EVALUATION OF BAYESIAN NETWORKS FOR RISK ASSESSMENT OF MAJOR HAZARDS IN OIL AND GAS FACILITIES

BY

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COLLEGE OF ENGINEERING STUDIES

(DEPARTMENT OF HEALTH, SAFETY AND ENVIRONMENT)

SUBMITTED TO

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IN PARTIAL FULFILMENT OF THE REQUIREMENT OF THE DEGREE OF DOCTOR OF PHILOSOPHY

TO

UNIVERSITY OF PETROLEUM AND ENERGY STUDIES, DEHRADUN

February 2016

Under the Guidance of

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Dedication

This work is dedicated to my parents M. Gopinathan Nair and Sarojam and to my wife Girija Unnikrishnan

Acknowledgement

This research work would not have been possible without the guidance and advice of my guides Dr. Srihari and Dr. Nihal Siddiqui. My sincere gratitude to both the professors for their support and encouragement given to me. I also thank Dr. Krishnan Pandey for his input on several topics. I gratefully acknowledge the help received from Dr. Mukesh Kumar Singhal.

My appreciation to my external guide Dr. Cyrus Rezaei for the discussions and helpful insights.

I thank my wife Girija and daughters Parvathy and Ranjini for giving me the confidence and moral support for completing this challenging task.

Declaration

I hereby declare that this submission is my work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgement has been made in the text.

Signature / Name / Date

Certificate

This is to certify that the thesis entitled "Evaluation of Bayesian Networks for Risk Assessment of Major Hazards in Oil and Gas Facilities" submitted by G. Unnikrishnan to University of Petroleum and Energy Studies for award of the degree of Doctor of Philosophy is a bona fide record of the research work carried out by him under our supervision and guidance. The content of the thesis, in full or parts have not been submitted to any other institute or University for the award of any other degree or diploma.

Dr. Shrihari	**Dr. Nihal Siddiqui**	**Dr. C. Rezaei**
Place: Dehradun		**Kuwait**

Date:

EVALUATION OF BAYESIAN NETWORKS FOR RISK ASSESSMENTS OF MAJOR HAZARDS IN OIL & GAS FACILITIES

Contents

Executive summary

Oil and gas industries handle highly inflammable and toxic fluids under pressure. They also have large inventories of the same. Therefore it is imperative that these fluids are processed under safe operating conditions and that any hazards posed during its operations are controlled and eliminated. Unless the risks are properly managed, hazards can escalate to accidents very rapidly.

The industry relies on certain tools like Hazard And Operability Studies (HAZOP), Quantitative Risk Assessments (QRA), Safety Integrity Level (SIL) studies, etc. to understand, analyze and mitigate risks. Of the above, QRA involve quantitative understanding of the risk. QRA studies originated in the nuclear industry and have been successfully adopted by the process industry including oil and gas.

Risk is a function of the hazard scenario, its likelihood of occurrence and its consequences and QRAs are the traditional method in the oil and gas industries to analyze risk quantitatively. QRA starts with identifying risk scenarios; mainly loss of containment (LOC) in a facility. Then the frequency or likelihood of occurrence of such scenarios is taken from published sources. (If site data is available the same is used). Consequences of LOC are computed by use of source term models and its impacts on personnel and property. These are combined to produce a measure of risk. The risk arrived at is compared with an established tolerable risk to see if it is acceptable and mitigation measures are taken up if it is not.

After nearly 25 years of practice, the practitioners of QRA have begun recognizing its limitations. A number of researchers have identified important limitations of QRA. In summary they are:

- QRA considers only the scenarios identified at the beginning of the study. If a scenario is missed, it will not be reflected in the study.
- It starts with a frequency of loss of containment (LOC) from published literature. No attempt is made to analyze the causes for loss of containment.
- The analyst's assumptions are not always transparent
- There could be wide variation in the results from a QRA study

In this context, alternate methods are being sought and Bayesian Networks (BN) or Bayesian Belief Networks (BBN) as it is sometimes known, have emerged as a likely choice. Although BN are being widely used in Computer Science, Medicine, Ecosystem modeling and to certain extent in chemical industries, it has not found much application in oil and gas.

Literature survey revealed that researchers have applied BN to certain aspects in the upstream oil and gas, such as human factors, offshore drilling, conceptual study of accidents, etc. However applications to specific equipment was not available

This research is about application of Bayesian Networks for risk assessment of major hazards in oil and gas industry.

The research focuses on applying the principles of BN for the most common equipment in the industry namely; loss of containment scenarios of oil and gas separator, hydrocarbon pipelines, Floating roof and Cone roof hydrocarbon storage tanks and centrifugal compressors.

What are the aspects that makes BN attractive for risk assessment? Fundamentally, it is the ability of BN to describe causal mechanisms (cause and effect) in a clear and visually understandable way that has made it the prime choice. BN can describe the complex interactions and inter relationships of cause and effect at various levels quite easily. Further, it can incorporate static probability numbers or more realistic probability distributions for failure rates.

A Bayesian Network is a directed acyclic graph (DAG) in which the nodes represent the system variables and the arcs symbolize the dependencies or the cause–effect relationships among the variables. A BN is defined by a set of nodes and a set of directed arcs. Probabilities are associated with each state of the node. The probability is defined, a priori for a root (parent) node and computed in the BN by inference for the others (child nodes). Each child node has an associated probability table called conditional probability table (CPT).

The principle behind the BN is the description of conditional probability by Bayes Theorem.

Bayes theorem can be written as Equation (i) for cause and effect, given that normally we see only the effect.

$$P\ (\text{ cause}|effect) = \frac{P\ (effect \mid cause\ )\ P\ (cause)}{P\ (effect)} \quad \text{Eqn. (i)}$$

It states that, given that we see an effect, the probability of its cause $P\ (\text{ cause}|effect),$ can be described by a combination of the probability of effect given the cause $P\ (effect \mid cause\ )$ –which would be observable in most cases and the unconditional probabilities of cause and effect ($P\ (cause)$, $P\ (effect)$). The right hand side of equation (i) is called the prior probability, which when computed will give the left hand side known as posterior probability. The right hand side denominator of the equation (i) requires calculation of the total probability of effect.

BN can be built up using simple building blocks of causal reasoning namely, single cause and effect, serial cause and effects, multiple causes and one effect, single cause and multiple effects. Thus the key steps involved in construction of BN for loss of containment are

- Selection of the loss of containment event (LOC) for the equipment under consideration

- Understanding of the causal mechanisms of immediate, intermediate and root causes of the LOC. Influence diagrams will help in understanding this.
- Converting the cause and effect relationships to BN.
- Populating the BN with data and parameterizing the Conditional Probability Tables (CPT) for each child nodes
- Simulating the BN using various data to see the probability values. BN can be run in predictive mode from left to right or in diagnostic mode backwards.

Loss of containment can be considered as a Bow-Tie, with LOC event in the middle, Fault tree on the left hand side (cause and effect) and Event tree on the right hand side (post event consequences). The above structure can be mapped in to BN along with the controls and barriers for preventing the LOC (as a part of Fault tree on left hand side) and post LOC mitigation measures on right hand side (Event tree). The BN represents the causes and effects in the entire network as joint probability distribution.

When we have a BN of n variables A_1, A_2 …An, using the chain rule the joint probability distribution can be written as

$$P\ (A_1, A_2 \dots A_n|) = \prod_{i=1}^{n} P\ (A_i \mid A_{i+1} \dots . A_n \qquad \text{Eqn. (ii)}$$

We can simplify this by using the knowledge of who the parents of each node are.

In general, if Parents (A_i) denote the set of parents of the node A_i, then the full joint probability distribution can be simplified as

$$P\ (A_1, A_2 \dots A_n|) = \prod_{i=1}^{n} P\ (A_i \mid Parents\ (A_i) \qquad \text{Eqn. (iii)}$$

Also, we can change the probability values of any of the nodes and see its effect on the rest of the nodes in the BN. This aspect makes the BN a powerful tool for what if (scenario) analysis, which is not possible with other risk assessment tools.

As part of this research detailed cause and effect for loss of containment (Fault tree) as well as post loss of containment scenarios (Event tree) have been developed for oil and gas separator, pipelines, Floating roof and Cone roof tank and compressor. These causes and effects have been converted to BN and parameterized suitably. Initial parent probabilities have been taken from published literature and the BN simulated by applying the principles noted the equations above. The complex calculations are best handled by software.

Causes or parents nodes have been combined in the child (effect) nodes by defining the CPT at each child node. One of the problems of completing the CPT is that, when the number of parent nodes increase, the number of entries in the CPT goes up. In such a situation NoisyOr distribution is used to reflect the contribution of each parent to the child node. The BN thus built up represents the causes, effects and post release scenarios of loss of containment for each equipment under consideration. With the initial values based on existing data and suitable definitions of CPTs, the outcome probabilities of these BN represent the current probabilities of occurrence of events. Further, the sensitivity analysis feature of BN provides the degree of influence that each of the parents have on a particular child node.

For each of the BNs, various scenarios, both predictive and diagnostic have been simulated. For oil and gas separator, the current failure rates for the vessel have been simulated. Further, application of BN for analyzing the layers of protection provided for separator and calculating the Safety Integrity Level (SIL) to be assigned to the Emergency Shutdown Valve (ESDV) have been presented. Common Cause Failures (CCF) has been illustrated in this BN. For pipelines, the BN for pipeline loss of containment as well as post release scenario are given together with a case study for the pre accident conditions for the natural gas pipeline failure at Andhra Pradesh. Loss of containment as well as post release situation of Floating roof and Cone roof tank have been included in the research. A case study also has been given for the Floating roof tank loss of containment. As part of the case study, the pre-accident conditions similar to those existing at the Jaipur oil storage tank have been simulated to see the effectiveness of BN. In both the case studies, the simulated probabilities of BN indicate that the pre-accident situations existing in these facilities were above that of existing (normal) conditions and that there is an increased risk of unwanted scenarios. BN for the compressor damage demonstrate the usefulness of the BN model in predicting as well as diagnosing potential problems.

An item wise comparison with conventional QRA has been provided. In order to provide comparison, case study of a conventional QRA has been presented for a Floating roof tank storing Motor Spirit similar to the tank that had loss of containment at Jaipur tank terminal.

Main contribution from this research are the following:

- Comprehensive cause and effect and its BNs for loss of containment and post release scenarios for the most common equipment in oil and gas industry namely; oil and gas separator, pipeline, Floating roof and Cone roof tanks and compressor.
- The BN can be used by the industry to understand, analyze and mitigate risks involving these equipment very easily on a day to day basis.
- The sensitivity analysis feature provides the degree of influence that each parent nodes have on its child (target) node, which is helpful in prioritizing actions for risk mitigation.
- The BN can be run in diagnostic mode to aid in root cause analysis studies.
- Overall, this research has shown that BN can provide a much more comprehensive perception of risk in a facility.

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1. INTRODUCTION

Oil and gas industry handles highly inflammable and toxic fluids under pressure and have high inventories of the same. Given the hazardous nature of its operations, it is important that the industry ensures such facilities are designed, maintained and operated in a safe manner. Different methods have evolved over period of time to analyze and mitigate the risks involved. However, major accidents continue to occur and at that time issues on safety and risk assessment come up. For example, risk assessment came into sharp focus during incident investigations of major accidents in British Petroleum's Texas City Refinery, Buncefield fuel storage and Indian Oil's Jaipur oil terminal. Oil and gas industry typically uses Quantitative Risk Assessment methodology to analyze and understand risks in its facilities. The method started in nuclear industry and was later adopted in process as well as oil and gas industries. Based on practice of more than 25 years, the industry is aware of limitations of the method.

Bayesian Network (BN) or Bayesian Belief Network (BBN) is being applied productively as probabilistic risk assessment method in several areas like medicine, computer science, ecology and chemical industry. The method offers certain advantages over Quantitative Risk Assessments and reveals a better risk picture. This research focuses on application of the BN methods to assess risk of major hazards in oil and gas industry. Specifically the aim is to develop BN models for the major hazards for oil and gas separator, atmospheric hydrocarbon storage tanks, hydrocarbon pipelines and compressors. The BN models are simulated with generic and site data. Further, BN is compared with Quantitative Risk Assessments to understand the advantages of the BN.

1.1 Statement of the proposal

Quantitative Risk Assessment (QRA) as practiced in oil and gas industry has several limitations in terms of uncertainties in data for failure frequencies, lack of precision in models and difficulties in identifying common cause failures. It is static and cannot be updated easily as and when the facilities are modified. QRA effort require considerable specialist time and money. The software is costly and is not transparent or flexible.

Bayesian Networks (BN) have been applied with good results in the areas like computer science, ecology, medicine and chemical industry [1] [2] [3] [4] [5]. However, applications to oil and gas facilities have been very limited. This research focuses on application of BN to understand the risks due to major hazards in oil and gas facilities. Loss Of Containment (LOC) scenarios constitutes major hazards in the oil and facilities. Therefore causal mechanisms and BN have been developed for such scenarios for the more common equipment namely oil and gas separator, atmospheric hydrocarbon storage tanks, hydrocarbon pipelines and compressors. The BN are simulated and analyzed with generic as well as site specific data. A comprehensive comparison of the BN and QRA is presented to demonstrate the advantages of BN.

1.2 Background and motivation

In brief, QRA method consists of the following

i. Identifying major hazard scenarios which in most cases is a loss of containment (LOC) for the equipment or section of the system under consideration.
ii. Assuming certain failure frequency for the major hazard.
iii. Calculating the rate of release in terms of mass flow
iv. Calculating the consequence of release namely fire, explosion or toxic gas release.

v. Calculating the impact of the consequences in terms of fatalities and asset loss.
vi. Combining the frequency of the scenario with the impact suitably to present a measure of risk.
vii. Comparing the risk measure with an acceptable risk criteria to see if it is within the 'As Low As Reasonably Practically (ALARP)' region.

Figure 1.1 shows the main steps of QRA. Details are available in CCPS book [6].

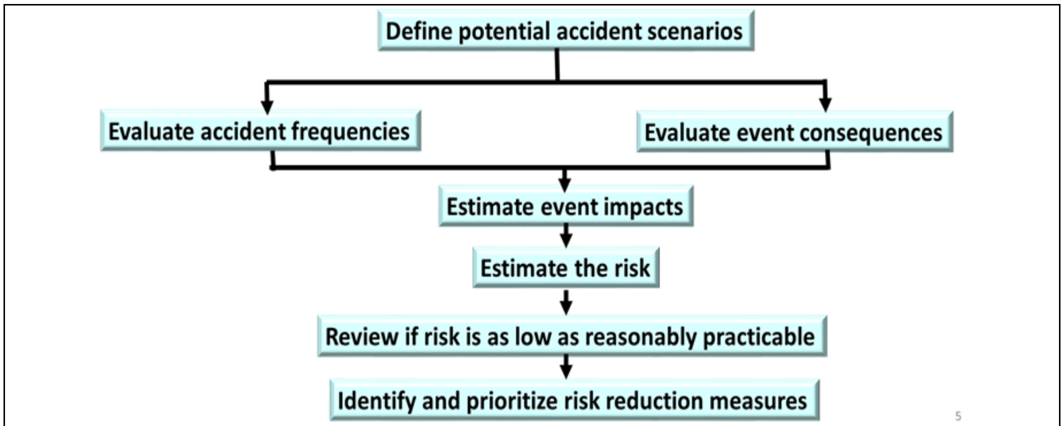


Figure 1.1 Summary of QRA steps

1.3 Major limitations of QRA

Industry and academia is aware of the limitations of QRA [7] [8]. The researcher's personal experience in conducting QRAs also highlighted these limitations. In summary they are:

i. Uncertainties in data for failure frequencies, lack of precision in models and difficulties in identifying common cause failures.
ii. Assumptions are not visible to all concerned.
iii. Models are static, difficulties in capturing variations / changes to the facility
iv. Requires considerable specialist efforts and time
v. Software is costly, calculations are not transparent and limits flexibility

Researcher's personal experience shows that majority of the QRAs done during the design stage end up in the records center or library shelves. During operational phase there is very little or no attempts to update these QRAs. When changes are made to the facilities, most of the time QRAs are done only for that portion that undergoes change, which has proven to be fundamentally wrong. Details of the limitations and gaps are given in section 8.4.

