result from Bow-tie-BN is almost 6 times higher than the result from HAZOP-BN model. There are many explanations that could contribute to such a large gap. Firstly, there are fewer causes identified from the HAZOP study because only one node, the export gas compressor system, is analyzed in this study; while from the Bow-tie study, 11 causes are identified. With the same set of assumptions, 11 causes from the Bow-tie study should double the probability of occurrence predicted when compared to 5 causes from the HAZOP study. Secondly, in the HAZOP-BN model, at least 2 barriers are attached to each cause, while in the Bow-tie-BN model, the internal erosion has only 1 barrier attached to it. This internal erosion cause is considered to be the largest contributor to the probability of occurrence of the LOPC event from the Bow-tie-BN model as explained in Section 4.2. In addition, five other causes in the Bow-tie-BN model namely: dropped object impact, structural failure, helicopter crash, ship collision, and thermal stress due to sudden temperature change, do not have any barrier at all. This is because those five causes are identified as a top event in other Bow-tie diagrams, which can be expanded into other BN models. However, to reduce the complexity of the model, the extension into other Bow-tie diagrams is not considered in this study. Lastly, the differences between the same barrier type in HAZOP-BN and Bow-tie-BN model should be addressed in a real application. For example, the PSV for upstream system barrier in HAZOP-BN model and the pressure relief system barrier in the Bow-tie-BN model, both, prevent overpressure scenario. However, the barrier in the HAZOP-BN model only consider the probability of failure for the PSV installed in the export gas compressor system, while the barrier in the Bow-tie-BN model considers the whole pressure relief system of the facility, from the PSVs to pressure relief piping, and flare system. Therefore, the same probability of failure on demand applied to both barriers may not reflect the most accurate value for the real world situation.

5. CONCLUSIONS AND FUTURE WORKS

The Bayesian network (BN) method enables traditional hazard identification and risk assessment techniques to update their probability and risk values by incorporating new observations or information. In this study, the BN method was applied to both HAZOP and Bow-tie studies to estimate the probability of occurrence of a loss of primary containment (LOPC) event using process safety indicator data. Integration of multiple indicators into the developed BN model is made possible by indicators aggregation method, which combined multiple specific indicators into three element indicators. The LOPC of high pressure hydrocarbon gas from the export gas compressor system is selected as a representative scenario for this research. Continuous type BN is selected because it can accommodate a complex and large scale system without the burden of the conditional probability table, which is needed for the discrete type BN.

The Bayesian estimation requires tremendous amount of data to perform a posterior probability estimation. Set of assumptions are provided for prior probabilities and conditional probabilities definition to allow computation and analysis of the study. The estimated probabilities of occurrence of the LOPC from the HAZOP-BN model are found to be between 0.0367 and 0.0574 times per month, while the prediction from Bow-tie-BN model are between 0.2433 and 0.3292 times per month. The differences in the computed probabilities from the two models are due to: 1) differences in number of causes for the LOPC event; 2) differences in number of barrier for each cause; and 3) differences in the definition of the barrier in place. Therefore, the predicted probabilities of occurrence of the LOPC event do not reflect the most accurate value. Albeit dissimilarities in terms of hazard identification approaches and the BN development process are presented, the results from both models show consistency in the pattern and a slightly decreasing trend toward the second year. The effects from process safety indicator data is found to be approximately in the same level. Therefore, both HAZOP-BN and Bow-tie-BN methods are reasonably acceptable. A company that currently has HAZOP or Bow-tie method practiced in its risk management can further adopt BN model to incorporate process safety indicator data and enhance their risk assessment capability.

In conclusion, this study demonstrates the method to incorporate process safety indicators into a probability estimation of a process safety event. The consequence analysis is excluded from the scope of this research. Therefore, it is prudent to explore the BN application in the consequence analysis to fulfil the second element of risk and obtain the overview of the dynamic risk assessment. In addition, more information should be incorporated into the BN, such as additional process safety indicators, operational process parameters, human error data, and safety culture. In order to achieve more accurate risk estimations, systematic data collection should be set up to collect company/plant specific data, which will be used for the prior probability definition of the fundamental elements and the conditional probability between them. The ultimate goal is to be able to identify weaknesses in the system such that preventive measures can be taken before incidents can be realized.

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