1.4 Bayesian Network and its advantages

In this context, alternative methods were sought and Bayesian Network (BN) is seen as a viable alternative to QRA methodology [9] [10]. As noted earlier BN is being widely applied to Computer Science, ecology, finance and chemical industries. However oil and gas applications were limited.

Main advantage of BN are:

i. It presents the risk in a visually and easily understandable manner
ii. The methodology is transparent.
iii. Failure data and thereby the risk profile can be easily updated in line with changes / updates of the facility
iv. Site-specific data (even if it is sparse) and experts' opinion can be incorporated.
v. BN can be simulated in predictive and diagnostic mode.

The above background and motivation prompted research to be taken up in the area of application of BN to risk assessment of major hazards in oil and gas facilities.

1.5 Objectives and scope

The research was taken up to understand how BN works and to demonstrate that it can be beneficially applied to oil and gas facilities. The main objectives of the research are

i. Identify major hazards and Layers Of Protection provided in a typical Oil & Gas facility by review of several designs, Piping & Instrument diagrams, HAZOP study & Layers Of Protection Analysis (LOPA) reports from industry.

ii. Develop causal relationship networks for critical equipment / systems failures & its causes, hazards & consequences using the above data

iii. Convert these causal relationships to Bayesian Networks

iv. Simulate the networks using suitable software. Test the networks with data. Compare & discuss the risk profiles with conventional QRA and advantages of Bayesian approach

The research scope can be shown as a flowchart as in Figure 1.2 below:

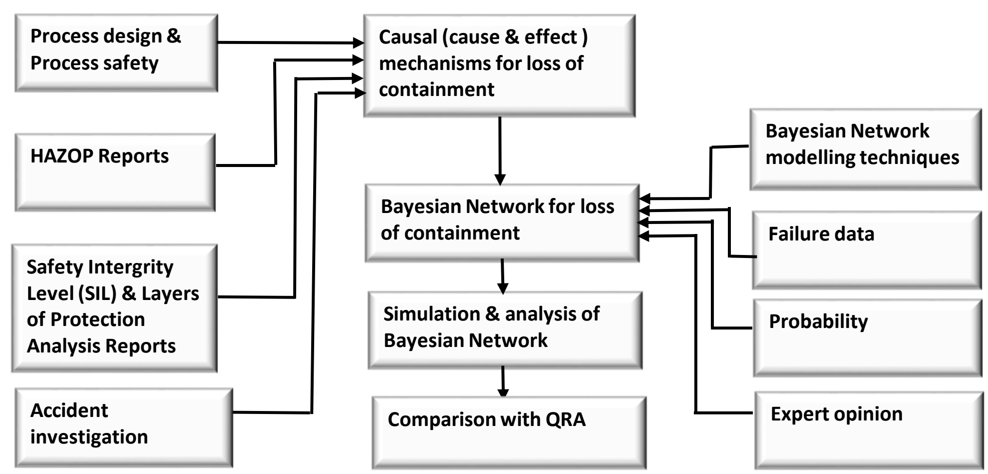


Figure 1.2 Research scope and objectives

Since the research work called for application of BN to major hazards for equipment in oil and gas facilities, which is a relatively new area, applications of BN to similar area has to be studied first. Therefore, a comprehensive literature survey was undertaken to review such applications.

1.6 Research framework

In order to develop cause and effect relationships, relevant process safety documents namely, HAZOP and SIL (Layers of Protection Analysis) study reports were studied in detail. These are actual reports from the industry and confidential in nature and therefore cannot be listed here. Several accident investigation reports were also studied in depth to analyze the root causes that led to such accidents [11] [12] [13] [14]. In parallel the techniques of developing BN were reviewed to select the right approach to model the cause and effects / influence diagrams [1] [3] [4].

BN requires parameterization with failure / incident data. Failure data from several data sources were analyzed to parameterize the BN and the same are given in Table 3.4. In certain cases expert opinion were also sought. In summary it required inter-disciplinary research and materials from many sources [15] [16] to understand the application of BN to risk assessments.

1.7 Structure of the thesis

The thesis is written in11chapters. Contents of each chapter is summarized below:

Chapter 1Introduction which is this chapter provides an overview of the topic as well as the background and motivation for taking up the research work. Purpose, objectives and scope are given in this chapter.

Chapter 2 Literature survey presents the comprehensive survey of the literature that was conducted to understand previous work done in this area and to place the research in the right context. The survey was done in three steps, first one was to illustrate the application of BN to a wide range of areas, second was to understand previous work related usage of BN to process industry and third step was specifically with regard to oil and gas. It is noted that application of BN to oil and gas facilities are very limited.

Chapter 3 Bayes Theorem, nature of causality and framework for application to major hazards in oil and gas facility contains description of Bayes theorem, how it can be applied to represent cause and effect and how complex cause and effect mechanisms can be visually represented as a graphical form using BN. It also presents two examples to illustrate the flexibility and power of the BN.

Chapter 4 Bayesian Network for loss of containment in oil and gas separator takes up the immediate and root (parent) causes for a loss of containment (LOC) scenario in a typical oil and gas separator. Causes for loss of containment as well as the post event scenario is modeled in BN. Application of BN to Safety Integrity Level (SIL) calculations is given here. Sensitivity feature of BN and how it can be used to find out the sensitivity of other nodes to a target node is given in this chapter.

Chapter 5 Bayesian Network for loss of containment in hydrocarbon pipeline gives the application of BN to a LOC scenario of a hydrocarbon pipeline. The immediate and root causes as well as the post LOC event scenarios are modelled as BN. Predictive and diagnostic modes of simulating the BN are described. Sensitivities of parent nodes to target node LOC is given. Further, the chapter contains a case study of a natural gas pipeline accident that happened in Andhra Pradesh.

Chapter 6 Bayesian Network for loss of containment in hydrocarbon storage tank describes the causes, sub-causes for the key causal factors involved in LOC of Floating and Cone roof tanks. Intermediate and immediate causes downstream of the key causal factors as well as its interrelationships are also defined in the BNs. Post LOC scenarios are modelled for Floating and Cone roof tanks in BN separately. Description of predictive and diagnostics modes of simulation as well as sensitivities of target nodes to other nodes are given here.

Chapter 7 Bayesian Network for compressor package presents the immediate and root causes for compressor damage. These have been converted to BN model and predictive and diagnostic modes of analysis are illustrated here. Sensitivities of nodes to target nodes enable fast assessment of the likely contributors to compressor damage.

Chapter 8 Comparison of Quantitative Risk Assessment (QRA) and Bayesian Network in analyzing risk contain a comprehensive comparison of QRA and BN methods in analyzing risk. Further, a case study of QRA of Floating roof tank similar to that of the tank involved in accident at Indian Oil's Jaipur fuel terminal, is presented and compared with BN approach for loss of containment of such tanks. The BN model is applied to the pre accident situation existing at the fuel storage terminal to illustrate the predictive nature of the Bayesian approach.

Chapter 9 Summary and conclusion provides overview of the research work and its outcomes

Chapter 10 Main contribution from the research gives an itemized list of the main contribution along with the publications and conference presentations.

Chapter 11 References lists the papers, books and other material referred in the thesis in the order it appears in the work.

Bio data of the author is given in the last section.

2.0 LITERATURE SURVEY

Bayes theorem can be applied in two ways to analyze risk. They are Bayesian analysis for inference about a conditional event P (A | B) and Bayesian Networks or Bayesian Belief Networks.

The first method uses the prior probability and likelihood function to compute the posterior probability about the unobserved parameter. When the prior probability and likelihood function are distributions, the posterior will be also a distribution, which in general continuous form can be written as equation n.

$$\pi 1(\theta \mid x) = \frac{f\ (x \mid \theta)\ \pi\ (\theta)}{\int f\ (x \mid \theta)\ \pi\ (\theta)\ d\theta} \qquad \text{(Eqn.2.1)}$$

Where θ is the unobserved parameter, $\pi\ (\theta)$ is the prior probability distribution, $f\ (x \mid \theta)$ is the likelihood function and $\pi 1(\theta \mid x)$ is the posterior probability distribution.

Statistical inference about the posterior distribution is made by computing different characteristics of this distribution. This computation is performed by sampling from a target distribution until convergence to the posterior distribution is achieved. Numerical integration is required for denominator of the right hand side, which is done by using specific software tools like WinBUGS. Such analysis is generally used for reliability analysis of components and for predicting failure probabilities using available failure data and failure models.

The second method uses Bayesian Network as described in Chapter 3, to denote graphically the immediate causes and root causes and its interrelationships for a particular event such as loss of containment as well as post event scenarios. This research work focus is about application of second method, that is, Bayesian

Network for risk assessments in oil and gas facility. Therefore only the literature relevant to the framework of this research have been included in the survey.

Bayesian Networks have been applied for risk assessment in several areas including Computer Science, Ecosystem modelling, Medicine, Finance, etc. Significant papers from diverse fields are noted below to demonstrate the wide range of areas in which BN have been applied:

2.1 Literature survey

The survey was done in three steps. First survey was to see the applicability of BN in different areas, second was to review the papers published that has direct relevance to the topic of research in process industry and third step was to specifically see the BN applications in oil and gas. Following gives a chronological summary of the papers.

The paper by Gulvanessian and Holicky in 2001 [17] is one of earliest publication that proposes a BN to analyze the efficiency of fire protection systems and to examine the most efficient arrangements. Oien [18] in his paper presented BN to identify qualitatively the root causes of organizational risk factors and its linkage to incidents during the same time.

The 2002 paper by Hudson et al [19] is about application of Bayesian Networks to antiterrorism risk management for military planners. Influence diagrams that takes into account human factors and its contribution to failure of safety critical system was developed by Embrey [20] in 2002. These influence diagrams could be readily converted to BN.

Cornalba and Giudici [21] developed a BN approach in 2004 for statistical modelling of operational risk faced by banking organization. In 2005 Bayraktarli et al. [22] published a paper on application of BN for earthquake risk management. All causal factors related to earthquake could be included in the BN model. Advantages of BN to model risk assessments of natural hazards were demonstrated by Straub [23] in his 2006 paper. During this time Kim and Seong [24] also described application of BN to model several scenarios in the nuclear industry.

In the Marine Transportation domain, BN has been applied by Trucco et al. [25] in 2008 to take into account all key factors and its influences and used in a case study for quantification of Human and Organizational Factors

One of the noteworthy medical applications include a medical expert system created by Twardy et al. [15] in 2005 for estimating risk of coronary heart disease (CHD) in the next 10 years. They used the data from the Busselton and the Prospective Cardiovascular Munster (PROCAM) study to develop a BN. They modelled the predictor variable, namely risk of coronary heart disease as a weighted sum of 8 risk factors and used the software 'Netica' to model the same as a BN.

In eco-system modelling, the Murray Darling Basin Authority's 'Developing a Bayesian Network for Basin Water Resources Risk Assessment' [16] published in 2010 provides valuable insights into BN modelling for risk computation of complex systems.

Weber et al [9] in 2012 produced an overview on BN applications on dependability, risk analysis and maintenance areas. They note that BN have been used to analyze risk situations from 2001 and that there has been a 6 fold increase in the number of papers on BN applications to risk assessment from 2001 to 2008. The authors specifically note that BN applications are developing rapidly and that it is well adapted for risk assessments due or its capability to quantify low probability numbers.

These papers from diverse areas illustrate that BN provide a sound framework for conducting risk assessments.

In parallel with the applications of BN in several domains, there were several papers describing BN applicability in process industries for conducting risk assessments. Those papers as well as certain others closely relevant to the research subject are summarized below in chronological order:

The paper by Papazoglou et al. [26] in 1992 presented one of the first comprehensive picture about probabilistic risk assessment as applicable to process industries. The authors based the risk assessment methodologies on the prevailing practices in nuclear industries. They described the entire assessment steps from hazard identification, accident sequence modeling, data acquisition, parameter estimation, accident sequence quantification, release and consequence assessment as well as procedures and methodologies for the same. However BN do not find any mention in this paper.

Bobbio et al. [27] in 2001 highlighted that BN provide a robust probabilistic method of reasoning under uncertainty. They showed that any Fault Tree (FT), which is used for modelling dependent systems, can be directly mapped into a BN and that basic inference techniques of the latter may be used to obtain classical parameters computed from the former (i.e. reliability of the Top Event or of any sub-system, criticality of components, etc.). The authors compared the two methodologies, by simulating case taken from the literature that consists of a redundant multiprocessor system.

Event trees are a popular technique for modeling accident sequences and can be viewed as a BN. Using a train derailment case study, Bearfield and Marsh. [28] in 2005 showed that BN enables modeling of all factors that influence the outcome of events explicitly. They concluded that the two methods are complimentary.

Pasman et al. [8] paper in 2009 questioned the conventional Quantitative Risk Assessment (QRA) methodology and highlighted the problems with current QRA practice. The authors cited the famous ASSURANCE project [29] where 7 teams were asked to conduct QRA for an ammonia storage tank. The spread of the results of the individual risk contours from the various teams were of the order of 3, which points to the unreliability of QRA results. The paper noted that ‘Quantitative Risk Analysis offers much, but has its weakness and drawbacks. The required effort is considerable, specialists are needed and variability is large. Yet a model built to go along with the life of an installation and updated periodically may be very useful’.

The British Petroleum (BP) Texas City Refinery accident was modelled and described by Kalantarnia et al. [30] in 2010 by using dynamic risk assessment approach. This approach integrated Bayesian failure updating mechanism with the consequence assessments. The accident itself happened in 23 March 2005 and raised many questions on process safety. The authors used generic individual equipment failure rates and updated the same with observed data. They noted that although QRA has proven effective in the industry, it lacks an important element namely; the interdependency of risk function with time. Risk values cannot be updated as changes happen in the facility without undertaking another study.

Kujath et al. [31] 2010 presented an accident prevention model for offshore oil and gas processing environments specifically related to hydrocarbon release scenarios and any consequent escalating events. From reported industry data, the elements to prevent an accident scenario were identified and included in the model for accident progression. The elements were modeled as safety barriers (barriers designed to prevent the accident scenario from developing). The comprehensive accident models were in the form of Fault Trees (FT) and highlighted vulnerabilities of oil and gas processing operations. The authors applied the 1988 Piper Alpha and the 2005 BP Texas City disaster scenarios to the model. Though BN was not explicitly stated, the FTs could be readily converted to BN with probability data.

The limitations of FTs were highlighted as its static structure and difficulties in uncertainty handing by Khakzad et al. [32] in 2011. The authors compared FT and BN approaches and noted that BN is an alternative technique with good potential for safety analysis, the main advantage being its ability in representing dependencies of events, updating probabilities and handling uncertainties. They developed the FT for a feed control system for transferring propane from an evaporator to a scrubbing column and converted the same to BN and illustrated the flexibility of BN.

A new approach using a combination of Fault Tree (FT) and BN was proposed by Duane et al. [33]. In this paper published in 2012, they described a FT for a fault diagnostic system to help maintenance crew to take efficient decisions. The FTs were mapped to BN and component failures were updated using Bayesian inference for each of cut sets that are required for the top event system failure to happen. The method was applied to an aircraft engine oil pressure warning instructions system to demonstrate that a better decision can be taken by combining both the methods.

Rathnayaka et al. [34] 2012 presented an accident model of a LNG processing facility based on the concept of Management and Organizational barriers to prevent a catastrophic accident. The barriers included Release prevention barrier, Dispersion prevention barrier, Ignition prevention barrier, Escalation prevention barrier, and Damage control and Emergency management barrier. Fault Tree (FT) diagrams were developed for each of barriers and its sub-components and Event Tree (ET) was used to model the barrier's sequential failures. Failure rates were input to the FT and ET. BN was not used as such, but the failure probabilities were updated using Bayesian inference and updating method by considering a prior probability distribution and likelihood function. The authors concluded that Bayesian updating method can be used to predict system failures with reasonable accuracy.

In the research work done as part of his PhD thesis in 2012 Khakzad [35] included the following BN models for chemical industry incidents. They are: feed control system failure for transferring propane from an evaporator to a scrubbing column described earlier, sugar dust explosion in a sugar manufacturing plant, simple gasoline release, heptane overflow from an open top mixing and heating tank, ammonia heat exchanger accident and deep water drilling blow out. The work mainly applied variety of Bayesian statistical methods including inference techniques to analyze accident scenarios and safety issues. These papers are summarized later in this chapter. He concluded that Bayesian approach offer a robust methodology for assessing risk in process plants.

Cai et al. [36] applied Bayesian dynamic Bayesian Network for quantitative risk assessment of human factors on offshore blowouts. In their paper in 2013, the authors described failure of human factor as consisting of failure of 3 sub barriers namely, individual factor barrier failure, (IFBF), organizational factor barrier failure, (OFBF) and group factor barrier failure (GFBF). They developed a pseudo-Fault Tree and translated it to BN. The results showed the degree to which the three categories of human factors influence occurrence of accidents.

Pasman and Rogers [37] did a comparative study of compressed and liquefied Hydrogen transportation and tank station risks in 2013. They evaluated the risks using BN for two types of refueling stations and three hydrogen supply transportation types. The authors were critical of QRA methods, noting that 'QRA software packages produce a risk matrix of potential consequences versus event probabilities without indicating uncertainty, and results are therefore shrouded in ambiguity. Due to the 'black-box' effect of a package, the calculations also lack transparency'. On the other hand, they found that BN can model cause and consequences in a transparent manner and better support for decision alternatives.

Discrete time BN (DTBN) was developed by Khakzad et al. [38] in 2013. The authors described the Dynamic Fault Tree (DFT), which can take into account the failure sequence of the participating components and its conversion to DTBN. However such DTBN requires very large Conditional Probability Tables (CPTs) and requires dividing the parent sets into subsets to reduce the probability tables. Neural dependency method was introduced by the authors to avoid this, thereby increasing the efficiency and reducing the computational time. Explosion of a simple heat exchanger was modelled using DFT for a mission time of 1 hour and same was converted to DTBN. The DTBN was simulated using HUGIN software. Overall the paper demonstrated that complex time dependent process can be analyzed using BN.

The same authors Khakzad et al. [39] 2013 presented mapping of a Bow-tie to BN. They mapped Bow-tie for a simple gasoline release and release of heptane and mineral spirits flammable vapors from an open top heated mixing tank. Failure probabilities from published literature was used to calculate the end values. Further the paper described the techniques of probability updating which is normally used in BN and a relatively newer method called probability adapting. In probability adapting the information about the cumulative occurrence number of an accident during a time interval is used as evidence. The paper concluded the BN and probability adapting can provide important insights in safety analysis of process systems.

Quantitative risk analysis of offshore drilling operations using Bayesian approach was presented by Khakzad et al [40] in 2013. In their work, the authors demonstrated the application of Bow-tie and Object Oriented Bayesian Network (OOBN) methods in conducting quantitative risk analysis of drilling operations. Firstly, they developed Bow-Tie model for potential accident scenario; namely loss of well control due to a pressure 'kick' and then mapped the Fault Tree to a complex Bayesian Network. The large BN was simplified using OOBN method to improve the understanding of dependencies. Prior probabilities were assigned from generic data. These prior probabilities were updated using accident precursor data. The authors concluded that the Bayesian Network method provides greater value than the Bow-Tie model since it can consider common cause failures and conditional dependencies along with performing probability updating and sequential learning using accident precursors

Pasman and Rogers [7] 2013 specifically applied Bayesian Network to LOPA and observed that it makes 'LOPA more effective, QRAs more transparent and flexible, and thus safety more definable'. They described two case studies using BN. First was the example of a batch polymerization reactor with 3 Independent Protection Layers (IPL). These IPLs were converted into a BN and simulated to obtain various cases of failure of for different frequencies. Second case study was a Quantitative Risk Assessment for a gas release in a Hydrogen filing station. The initiating event (release), safety barriers (detection and operator action) and the consequences were modelled in BN. The models were simulated using a software (GeNIe). The model used failure frequency distributions for Hydrogen leaks for better representation of reality. They concluded that BN approach to model the process information is flexible and transparent and is ideally suitable to learning from the past and forecasting the future

Tan et al [41] 2013, developed a dynamic accident model for a gas gathering station with the objective of preventing high Sulphur natural gas leakage and for developing equipment inspection and maintenance strategy. They developed the fault tree and event tree inclusive of the safety barriers. Consequences of abnormal events were divided into accidents and accident precursors, i.e. incidents, near misses etc. Corresponding BN was used to update the failure probability of basic events and that of the safety barriers when new observations were noted. They noted that the trend of failure probability of the safety barriers as well as basic events could be ascertained using this approach. It was concluded that the BN provide useful information for inspection and maintenance.

The increasing applicability of BN was mentioned by Ale et al. [42]. In their paper of 2014, they noted that recent disasters in high hazard industries have been found to have causes that range from direct technical failures through organizational shortcomings to weak regulation and inappropriate company cultures. Risk models have generally concentrated upon technical failures, which are easier to construct and for which there is data that are more concrete. The primary causes however are rooted in the organizational culture and determine the way in which individuals conduct risky operations. Modelling collective human activities, and complex interactions between different individuals is difficult. Their paper described the development of a dynamic integrated BN model for assessing risk in a real- time environment for the hydrocarbon industry. The model was based on the Causal Model for Air Transport Safety (CATS) used in commercial aviation safety. The authors observed that aviation is relatively simpler than oil and gas industry which covers a wide range of activities from exploration, drilling, production, transport, refining and chemical production. The potential for large scale disaster is very high in all these activities. They argued that management actions that are common causes for failures can be modelled in BN system. The paper noted that work still needs to be done in the area for developing BN for large systems.

Abimbola et al. [43] 2014 studied the underbalanced drilling which involves designing the hydrostatic pressure of the drilling fluid to be lower than the pore pressure of the formation being drilled. Due to lower hydrostatic pressure, underbalanced drilling poses higher safety risk than its alternatives of conventional overbalanced drilling and managed pressure drilling. The safety risk includes frequent kicks from the well and subsequent blowout with potential threat to human, equipment and the environment. In their study, a dynamic safety assessment approach was presented. This approach is based on Bow-Tie (BT) analysis and real time barriers failure probability assessment of offshore drilling operations involving subsurface Blowout Preventer. Conventional Bow-tie model represents the potential accident scenarios, their causes and the associated consequences in a static manner. The authors developed Fault Trees for well blow-out and Event Tree consequences. Failure probabilities of key barriers were incorporated into the Bow-tie. Further, real time observed data was used to update the failures probabilities by Bayesian update technique and used for safety assessment. The authors concluded that this methodology can be considered as real time risk monitoring tool for practical applications in drilling.

A review of the Bayesian methods in risk and reliability assessment in chemical process industries was produced by Roy et al. [10] in 2014. The paper covered the various applications of Bayesian statistical methods including predictions based on accident precursor data, BN, decision support systems and dynamic risk assessments. After extensive review, the authors noted that Bayesian methods might be useful in meeting the need for 'reconstruction of reality to identify the causes of accidents either in a quantitative or in a qualitative way'. They concluded that Bayesian approach provides comprehensive framework for risk analysis of complex systems.

As can be seen, Bayesian approach has been used in a variety of ways in process industry and key papers number about 20. Of the above, 4 papers are related to application of BN to oil and gas facilities. Nevertheless cause and effect mechanisms and its interdependencies specific to major hazards in typical oil and industry equipment like oil and gas separator, pipelines, storage tanks and compressors do not find any mention in these papers.

2.2 Survey of software

A survey of the most popular BN software was also carried out to access the capabilities, affordability and technical support. They are given below in Table 2.1:

Table 2.1. List of popular software for BN

Sl. No	Name of software	Company / Organization	Internet site
1	Analytica	Lumina Decision System Inc	www. lumina.com
2	Bayesia	Bayesialab	www. bayesia.com
3	GeNIe	Decision System laboratory, University of Pittsberg	http://dslpitt.org/genie/
4	Netica	Norsys Corporation	www. norsys.com
5	Hugin	Hugin Expert	www.hugin.com
6	JavaBayes	University of Sao Paulo	http://www.cs.cmu.edu/~javabayes/ sites.poli.usp.br/pmr/ltd/Software/javabayes/ Home/node3.html
7	MSBNx	Microsoft	http://research.microsoft.com/adapt/ MSBNx
8	AgenaRisk	Agena Ltd	www.AgenaRisk.com

Of the above, Netica® [44] was chosen for this research work.

2.3 Inferences from literature survey

As seen from the survey, Bayesian theory is being applied for risk assessment in several domains [9] [15] [16] [17] [18 [19] [20] [21] [22] [23] [24] and [25] In all the above the authors highlight that flexibility and advantages of application of BN. With respect to process industry, all the papers conclude that BN is an option that should be thought of for safety and risk assessment. In [8] the authors raise important questions about the limitations of QRA and notes that the risk assessment methodology has to be improved to make it effective.

However direct applications to oil and gas are limited. Paper [30] models the accident at BP city refinery. The analysis is confined to technical aspects only. The authors used previous data from the plant as the prior probabilities and predicted posterior failure probabilities before the accident. [31] did not apply BN explicitly. Only human factors related to preventing an accidental blowout were considered in were on [36]. In [27] Bayesian approach was used to study precursor data comprehensive model for offshore blowout has been presented and Bayesian analysis has been applied to the same.

Research work [35] and [38], [39] include BN models for chemical industry units / equipment as well as papers on applications of BN. The work demonstrates a range of Bayesian statistical methods applied to access safety and risk in process industry. [40] deals with drilling operations and Bayesian inference. BN for LOC of equipment in oil and gas industry was not part of this research.

In [42] the authors presented a case for modelling process plants with BN techniques to have better understanding of the risk profiles and minimize high risks.

Considering the survey and its outcome, it can be concluded that BN is technique that has certain definitive advantages over conventional QRA and needs to be encouraged and popularized in the industry. From author’s experience very few decision makers in the oil and gas industry are aware of the limitation of QRA and the advantages of BN. The industry needs a methodology that is easy to implement and understand at all levels. Most importantly, it needs to be flexible for incorporating changes that happen to facility during its life time. It is difficult nor practicable to conduct QRAs for every change that happen in the facility. Currently, QRA is the tool predominantly in use, with its disadvantages. BN is an alternative tool that needs to be applied for risk assessment in oil and gas industry in view of its advantages.

2.3 Chapter summary

The literature survey shows that BN is a viable option to model risk and is starting to be used in the process industry. In fact there has been certain criticism also about QRA that is currently being used. It limitations are known to researchers. Though BN is applied in wide range of areas, applications to process industry and to oil and gas in particular is limited. It is also observed that majority of the research is still confined to academia.

Next chapter presents the fundamentals of Bayes Theorem, how it can be used to represent causality and framework for application of the same to hazards in oil and gas industry.

3. BAYES THEOREM, NATURE OF CAUSALITY AND FRAMEWORK FOR APPLICATION TO MAJOR HAZARDS IN OIL & GAS FACILITY

A Bayesian Network (BN) is a directed acyclic graph (DAG) in which the nodes represent the system variables and the arcs symbolize the dependencies or the cause–effect relationships among the variables. A BN is defined by a set of nodes and a set of directed arcs. Probabilities are associated with each state of the node. The probability is defined, a priori for a root (parent) node and computed in the BN by inference for the others (child nodes). Each child node has an associated probability table called conditional probability table (CPT).

3.1 Bayes Theorem and nature of causality

Bayes theorem states that if probability of occurrence of A and B are stated as P (A) and P (B), then P (A) happening given that B has happened can be written as

$$P\ (\mathrm{A}|B) = \frac{P\ (B\ |A\ )\ P\ (A)}{P\ (B)} \qquad \text{Eqn. (3.1)}$$

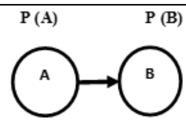
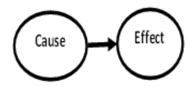
Equation 3.1 can be rewritten as in equation 3.2 for cause and effect, given that normally we see only the effect.

$$P\ (\ \mathrm{cause}|\mathrm{effect}) = \frac{P\ (effect\ |\ cause\ )\ P\ (cause)}{P\ (effect)} \qquad \text{Eqn. (3.2)}$$

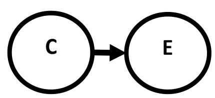
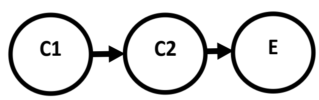
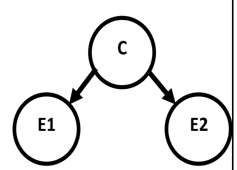
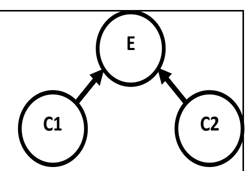
It states that, given that we see an effect, the probability of its cause can be described by a combination of the probability of effect given the cause –which would be observable and the unconditional probabilities of cause and effect. The right hand side of equation (3.2) is called the prior probability, which when computed will give the left hand side known as posterior probability. The right hand side denominator of the equation (3.2) requires calculation of the total probability of effect.

$$P\,(\,\text{effect}|) = \frac{P\,(effect)\,P(cause)}{P\,(cause)} + \frac{P\,(effect)\,P(no\ cause)}{P\,(no\ cause)} \quad \text{Eqn. (3.3)}$$

The relationship is shown schematically in Figure 3.1

<table>
<tr><td></td><td></td></tr>
<tr><td>$P\,(A \mid B) = \dfrac{P\,(B \mid A).\,P\,(A)}{P\,(B)}$</td><td>$P\,(\text{Cause} \mid \text{Effect}) = \dfrac{P\,(\text{Effect} \mid \text{Cause}).\,P\,(\text{Cause})}{P\,(\text{Effect})}$</td></tr>
<tr><td colspan="2">Figure 3.1 Bayes theorem for cause & effect</td></tr>
</table>

Major hazard in an oil and gas facility is a Loss Of Containment (LOC). Once LOC happens, it could lead to jet fire, vapor cloud explosion or flash fire, pool fire and or toxic cloud dispersion. With the above equation 3.2, relationships can be built up for all the identified causes and effects for loss of containment of the selected equipment. Different types of relationships are shown in Figure 3.2.

<table>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>a-Direct cause C & effect E</td><td>b- Serial connection. Single effect E with root cause C1 and intermediate cause C2</td><td>c- Divergent connection. Single cause C with two effects E1 & E2</td><td>d- Convergent connection. Two causes C1 & C2 with one effect E1</td></tr>
<tr><td colspan="4">Figure 3.2 Types of relationships (cause and effects) and their Bayesian representation</td></tr>
</table>

In serial connections as in Figure 3.2 b, hard evidence entered at C2 is transmitted to E, at the same time blocking any evidence from C1 reaching E. This is called d-separation. In other words C1 & E are d-separated given C2 [1] and this aspect plays an important role in computing of BN.

Causes and effects are typically modelled with influence diagrams / fault trees and event trees. The Bow tie diagram is a combination and represents fault tree on left hand side and event tree on the right hand side. The loss of containment event is at the center.

3.2 Bayesian Network (BN)

Effectively BN is an explicit description of the direct dependencies between a set of variables [1].

3.2.1 General expression for full joint probability distribution of a BN. [1]

When we have a BN of n variables A_1, A_2 …An, using the chain rule the joint probability distribution can be written as

$$P\ (A_1, A_2 \dots A_n|) = \ P\ (A_1\ |A_2, A_3 \dots A_n)\ \ P\ (A_2\ |A_3, A_4 \dots A_n)$$

$$P\ (A_{n-1}\ |A_n)\ P(A_n) \qquad \text{(Eqn.3.4)}$$

which can be written using the product symbol

$$P\ (A_1, A_2 \dots A_n|) = \ \prod_{i=1}^{n}\ P\ (A_i \mid A_{i+1} \dots . A_n \qquad \text{(Eqn. 3.5)}$$

However if we know that A_1 has exactly two parents A_3 and A_5, then the generic part of the joint probability of equation's left hand side

$$P\ (A_1\ |A_2, A_3 \dots A_n)$$

reduces to

$$P\ (A_1 \mid A_3, A_5)$$

Therefore in general, if Parents (A_i) denote the set of parents of the node A_i, then the full joint probability distribution can be simplified as

$$P\ (A_1, A_2 \dots A_n|) = \ \prod_{i=1}^{n} P\ (A_i \mid Parents\ (A_i) \qquad \text{(Eqn. 3.6)}$$

3.3 Illustrative example of application

Application of the above principles will be illustrated in the following two simple Bayesian Network for process systems.

3.3.1 Emergency Shut down valve (ESDV) operation

An ESDV acts to prevent a hazardous situation from developing in to an accident. The situation can be represented as an Event tree given in Figure 3.3. Let us assume that the probability of an Emergency Shut Down Valve (ESDV) working is 0.85. The probability values are hypothetical and not from any database. Conversely, probability of ESDV not working is 0.15. If ESDV works the probability of Safe Shutdown is 0.97. If ESDV does not work the probability of Safe Shut down is only 0.02.

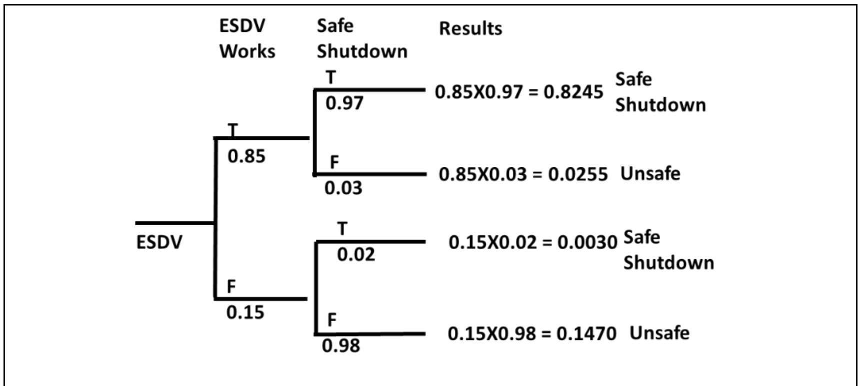


Figure 3.3 Event tree for ESDV action and Safe shutdown

From the Event Tree the following can be calculated:

Probability of Safe Shutdown = 0.8245 + 0.0030 = 0.8275

Probability of Unsafe situation= 0.0255 + 0.1470 = 0.1725

The Even tree can be converted to an influence diagram shown below in Figure 3.4.

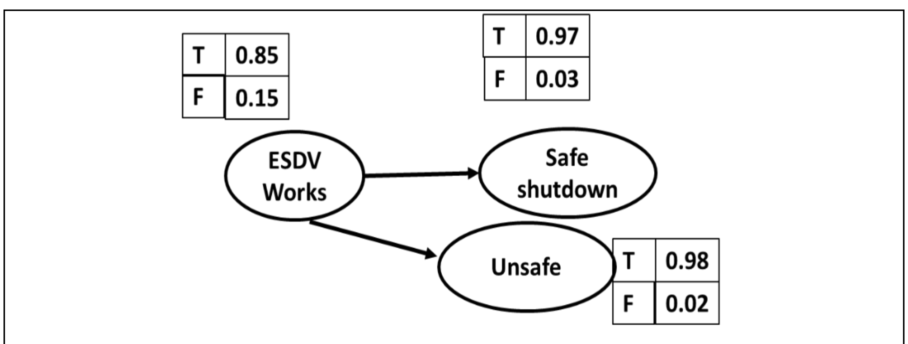


Figure 3.4 Influence diagram for ESDV action and Safe shutdown

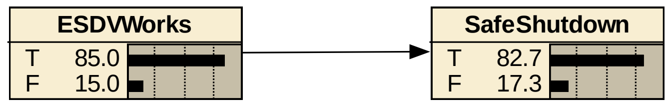


Figure 3.5 BN for Event tree for ESDV action and Safe shutdown

The equivalent BN is given in Figure 3.5

The BN shows the end results of the Event Tree calculation when input to the conditional probability statements for node 'SafeShutdown' are given as in Table 3.1 below:

Table 3.1 CPT for 'SafeShutdown'

ESDV works	**Safe shutdown**	
	T	**F**
T (0.85)	0.97	0.03
F (0.15)	0.02	0.98

The BN model in Figure 3.5 shows the forward probabilities which are same as the results from Event Tree. Now we have a situation where we know that Safe Shutdown has occurred. What is the probability that ESDV has worked?

In order to calculate the same, Bayes theorem has to be used which is illustrated below:

Probabilities of Safe Shutdown and No Safe Shutdown, given that ESDV has worked

$$\mathrm{P}\ \frac{\text{Safe Shutdown}}{\text{ESDV works}-\text{True}} = 0.97 \qquad \text{(Eqn.3.7)}$$

$$\mathrm{P}\ \frac{\text{Safe Shutdown}}{\text{ESDV works}-\text{False}} = 0.02 \qquad \text{(Eqn.3.8)}$$

Applying Bayes theorem for finding the probability ESDV working given there is Safe Shutdown:

$$\mathrm{P}\ \frac{\text{ESDV Works}-\text{True}}{\text{Safe Shutdown}} = \frac{\mathrm{P}\frac{\text{Safe Shutdown}}{\text{ESDV works}-\text{True}}\ \mathrm{X}\ \mathrm{P}(\text{ESDV Works}-\text{True})}{\mathrm{P}\ (\mathit{Safe\ Shutdown})} \qquad \text{(Eqn. 3.9)}$$

In the above expression, right hand side numerator values are known. The unconditional probability of Safe Shutdown P (Safe Shutdown) in the denominator needs to be calculated.

P $(Safe\ Shutdown)$ =

$$P(\text{ESDV Works} - \text{True}) \text{ X } P\,\frac{\text{Safe Shutdown}}{\text{ESDV works}-\text{True}} + P(\text{ESDV Works} - \text{False}) \text{ X } P\,\frac{\text{Safe Shutdown}}{\text{ESDV works}-\text{False}} \qquad \text{(Eqn.3.10)}$$

= 0.85 X 0.97 + 0.15 X 0.02 = 0.8275

Substituting the above value in the equation 3.10

$$P\,\frac{\text{Safe Shutdown}}{\text{ESDV works}-\text{False}} = \frac{0.97 \text{ X } 0.85}{0.8275} = 0.9963$$

The above computation can be readily achieved in the Bayesian simulation by changing the Safe Shutdown True to 100%. The computation is propagated backwards using the Bayes theorem to give the result as 0.9963 as shown in Figure 3.6 below

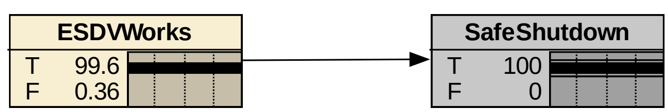


Figure 3.6 BN for ESDV action when Safe shown is confirmed

Simple situations like the above can be done manually or with spreadsheet. But complex and large BN require software. For this research work Netica® [44] was chosen. Several other software are available for BN simulation. List of most popular software for BN is given in Chapter 2.

3.3.2 Oil & Gas separator

Figure 3.7 shows a typical upstream oil and gas production separator with critical safety barriers. The inlet is reservoir fluid consisting of oil, gas and water. The separator is envisaged as device to separate gas and liquid with outlets for each of them. Figure 3.8 shows an example of a Bow tie diagram for a simplistic and illustrative Fault Tree & Event Tree for LOC for a separator.

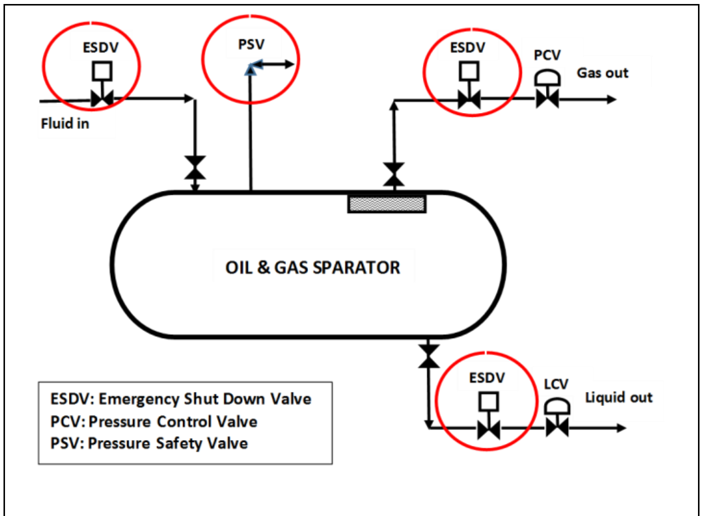


Figure 3.7 Typical oil & gas production Separator

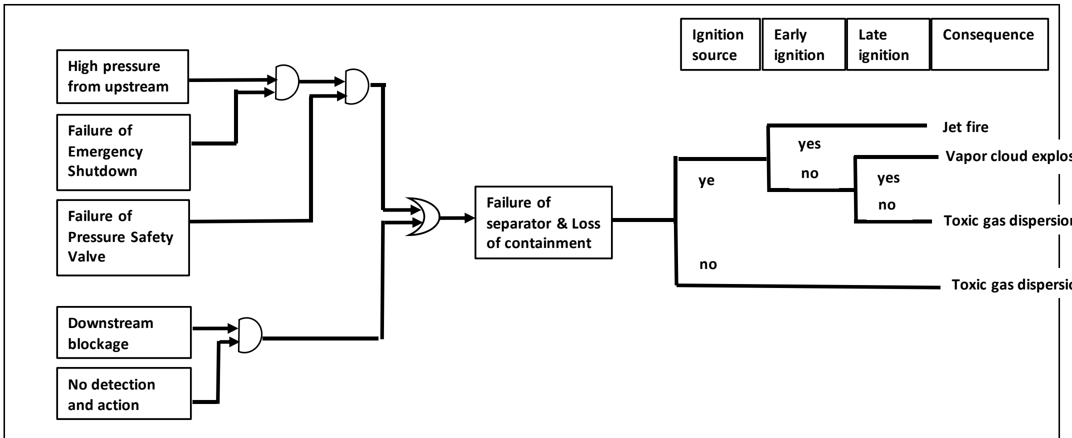


Figure 3.8 Separator Loss of Containment : Bow tie diagram example

In Figure 3.8, the Fault Tree on the left hand side depicts the potential hazards and its corresponding mitigating measures and is built up using OR and AND gates.

Probability of LOC can be calculated when probabilities are assigned to each of failures. From LOC, the event can proceed to any of the scenarios in the event tree. With probabilities are known for each branch in the event tree, the probability of each end consequence is calculated.

Using the connections described in Figure 3.8, the equivalent BN to the above Bow tie has been developed and the same is shown in Figure 3.9. Mapping of the Fault Tree, Bow tie and Event tree are described in literature [27] [38] and in [45]. The compact model given in [45] is used here. The BN developed using Netica® is shown below in Figure 3.9.

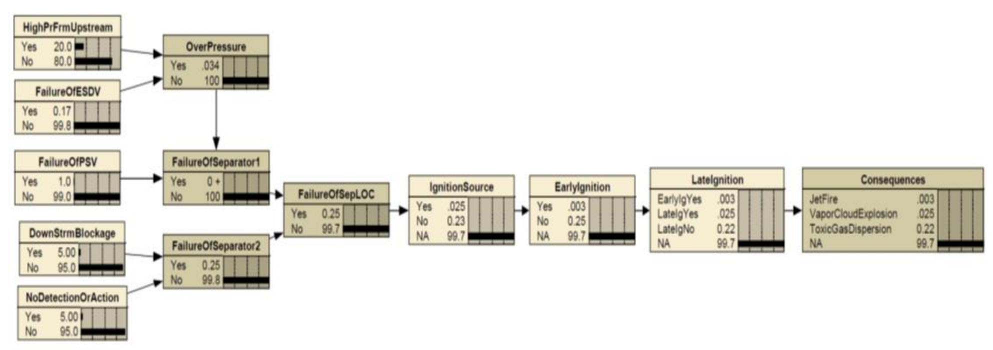


Figure 3.9 BN network for Bow tie diagram of separator

Once the BN has been finalized, it is parameterized with the probability of failure values in the parent nodes (nodes without any predecessors). The probability values used in the illustrative BN is given in Table 3.2.

Table 3.2 Details of parent nodes for Separator LOC

Sl. No.	Node name	Node full form	States & probability value	Parameterization method	Description
1	HiPrFrom Upstream	High pressure from upstream	Yes [0.20] No [0.80]	Manual	High pressure can come from upstream well side
2	Failure of ESDV	Failure of ESDV	Yes [0.00165] No [0.998]	Manual	The Probability of Failure on Demand for ESDV is used.

Table 3.2 Details of parent nodes for Separator LOC

Sl. No.	Node name	Node full form	States & probability value	Parameterization method	Description
3	Failure of PSV	Failure of Pressure Safety Valve	Yes [0.001] No [0.0099]	Manual	The Probability of Failure on Demand for PSV is used.
4	DownstreamBlockage	Downstream blockage	Yes [0.005] No [0.0095]	Manual	There could be downstream blockage from demister or valves
5	NoDEtectionOrAction	No detection or action	Yes [0.005] No [0.0095]	Manual	Operator may not detect the downstream blockage & take action

The conditional relationships, OR and AND gates in this case, are encoded in the Conditional Probability Tables (CPTs) of the child nodes. CPTs for child nodes OverPressure and FailureOfSepLOC are given in Figure Table 3.3.

Table 3.3 Conditional Probability Tables (CPTs) example

OverPressure:		
	HighPrFrmUpstream	FailureOfESDV
Yes	Yes	Yes
No	Yes	No
No	No	Yes
No	No	No

a-CPT for child node OverPressure (AND gate)

FailureOfSepLOC:		
	FailureOfSeparator1	FailureOfSeparator2
Yes	Yes	Yes
Yes	Yes	No
Yes	No	Yes
No	No	No

b-CPT for child node FailureOfSepLOC (OR gate)

The BN basically describes the joint probabilities of the events and can be used for several types of analysis. Predictive mode will calculate the probability of occurrence of the event namely LOC. On the other hand, if LOC can be assumed to have occurred, by making the ‘Yes’ state in the node FailureOfSepLOC 100%, then the state values for corresponding parents are back calculated by the software. This is the diagnostic mode which is useful for understanding the causes that would have contributed to larger extent in causing the event. Corresponding result of the separator model in Figure 3.10, with LOC equals 100%.

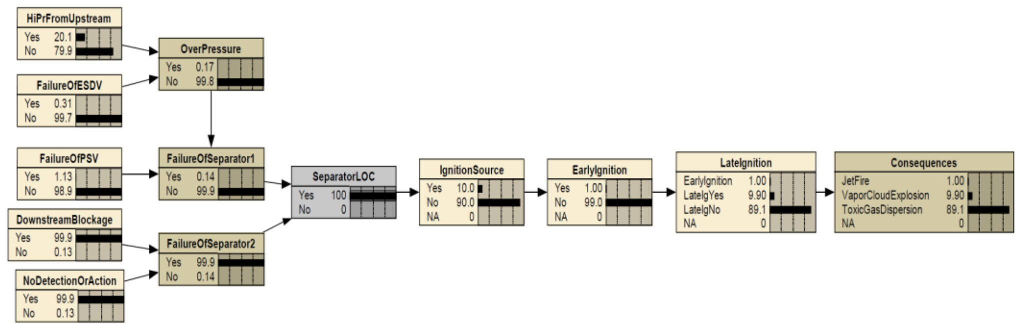


Figure 3.10. BN with LOC 100%.

The model with new evidence of LOC equal 100%, indicates that the main casual factor could be downstream blockage with no detection or action. The flexibility and power of BN is evident from the above example.

Using the principles described above, BN for oil and gas separator, hydrocarbon atmospheric storage tank, hydrocarbon pipeline and compressor have been developed. CPTs for the BNs have been populated with failure data taken from various sources that are listed in Table 4.1.

3.4 Sensitivity to findings

It would be of interest to know how the changes in values of child nodes (findings of effect nodes) can affect the parent nodes. One way of doing this is to manually change the value of the probability (findings) of child nodes and see the how the probabilities change at the parent nodes in BN. An easier way will be to use the tool ‘Sensitivity to Findings’ available in Netica [44].

In other words, sensitivity analysis is a tool that can be used to study of how the variation (or uncertainty) in the output (child nodes) of a model can be apportioned to different sources of variation in the input (parent nodes) of a model. Through sensitivity analysis, variables or parent nodes that have the highest influence in BN models effect (Child) nodes as well as its relative importance, can be obtained.

Two types of sensitivity analyses can be used in evaluating a Bayesian network. The first, 'Sensitivity to findings' considers how the Bayesian network's posterior distributions change under different conditions, while the second, 'Sensitivity to parameters' considers how the Bayesian network's posterior distributions change when parameters are altered. In the Netica® [44] version used in this research only 'Sensitivity to findings' are available and the same has been used to find out which of the nodes have the highest impact on the loss of containment. The following description is from [3].

Sensitivity to findings uses two types of measures, entropy reduction or mutual information for discrete variables and variance reduction for continuous variables.

Entropy is a measure of randomness. The more random the variable is, the higher its entropy will be. In other words Entropy is a measure of how much the probability mass is scattered over the states of a variable (the degree of chaos in the distribution of the variable).

If X be a discrete random variable with n states x1,x2, …..xn and probability distribution of X is P (X), then the entropy of X is defined as

$$H\ (X)\ = -\sum_x P\ (X) \log P\ (X) \qquad \text{(Eqn. 3.11)}$$
$$\geq 0$$

Where log is to the base 2

The mutual information of X and Y is denoted as I (X, Y). The conditional entropy H (X | Y) is a measure of the uncertainty of X given an observation on Y, while the mutual information I (X, Y) is a measure of the information shared by X and Y. If X is the variable of interest, then I (X, Y) is a measure of the value of observing Y. The mutual information is computed as

$$I\ (X, Y) = H(X) - H\ (X\ |Y) \qquad \text{(Eqn. 3.12)}$$
$$= H\ (Y) - H\ (Y|X) \qquad \text{(Eqn. 3.13)}$$

$$= \sum_{Y} P\ (Y) \sum_{X} P\ (X\ |Y) \log \frac{P\ (X,Y)}{P\ (X) P\ (Y)} \qquad (Eqn. 3.14)$$

In principle I (X, Y) is a measure of the distance between P (X) P (Y) and P (X, Y). The conditional mutual information given a set of evidence ε is computed by conditioning the probability distributions on available evidence ε:

$$I\ (X,Y|\ \varepsilon)\ =\ \sum_{Y} P\ (Y\ |\ \varepsilon) \sum_{X} P\ (X\ |Y,\varepsilon) \log \frac{P\ (X,Y|\varepsilon)}{P\ (X\ |\varepsilon) P\ (Y\ |\varepsilon)} \qquad (Eqn. 3.15)$$

$I\ (X,Y|\ \varepsilon)$ is computed for each possible observation of Y. Netica® readily calculates the probabilities needed for the computation.

The other measure is the variance which is a measure of the dispersion of X around mean [4]:

$$Var\ (X)\ = \sum_{x} P\ (x-\mu)^{\,2}\ P(x) \qquad (Eqn. 3.16)$$

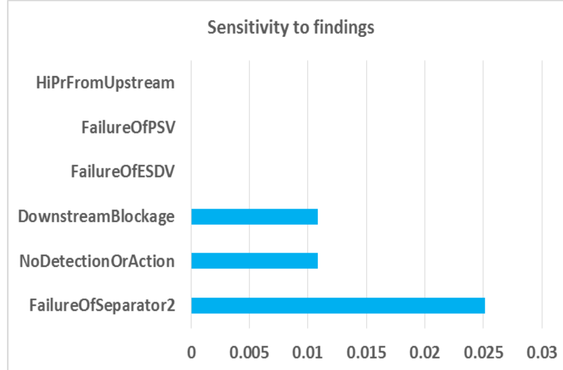
where μ is the mean

The greater the dispersion, the less is known and the sensitivity between the connected nodes is higher.

Figure 3.11 shows the 'Sensitivity to findings' computed by Netica® for the example of oil and separator for the node 'Separator LOC'. For discrete variables Mutual information is the parameter used as a measure of sensitivity. It can be seen that of all the parent (root) nodes, 'Downstream blockage' and 'No detection or action' has the highest influence on the occurrence of the event. The values have been converted to a bar chart as shown here in Figure 3.11.

Node	Mutual Info
FailureOfSeparator2	0.02517
NoDetectionOrAction	0.01086
DownstreamBlockage	0.01086
FailureOfESDV	0
FailureOfPSV	0
HiPrFromUpstream	0

Netica output



Bar chart

Figure 3.11. Sensitivity to findings-Netica output and bar chart

3.5 Framework for BN application for major hazard

The principles of Bayes theorem and network described under earlier sections were applied to development of Bayesian Networks for major hazards in oil and separator, atmospheric hydrocarbon storage tanks, hydrocarbon pipelines and compressors. Major hazards in these equipment are mainly LOC, except in the case of compressors. Oil and separator, atmospheric hydrocarbon storage tanks and hydrocarbon pipelines have LOC scenarios that can lead to high consequence accidents. LOC of the compressor itself is very rare and therefore damage is considered as major hazard for compressor. Leakage of process gas is considered separately in the event tree. Once the BN is defined and constructed using the causal relationships, the parent nodes needs to be parametrized with probability data. These are obtained from the following sources.

3.6 Sources for failure data

A. Published data

A comprehensive survey was undertaken to identify the sources for failure data for the equipment under consideration. Table 3.4 lists the main sources that were used in development of BN.

Table 3.4. Sources for failure data

Sources for failure data	
Organization	**Reference**
International Association of Oil & Gas Producers	Process release frequencies [46]
International Association of Oil & Gas Producers	Ignition probabilities [47]
Offshore Reliability Data	OREDA Handbook 2002 [48]
DNV-Failure frequency guidance	DNV [49]
Center for Chemical Process Safety	Layers of Protection Analysis [50]
European Gas Pipeline database	[51]
USDOT PHMSA database	[52]
CONCAWE database	[53]
Marshal & McLennan	Atmospheric storage tanks. [54]
Large Atmospheric Storage Tank Fires	LASTFIRE 2001 [55]
Accidental Risk Assessment Methodology for Industries	ARAMIS User Guide [56]
Flemish Government	Handbook of Failure Frequencies 2009 Safety report [57]
M.B Lal Committee: Report of the Committee on Jaipur Incident	[10]
Buncefield Fire Report of the Major Incident Investigation Board	[11]
E&P Forum Hydrocarbon Leak and Ignition Database	[58]
TNO (VROM) –Netherlands. Purple Book	[59]
Health and Safety Executive UK	Failure Rate and Event Data for use within Risk Assessment [60]

B. Industry reports

Apart from the above, several industry study reports and documents on Hazard and Operability Studies (HAZOP), Layers Of Protection Analysis (LOPA) and Safety Integrity Level (SIL) were studied to understand the identified failure mechanisms and failure rates used in in practice. They are not listed due to confidential nature of the contents.

3.7 Chapter summary

Basics of Bayes theorem and how it can be applied to causal mechanisms are illustrated in this chapter. Manual calculations are given for predictive forward calculations typical of an Event Tree and for diagnostic (backward) calculations given an evidence using Bayes theorem. BN and how it can give both these calculations are shown. Two examples of simple BN; ESDV action and oil and gas separator hazards are described to bring out the methodology that are implemented in the subsequent chapters. The feature of 'Sensitivity to a finding' of the Netica® [44] software is described. This feature allows determination of contribution of each parent node to a finding at a target (child) node. The framework of how the above are employed for developing BNs for LOC of the equipment under consideration is given in the last section.

The ensuing chapters describe the development and evaluation of BN applications to the most common equipment in oil and gas industry.

4 BAYESIAN NETWORK FOR LOSS OF CONTAINMENT IN OIL AND GAS SEPARATOR

4.1 Oil & Separator basics

Oil and gas production separator receives the reservoir fluid coming from the oil well and separates it into oil, gas and water. It can be three phase separation or two phase (liquid and gas only). Oil and separators are usually designed for a lower pressure than that of the shut off pressure of the well due to economic reasons and sufficient layers of protection are provided for the vessel to mitigate the risk of an overpressure. Figure 4.1 shows the oil and separator and its layers of protection for easy reference.

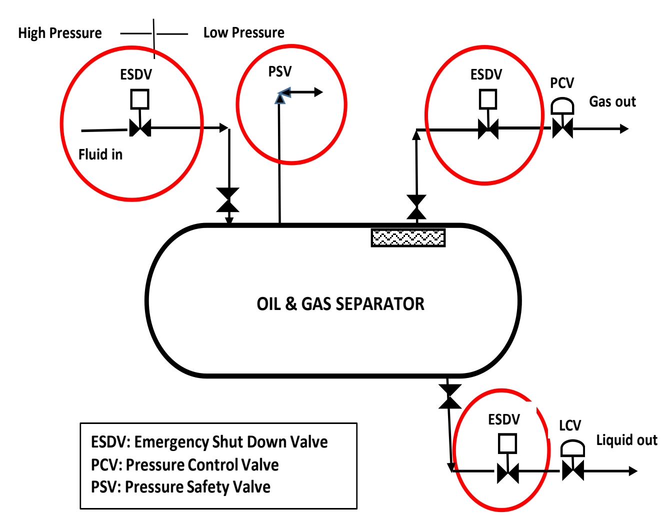


Figure 4.1 Oil and gas separator and its layers of protection

4.2 Causes for loss of containment

The main causes for loss of containment in a typical oil & gas separator as shown are due to overpressure and leakage of flammable gas or liquid. Ignition of the same can result in serious fire accidents. Fire near the separator due to any extraneous causes could weaken the mechanical integrity of the vessel and in LOC. All causes considered are shown in the influence diagram in Figure 4.2. The nodes and their states used in BN is given in Table 4.1. The BN itself is shown in Figure 4.3.

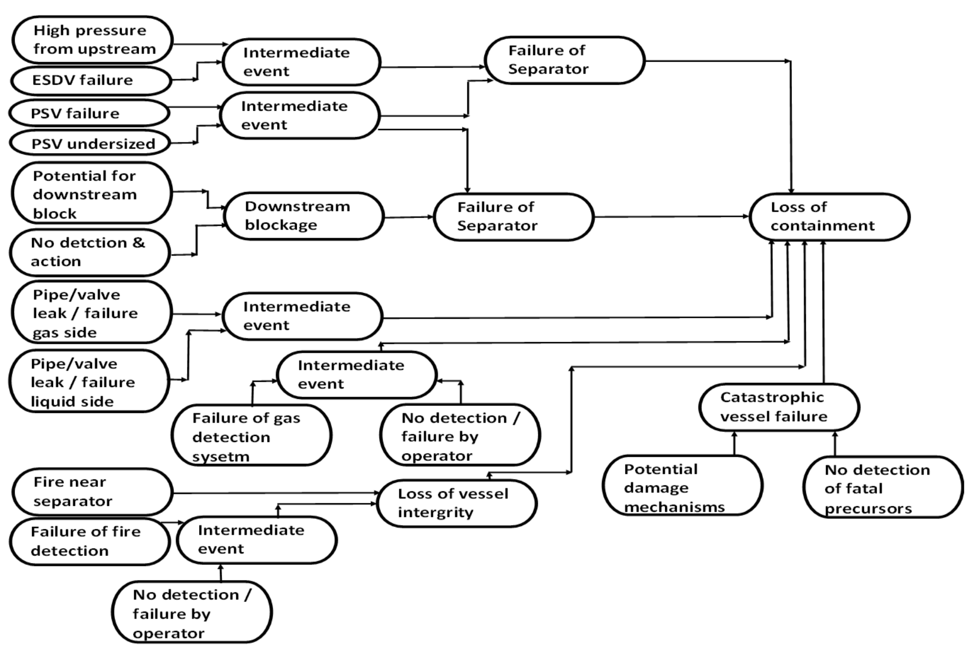


Figure 4.2 Influence diagram for loss of containment in oil and gas separator

Table 4.1 Details of parent nodes for LOC in O&G Separator					
Sl. No.	**Node name**	**Node full form**	**States & probability value**	**Parameterization method**	**Description**
1	HiPrFromUpstream	High pressure from upstream	Yes [0.20] No [0.80]	Manual	High pressure can come from upstream well side
2	ESDV Failure	ESDV failure of	Yes [0.00165] No [0.998]	Manual	The Probability of Failure on Demand for ESDV is used.
3	PSV failure	Failure of Pressure Safety Valve	Yes [0.001] No [0.99]	Manual	The Probability of Failure on Demand for PSV is used.
4	PSVUndersized	PSV undersized	Yes [0.001] No [0.0099]	Manual	PSV could be undersized
5	PotentialForDownstreamBlock	Potential for downstream blockage	Yes [0.005] No [0.95]	Manual	There could be downstream blockage from demister or valves
6	NoDetectionAndAction	No detection and/or action	Yes [0.005] No [0.95]	Manual	Operator may not detect the downstream blockage & take action
7	PipeValveLeakOrFailureGasSide	Pipe or valve leak or failure gas side.	Yes [0.001] No [0.99]	Manual	Piping of valve leakage on gas side
8	PipeValveLeakOrFailureGasSide	Pipe or valve leak or failure liquid side.	Yes [0.001] No [0.99]	Manual	Piping of valve leakage on liquid side
9	FailureOfGasDetSystem	Failure of gas detection system	Yes [0.008] No [0.92]	Manual	The Probability of Failure on Demand for gas detection system is used.
10	NoDetByOprOrFailureOFActions	No detection by Operator or failure of actions	Yes [0.05] No [0.95]	Manual	There could be no detection by Operator or failure of his actions

Table 4.1 Details of parent nodes for LOC in O&G Separator					
Sl. No.	**Node name**	**Node full form**	**States & probability value**	**Parameterization method**	**Description**
11	FireNearSeparator	Fire neat separator	Yes [0.005] No [0.95]	Manual	There could be fire near separator
12	FailureOfFireDet	Fire near separator	Yes [0.006] No [0.94]	Manual	Fire near separator may not be detected
13	PotentialDamageMechanisms	Potential damage mechanisms	Yes [0.005] No [0.95]	Manual	Damage mechanisms like Sulfide stress cracking, Hydrogen induced cracking etc.
14	NoDetOfFatalPrecursors	No detection of fatal precursors	Yes [0.001] No [0.99]	Manual	The damage mechanisms could be fatal and may cause catastrophic failure

4.3 Bayesian Network for LOC in oil and gas separator

The Table 4.1 above depicts causes and its mitigation measures typically employed for an industrial oil and gas production separator. The equivalent BN for loss of containment is given below in Figure 4.3.

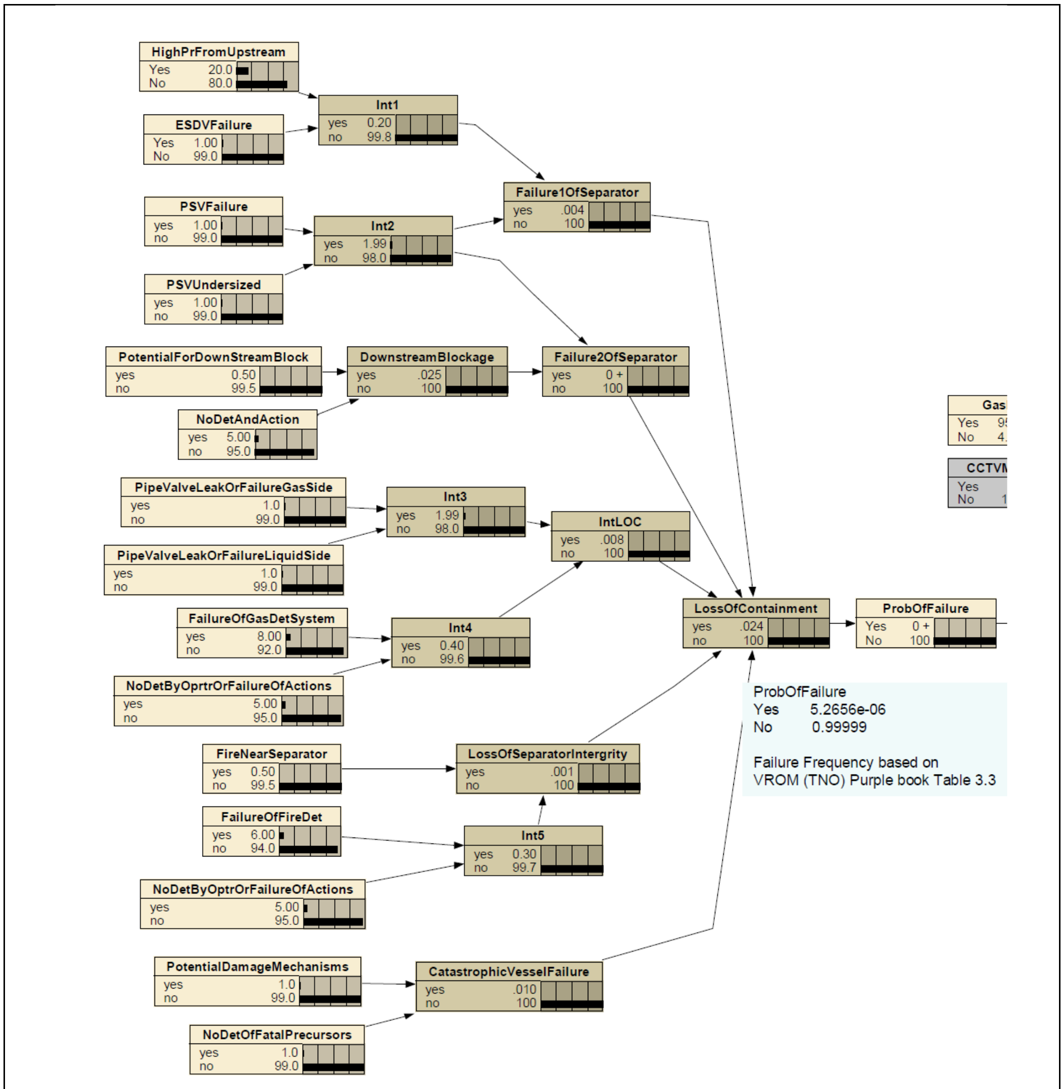


Figure 4.3. BN for loss of containment in oil and gas separator

The node 'LossOfContainment' is an OR gate that combines the parent nodes as per the equation 5.1 given below:

P (LossOfContainment | Failure1OfSeparator, Failure2OfSeparator, LossOfSeparatorIntergrity, CatastrophicVesselFailure, IntLOC)

= (Failure1OfSeparator || Failure2OfSeparator || LossOfSeparatorIntergrity || CatastrophicVesselFailure || IntLOC) (Eqn.4.1)

As can be seen from the BN, given the probabilities (in BN above they are given in percentages), on a relative scale the probability of loss of containment is 0.00024. This relative probability has been transformed in the next node Probability of failure using the industry average value of 5 x 10-6 failures per year [59]-TNO Purple book and assuming constant failure rate.

On predictive mode of the BN, any change of the values in states of the parent nodes will impact the value of the last child node, loss of containment.

Event tree for loss of containment can be readily mapped in to BN [30] [32]. The combined BN that is Fault tree and Event tree for post LOC is given in 4.4. The mitigation barriers after LOC are the gas detection and CCTV monitoring and control action by operators.

Further, the BN can work in diagnostic mode. If there is a loss of containment, the yes state in that node is set to 100%. Then the BN recalculates the values all the nodes. The diagnostic mode is given in Figure 4.4 along with the event tree. It states that the most probable causes of the loss of containment is the failure of no detection of potential damage mechanism followed by leak from gas or liquid side piping.

Various analysis can be done on the BN. For example with the LOC as 100%, if the node 'GasDetection' state is made 100% No, then the probability of fire will jump from 0.007 to 0.011. This underlines the need to have a properly designed and well maintained gas detection system in the facility.

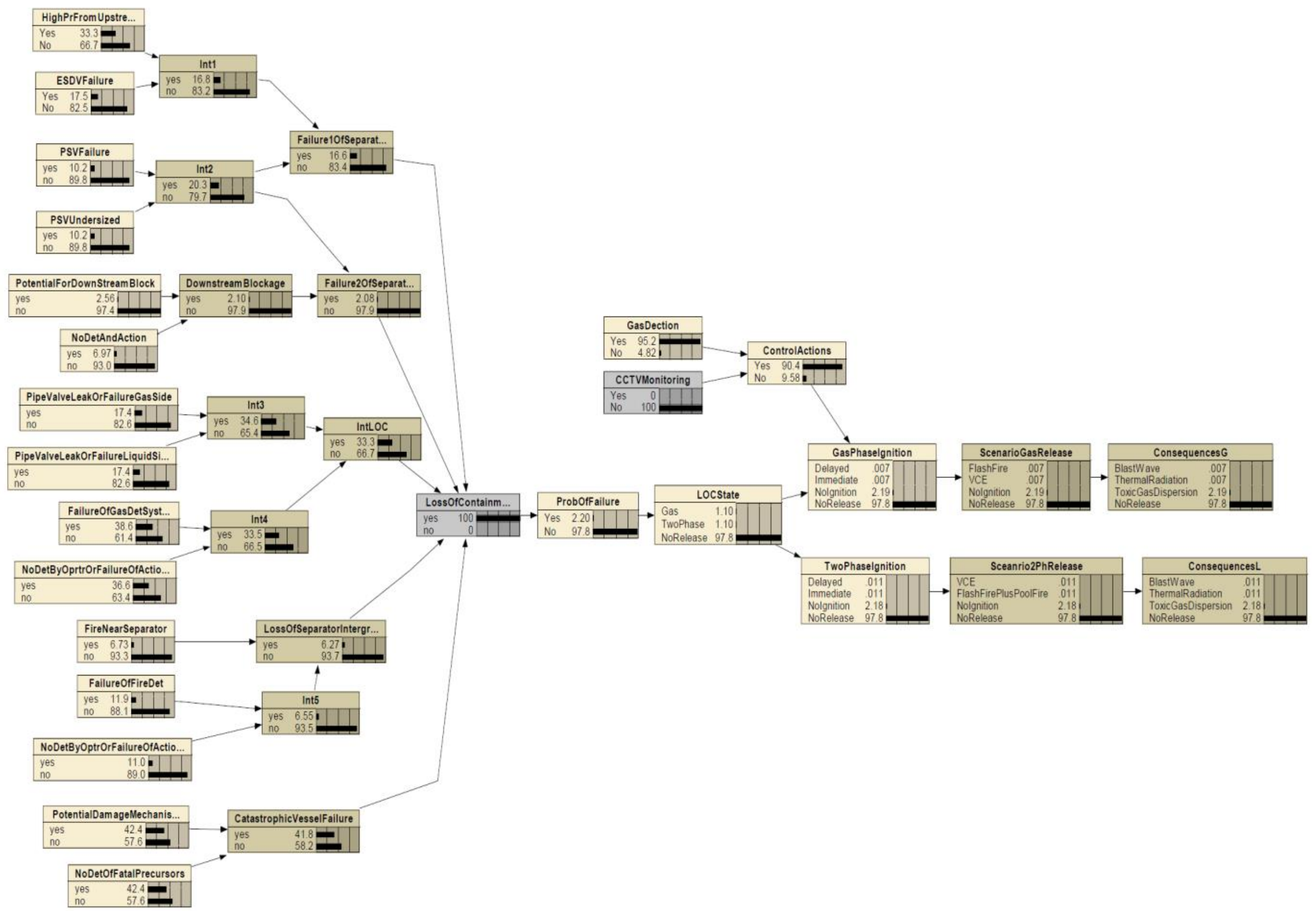


Figure 4.4 BN for loss of containment in diagnostic mode. LOC set to 100%

4.4 Sensitivities

Netica® can calculate parameters for sensitivities of findings at other nodes to a target parameter called query node. A typical graph showing sensitivities of other nodes to loss of containment node is give below in Figure 4.5.

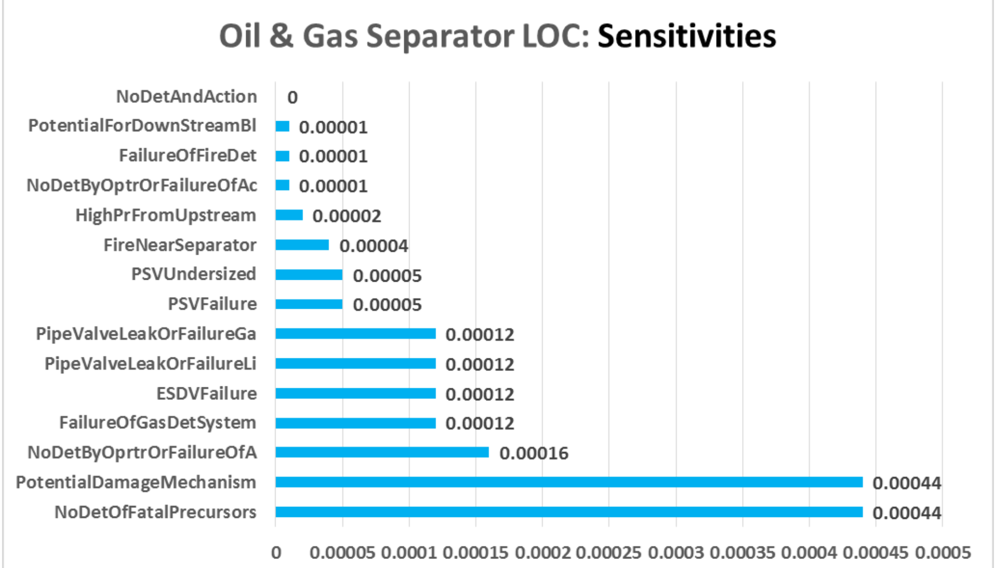


Figure 4.5. Sensitivity of other nodes to loss of containment

As expected it shows that given the current prior probabilities, the highest change in the relative probability of LOC will happen when there is no detection of fatal precursors and potential for damage mechanisms coexist.

4.5 Application of BN to Safety Integrity Levels (SIL) calculations for Oil and Gas separator

As part of the research, an analysis of independent protection layers and Safety instrumented system for oil and gas separators using BN was also taken up. Figure 4.6 shows the layers of protection for a 3-phase oil and gas separator.

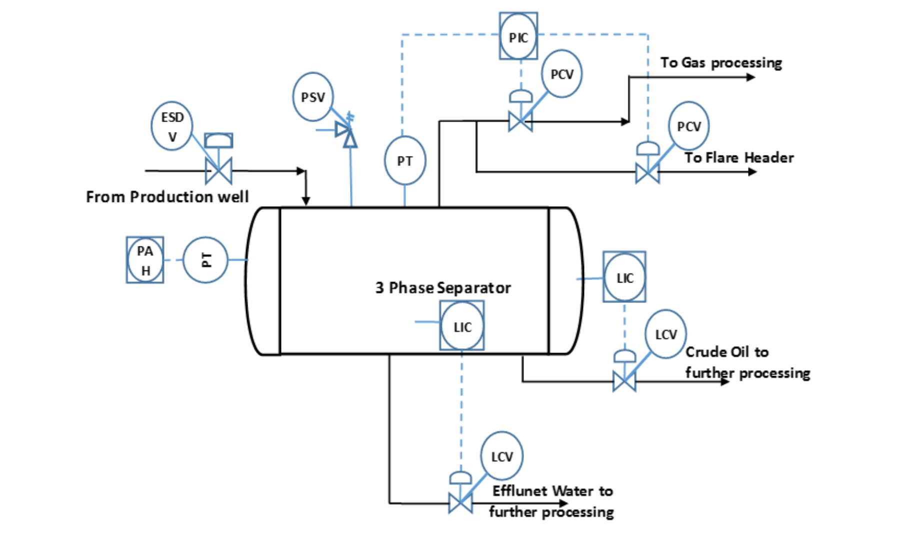


Figure 4.6 Typical 3-Phase Oil & Gas separator showing the Independent Protection Layers

4.5.1 The Independent Protection Layers (IPLs) are:

i. IPL1: Adequate process and mechanical design of the separator vessel is the first layer of protection, which is not usually considered in SIL calculations (Probability of Failure on Demand (PFD) =1.0). Node name: IPL1ProbDesignFailure

ii. IPL2: Basic Process Control Systems-here there are two, the Pressure Control Valve PCV for controlling the vessel pressure (BPCS1) and the other PCV for letting the gas out to the flare in case the pressure goes up beyond the set point (BPCS2). They are not independent and therefore PFD of both the control systems together are taken as 0.10. Node name: IPL2BPCSPCVFailure

iii. IPL3: The SIS forms the next IPL; namely the Emergency Shutdown Valve (ESDV) that comes into action independently once the BPCS and Operator action has failed. SIL calculations are done without considering this. PFD is set to 1. Node name: IPL3ESDVSISFailure.

The (PAH) alarm coming from the control system (Not shown in BN) is meant to initiate Operator action to control the sudden rise in pressure. However Operator action is not considered as an IPL in this study. Depending on company's policies this IPL may be included in SIL calculations.

Figure 4.7 gives the BN for SIL calculations for the Emergency Shut down valve.

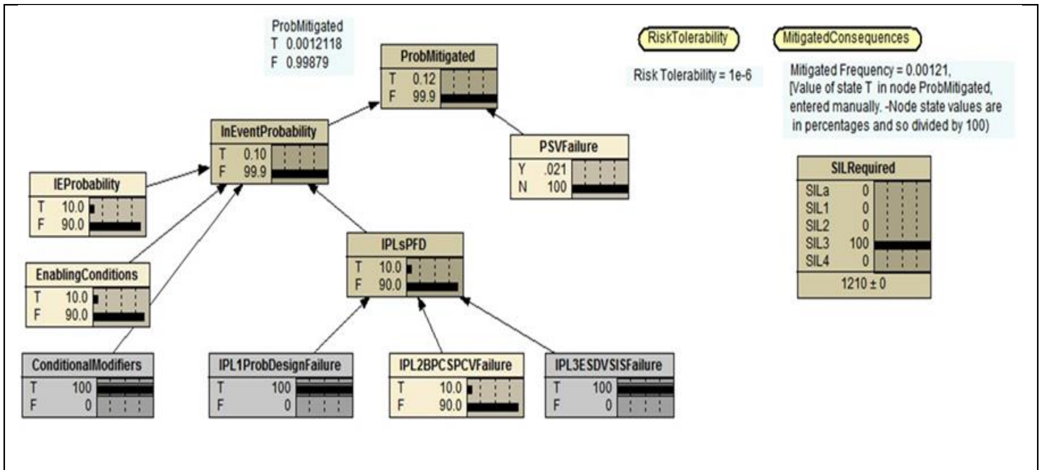


Figure 4.7 BN for SIL calculations for Emergency Shut down valve

The node 'IPLsPFD' combines the other IPL nodes using the Conditional probability table (CPT) defined as in Table 4.2

Table 4.2 CPT for the node IPLsPFD

IPLsPFD:			
	IPL1ProbDesignFailure	**IPL2BPCSPCVFailure**	**IPL3ESDVSISFailure**
T	T	T	T
F	T	T	F
F	T	F	T
F	T	F	F
F	F	T	T
F	F	T	F
F	F	F	T
F	F	F	F

The SIL calculations indicate requirement of a SIL 3 valve to bring down the probability of failure from 0.00121 (Node name: ProbMitigated) to Risk tolerability value of 1 x 10-6.

BN can include any influencing factors that affect the IPLs. For example the effect of testing regime of Pressure Safety Valve (PSV) can be directly visualized in BN by adding a node ‘PSVTesting’ with states On Schedule and Not on Schedule with probability values assigned to it.

Further Common Cause Failures (CCF) that affect components can be also be included in BN. Typical case is that of maintenance planning for components of the oil and gas separator. In a simplified version, nodes ‘LackOfMaintPlanning’ with states True (T) and False (F) and ‘CCF’ with states True (T) and False (F) are added to the BN. Probability of lack of maintenance planning is 0.01 and CCF is 0.06.

Figure 4.8 shows the BN with the additions of PSVTesting with state ‘OnSchedule =100% and the above probabilities for ‘LackOfMainPlanning’ and CCF.

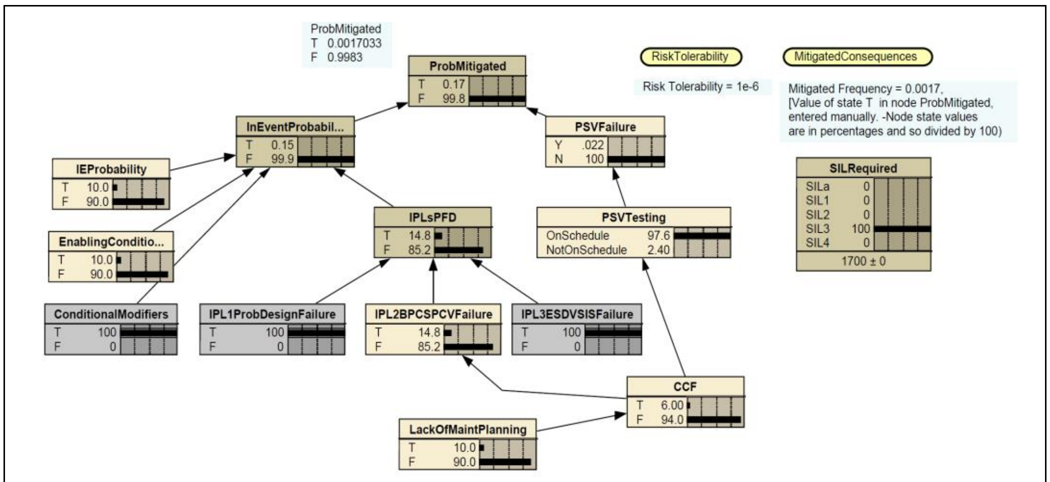


Figure 4.8 BN showing failure probabilities with addition of PSV testing & CCF for lack of maintenance planning

When there is a CCF of lack of planning, it affects the probability of failure of control valve (IPL2) and the schedule for testing of PSV. In such situation it can seen that the value of ‘yes’ at node ‘ProbMitigated’ has gone up to 0.0017. Even though the overall SIL requirement did not change, it important to recognize that influencing factors and CCF can be easily included in SIL study through BN.

4.6 Chapter summary

BN for oil and separator is discussed in this chapter. The root and intermediate causes for a LOC along with mitigation measures are summarized in a table and converted to BN. The usefulness of diagnostic mode of BN simulation is illustrated. Sensitivity of parent nodes to LOC is given which shows that 'No detection of fatal precursors' has the highest contribution to a LOC. Method for application of BN to calculate SIL values is described to highlight that all the factors that affect the IPL can be included in the BN.

Development of BN for hydrocarbon pipeline hazards is taken up in the next chapter.

5 BAYESIAN NETWORK FOR LOSS OF CONTAINMENT IN HYDROCARBON PIPELINE

5.1 Causes of pipeline failures

Pipelines carry crude oil as well product liquid and gas hydrocarbons from production centers to consumer points. Huge pipeline networks exit in USA, Europe, UK and Canada. In fact such pipeline networks are critical infrastructure and therefore need to designed, operated and maintained at the highest level of safety. Several agencies have been collecting data on pipelines and causes of pipeline failures and the data have been documented and analyzed by these organizations. Prominent among them are European Gas pipeline Incident data Group (EGIG) [51] for gas pipelines, US Department of Transportation Pipeline and Hazardous Material Safety Administration (US DoT-PHMSA) [52] and CONCAWE (Oil pipelines–Europe) [53], for liquid pipelines. Their data is available in public domain. Contribution of various causes to the overall pipeline failure is reproduced here from [51], [52] and [53] in Figure 5.1 a, b and c for gas and liquid pipeline failures respectively. Table 5.1 presents the main causes and sub causes identified in these reports in a tabular form.

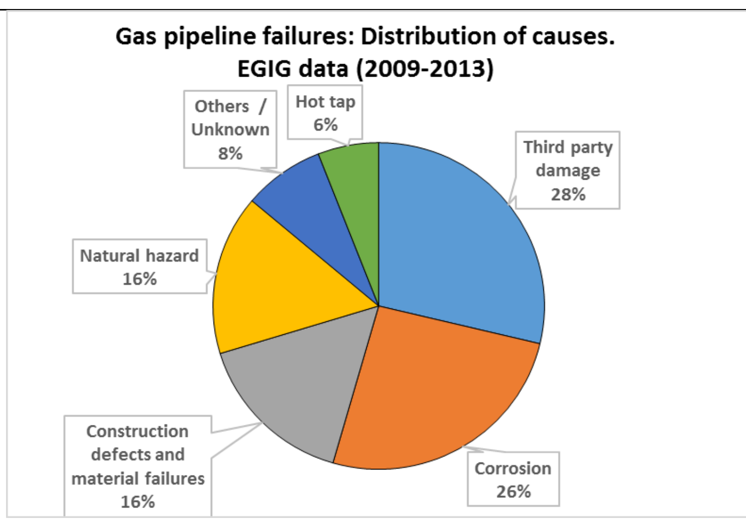


Figure 5.1a Distribution of causes for gas pipeline failure.
EGIG Report Figure 15 [51]

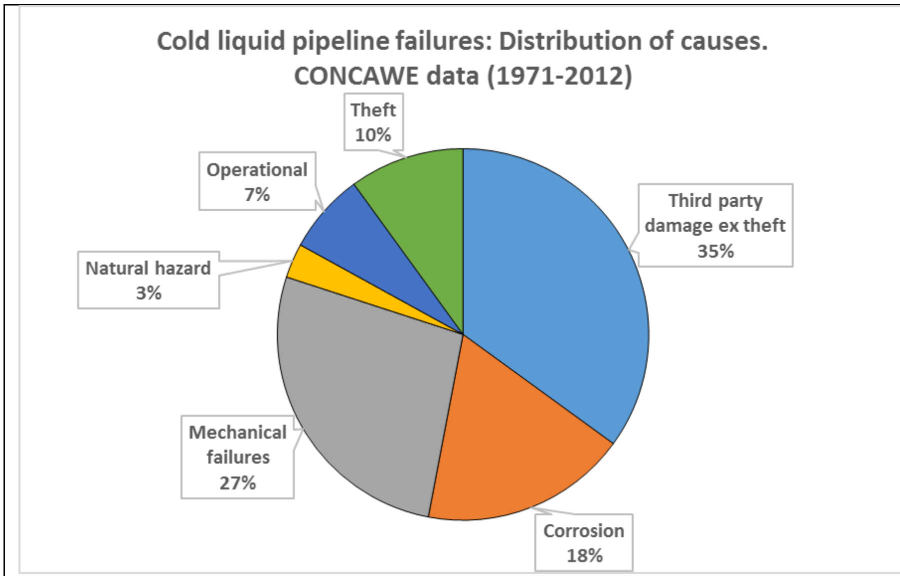


Figure 5.1b Distribution of causes for liquid pipeline failure. CONCAWE data Figure 18 [52]

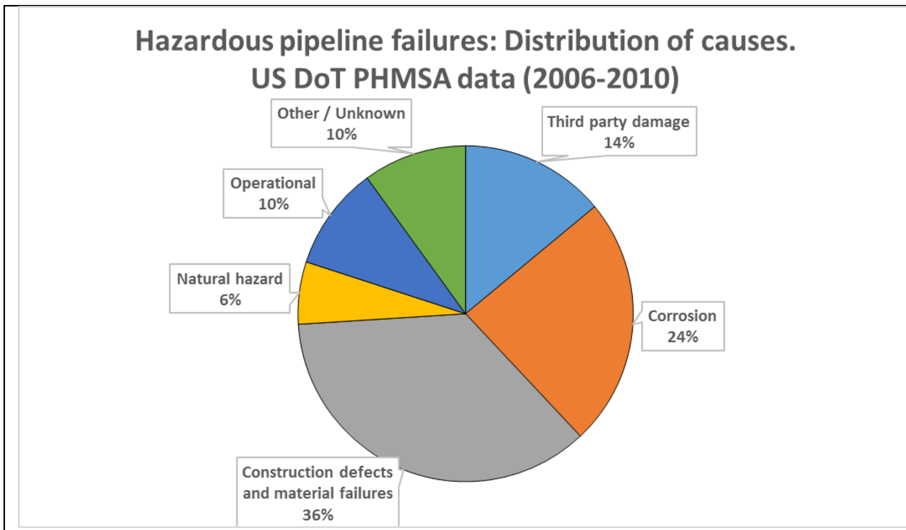


Figure 5.1c Distribution of causes for liquid pipeline failure. US DoT PHMSA data [53]

Table 5.1 Main Causes and Sub Causes For Pipeline Failures

EGIG (2009-2013)	**CONCAWE-Liquid pipelines (1971-2012)**		**US Dot PHMSA (2006-2010)**
Main causes	**Main causes**	**Sub-causes**	**Main causes**
1. Construction defects /Material failures	1.Mechanical failure	-Design -Construction -Materials fault	1.Mechanical / weld / Equipment failure
2. Hot tap			
	2. Operational	-System malfunction -Human error	2.Incorrect Operation
3.Corrosion	3. Corrosion	-External -Internal -Stress cracking	3.Corrosion
4.Ground movement	4.Natural hazard	-Ground movement -Other	4.Natural force damage
5.External interference	5.Third party activity	-Accidental -Malicious -Incidental	5.Other outside force damage 6.Excavation damage
6 Other /unknown			7. All other causes

5.2 Mitigation measures

It is important to note that the reports does not specifically identify the type of mitigation measures employed in the pipelines from where the data originated. For example EGIG report [51] contain analysis of the following parameters as shown in Table 5.2:

Table 5.2 Parameters considered for gas pipeline failure-EGIG

Sl. No.	**Main cause**	**Parameters**
1	Third party damage	Diameter of pipeline, depth of cover, wall thickness
2	Corrosion	Year of construction, type of coating, wall thickness
3	Construction defect/ Material failure	Year of construction
4	Natural Hazard	Diameter of pipeline
5	Others	Main causes
6	Hot tap error	Diameter of pipeline

CONCAWE [53] analyzes the sub causes further as given in Table 5.3:

Table 5.3 CONCAWE Report: Analysis of sub causes	
Main Causes	Sub causes
1.Mechanical failure	-Design [Incorrect design] -Construction [Faulty weld, Construction damage, incorrect installation -Materials fault [Incorrect material specification]
2. Operational	-System malfunction [Equipment, Instrumentation & control systems, -Human error [Incorrect operations, maintenance, procedures]
3. Corrosion	-External -Internal -Stress cracking
4.Natural hazard	-Ground movement[Landslide, subsidence, earthquake, flooding] -Other
5.Third party activity	-Accidental [Drilling/blasting, bulldozing, digging /trenching -Malicious -Incidental

In order to develop BN, influencing factors are needed and therefore the nature of mitigations measures were taken from [61] [62] [63] [64] [65] and from experts' opinion. Based on the above, a list of causes and sub causes and mitigation measures adopted to counter the causes for pipeline failures were finalized. They are given in Table 5.4. Note that ME in the last column stands for Manual Entry.

Table 5.4 Causes & Mitigation measures for prevention of pipeline failures				
Sl. No.	**Main cause (Node name)**	**Sub-cause (Node name)**	**Mitigation Measure (Note 1)**	**States**
1	Construction defect / Mechanical failure (ConstDefect MatFailure)			Yes No (ME)
		Construction failure (ConstFailure)	Procedures and implementation	None, Average, Good (ME)

Table 5.4 Causes & Mitigation measures for prevention of pipeline failures				
Sl. No.	**Main cause (Node name)**	**Sub-cause (Node name)**	**Mitigation Measure (Note 1)**	**States**
			Supervision	Adequate, Not adequate (ME)
		Defective design / Materials fault (DefectivedesignOrMat)	Design factors	Yes, No (ME)
			Procedures & review not adequate	Yes, No (ME)
			Intelligent pigging not available	Yes, No (ME)
2	Operational failure			Yes, No (ME)
		System malfunction (SystemMalfunction)		Yes, No (Equation) NoisyOrDist (SystemMalfunction, 0.001, SCADANotAvailable, 0.05, OverPrProtectionNotAvail, 0.15, SafetySystemsHIPPSNotAvail, 0.10, HazardIdentificationNotDone, 0.10, RiskAssessmentNotDone, 0.10, CompositionMonitoringNotDone, 0.10, MOCProceduresNotAvail, 0.10 (See section 5.4)
			SCADA not available	Yes, No (ME)
			Overpressure protection not available	Yes, No (ME)
			Safety systems (HIPPS) not available	Yes, No (ME)
			Hazard identification not done	Yes, No (ME)
			Risk assessments not done	Yes, No (ME)

Table 5.4 Causes & Mitigation measures for prevention of pipeline failures				
Sl. No.	**Main cause (Node name)**	**Sub-cause (Node name)**	**Mitigation Measure (Note 1)**	**States**
			Composition monitoring not done	Yes, No (ME)
			Management Of Change (MOC) Procedure not available	Yes, No (ME)
		Human error (HumanError)		Yes, No (Equation) NoisyOrDist (HumanError, 0.005, TrainingNotAdeqaute, 0.20, OpAndMManualNotAvailNotR, 0.10, DrawingsNotUpToDate, 0.15, SafetyCultureNotPositive, 0.10)
			Training not adequate	Yes, No (ME)
			Operations & Maintenance manual not available or not reviewed	Yes, No (ME)
			Drawings not Up-to-date	Yes, No (ME)
			Safety culture not positive	Yes, No (ME)
3	Failure due to corrosion (FailureDueTo Corrosion)			Yes, No (Equation) NoisyOrDist (FailureDueToCorrosion, 0.002 , InternalCorrosion, 0.30, ExternalCorrosion, 0.25, DetectionOfSCC, 0.25, IntelligentPiggingNotAvail, 0.20)
			Intelligent pigging not available	Yes, No (ME)
		External Corrosion (ExternalCorr ision)	Cathodic protection not available	Yes, No (ME)
			Pipeline coating not available	Yes, No (ME)

Table 5.4 Causes & Mitigation measures for prevention of pipeline failures				
Sl. No.	**Main cause (Node name)**	**Sub-cause (Node name)**	**Mitigation Measure (Note 1)**	**States**
		Internal Corrosion (InternalCorrosion)	Internal lining not available	Yes, No (ME)
			Corrosion inhibitor Inj. not available	Yes, No (ME)
			Fluid corrosivity not considered	Yes, No (ME)
		Sulphide Stress cracking (DetectionOfSCC)	Closed interval survey not done	Yes, No (ME)
4	Failure due to Natural hazard (FailureDueToNatuaralHazards)			Yes, No (ME)
		Ground movement / subsidence (Subsidence)		Yes, No (ME)
		Flooding (Flooding)		Yes, No (ME)
		Other (Other)		Yes, No (ME)
5	Third party activity (FailureDueToThirdPartyactivity)			Yes, No (ME) Equation. Please see section 5.4
		Accidental	Increase in wall thickness not adequate	Yes, No (ME)
		Malicious	Pipeline safety zones not identified	
		Incidental	Depth of cover minimum 1 M not provided	
			Warning marker posts not available	

Table 5.4 Causes & Mitigation measures for prevention of pipeline failures				
Sl. No.	**Main cause (Node name)**	**Sub-cause (Node name)**	**Mitigation Measure (Note 1)**	**States**
			Plastic marker tapes not installed	
			Concreate slabbing not provided	
			Physical barriers not provided	
			Vibration detection not available	
			Right Of Way patrolling not done	
			Video cam monitoring not available	
			Site survey before construction not done	
6	Failure due to other causes (FailureDueToOtherCauses)			Yes, No (ME)

Note 1: Mitigation measures are expressed as 'Not available or not done' in most cases to match with the syntax usage of Noisy-Or Distribution in the BN.

It is also noted that there is lack of data on how much each of the mitigations measures have reduced pipeline failure rates.

5.3 Bayesian Network for loss of containment in pipeline

Based on the above causes, effects and mitigations measures and their interrelationships, BN has been developed for loss of containment in pipeline and is given in Figure 5.2. Each of the main causes have been modelled with the sub-clauses as parent nodes. The parents have binary states except node 'Procedures and implementation', which has 3 states 'None, Average, Good'. The parent nodes have been formulated as probability of not implementing a mitigation measure to match the syntax of the network. For example for the factor Failure due to third party activity, the mitigation measure of providing 1 meter depth of cover is formulated as node 'DepthOfCover1MNotProvided' with binary states yes and no.

As can be seen from the BN in Figure 5.2, 50% probability has been assumed instead of a 100% negative state, for the parent nodes Supervision, Procedure And Reviews Not Adequate, Training Not Adequate, Cathodic Protection Not Available and Plastic Marker Tape Not Installed in line with general industry practice.

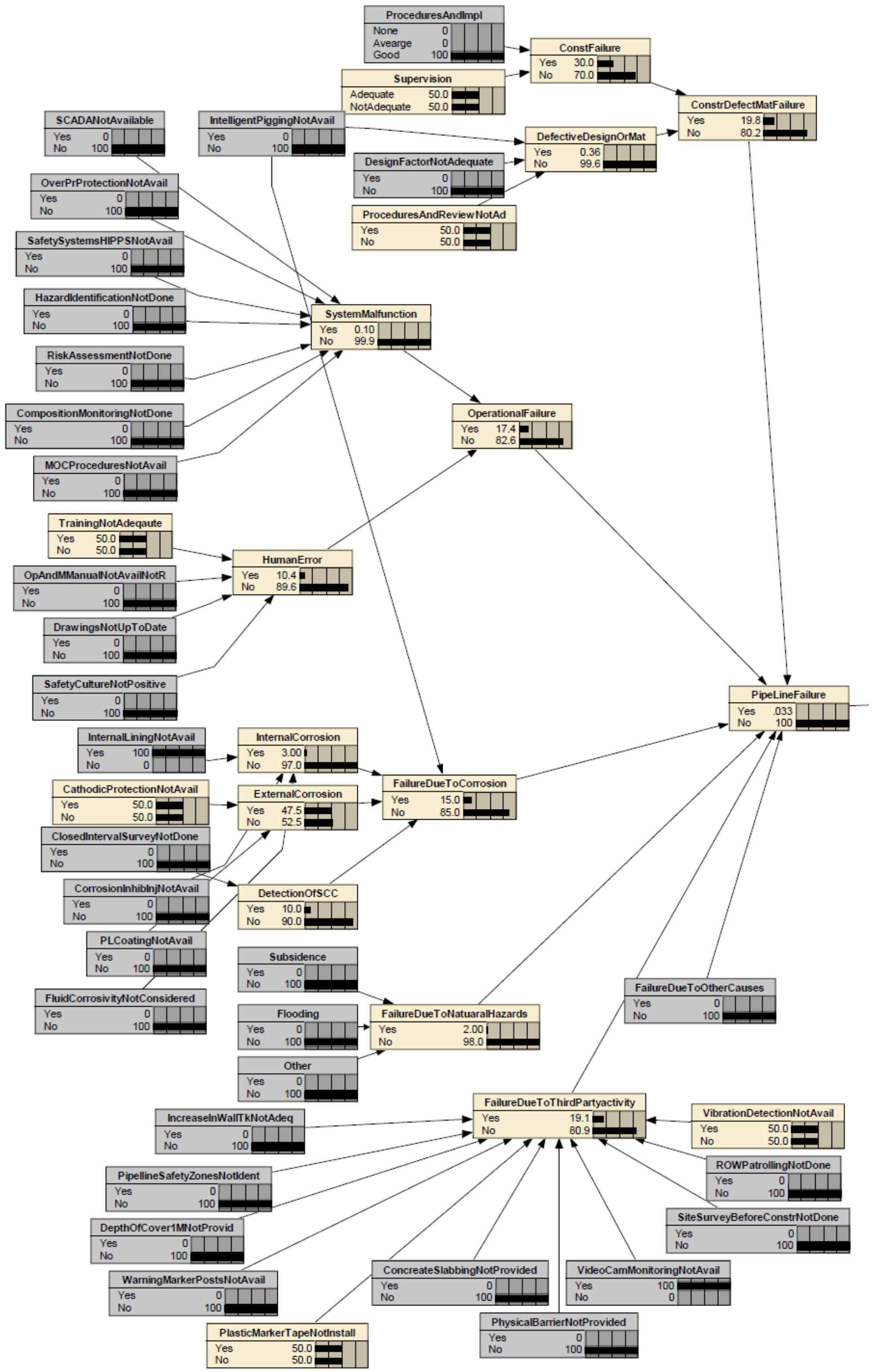


Figure 5.2 BN for loss of containment for pipeline

It is worthwhile to note that as the number of parent nodes increase, the number of entries in the CPT goes up. For example there are 11 parents for child node 'Failure due to Third party activity'. Therefore with 2 states for each parent there will be (2^11) x 11 entries in the CPT. In such a situation NoisyOr distribution is used to reflect the contribution of each parent.

5.4 NoisyOr Distribution

Noisy-Or distribution can be used when there are several possible causes for an event, any of which can cause the event by itself, but only with a certain probability. Also, the event can occur spontaneously (without any of the known causes being true), which can be modelled with 'leak' probability. (This can be zero if it cannot occur spontaneously).

Noisy Or Dist (e, leak, b1, p1, ... bn, pn) Eqn. (5.1)

Where e is the effect node, 'leak' is the leak factor which is the probability of the effect node even when all causes are zero, b1 is the node name for the cause, p1 is the probability of that cause impacting the effect node. The above can be written as equation 5.2 for better understanding.

(Effect | Cause1, Cause2) =NoisyOrDist (Effect, leak, Cause1, p1, Cause2, p2) Eqn. (5.2)

Application of the NoisyOr distribution is given below with regard to the node 'FailureDueToThirdPartyactivity'. Refer Figure 5.3

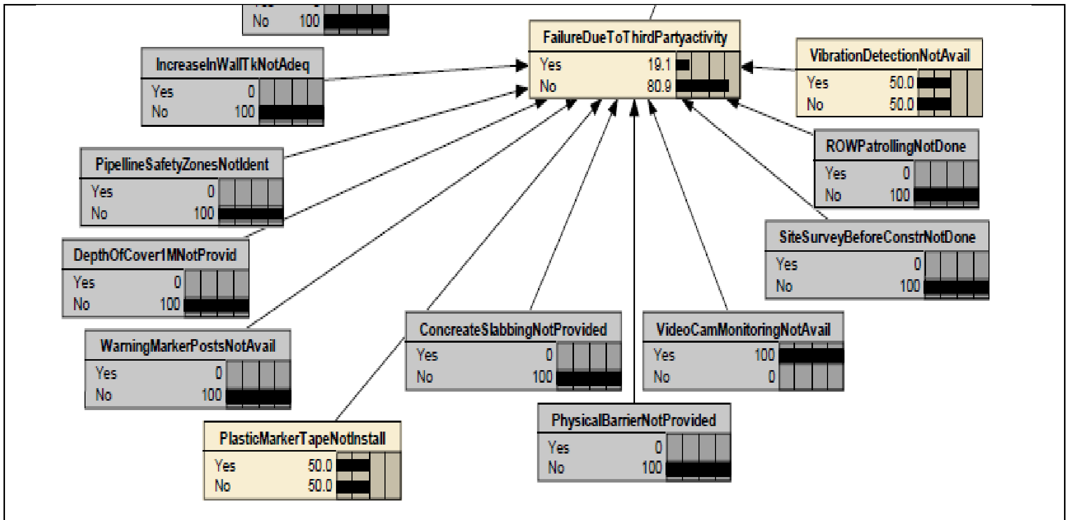


Figure 5.3 BN for Failure due to Third party activity

For filling the probability values in the CPT for the node ‘FailureDueToThirdPartyactivity’, the Noisy-Or distribution equation is written as in equation 5.3. Further details are available in [44].

NoisyOrDist (Failure Due To Third Party activity, 0.0035, Increase In Wall Tk Not Adeq, 0.30, Pipelline Safety Zones Not Ident, 0.10, Depth Of Cover1M Not Provid, 0.35, Warning Marker Posts Not Avail, 0.35, Plastic Marker Tape Not Install, 0.20, Concreate Slabbing Not Provided, 0.20, Physical Barrier Not Provided, 0.20, Vibration Detection Not Avail, 0.10, ROW Patrolling Not Done, 0.10, Video Cam Monitoring Not Avail, 0.05, Site Survey Before Constr Not Done, 0.20) Eqn. (5.3)

In the above equation the first value on the RHS after the ‘Failure Due To Third Party activity’ is the leak factor that determines the probability of the event, even if all causes are not true. This has been set to 0.0035. Rest of the values after each cause (parent) node name represents the probability of that particular cause (parent) impacting the effect (child) node. Once the NoisyOr distribution is specified the CPT is table is automatically filled by the software with the probability values. A portion of the CPT for the node ‘FailureDueToThirdPartyactivity’ is shown in Table 5.5.

Table 5.5 Portion of CPT for the node ‘FailureDueToThirdPartyActivity’

FailureDueToThirdPartyactivity: R1-14-10-15												
Yes	No	IncreaseInWallTkNotAdeq	PipellineSafetyZonesNotIdent	DepthOfCover1MNotProvid	WarningMarkerPostsNotAvail	PlasticMarkerTapeNotInstall	ConcreateSlabbingNotProvided	PhysicalBarrierNotProvided	VibrationDetectionNotAvail	ROWPatrollingNotDone	VideoCamMonitoringNotAvail	SiteSurveyBeforeConstrNotDone
0.916399	0.083601	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
0.895498	0.104502	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
0.911999	0.088001	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
0.889998	0.110002	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
0.90711	0.09289	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
0.883887	0.116113	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No
0.902221	0.097779	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes
0.877776	0.122224	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No
0.90711	0.09289	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
0.883887	0.116113	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No
0.902221	0.097779	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes
0.877776	0.122224	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No
0.896788	0.103211	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes
0.870986	0.129014	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No
0.891356	0.108644	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes
0.864195	0.135805	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No
0.895498	0.104502	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
0.869373	0.130627	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No
0.889998	0.110002	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes
0.862498	0.137502	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No
0.883887	0.116113	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes
0.854859	0.145141	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	No
0.877776	0.122224	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No	Yes
0.84722	0.15278	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No	No
0.883887	0.116113	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes
0.854859	0.145141	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No
0.877776	0.122224	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes
0.84722	0.15278	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	No
0.870986	0.129014	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes
0.838732	0.161268	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	No
0.864195	0.135805	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes
0.830244	0.169756	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No
0.895498	0.104502	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
0.869373	0.130627	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No
0.889998	0.110002	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes
0.862498	0.137502	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	No
0.883887	0.116113	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes
0.854859	0.145141	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	No
0.877776	0.122224	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	Yes
0.84722	0.15278	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	No
0.883887	0.116113	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes
0.854859	0.145141	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No
0.877776	0.122224	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	No	Yes
0.84722	0.15278	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	No	No
0.870986	0.129014	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes
0.838732	0.161268	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No	Yes	No
0.864195	0.135805	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No	No	Yes
0.830244	0.169756	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No	No	No
0.869373	0.130627	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes
0.836716	0.163284	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	No
0.862498	0.137502	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes
0.828122	0.171878	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	No
0.854859	0.145141	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes	Yes

Parent nodes for all the six main causal factors have been formulated on the above basis. It is emphasized that the scale of probabilities for each of the main casual factors is independent of other causes. The resulting node Pipeline failure has been given the NosiyOr distribution to combine all the main causal factors to yield a generic failure rate matching with the current EGIG gas pipeline failure rate. This is given in equation Eqn. (5.4)

P (PipeLineFailure | FailureDueToCorrosion, FailureDueToNatuaralHazards,

FailureDueToThirdPartyactivity, OperationalFailure, ConstrDefectMatFailure,

FailureDueToOtherCauses) =

NoisyOrDist (PipeLineFailure, 0.00018, FailureDueToCorrosion, 0.000265,

FailureDueToNatuaralHazards, 0.00017, FailureDueToThirdPartyactivity,

0.00030, OperationalFailure, 0.00006, ConstrDefectMatFailure, 0.000175,

FailureDueToOtherCauses, 0.000080) Eqn. (5.4)

Once the BN has been set up it can be analyzed for impact of findings on any node/s on the pipeline failure and loss of containment scenario.

As an example, let us see what will be the major contributing factors when there is a confirmed pipeline failure (loss of containment). When the node state for Pipeline failure is set to 'Yes =100%' for the given set of prior conditions, the BN will recalculate the node values. It is seen that the main contributions factors are 'Failure due to Third party activity' followed by 'Construction defect / material failure' and 'Failure due to Corrosion'. This is shown in Figure 5.4.

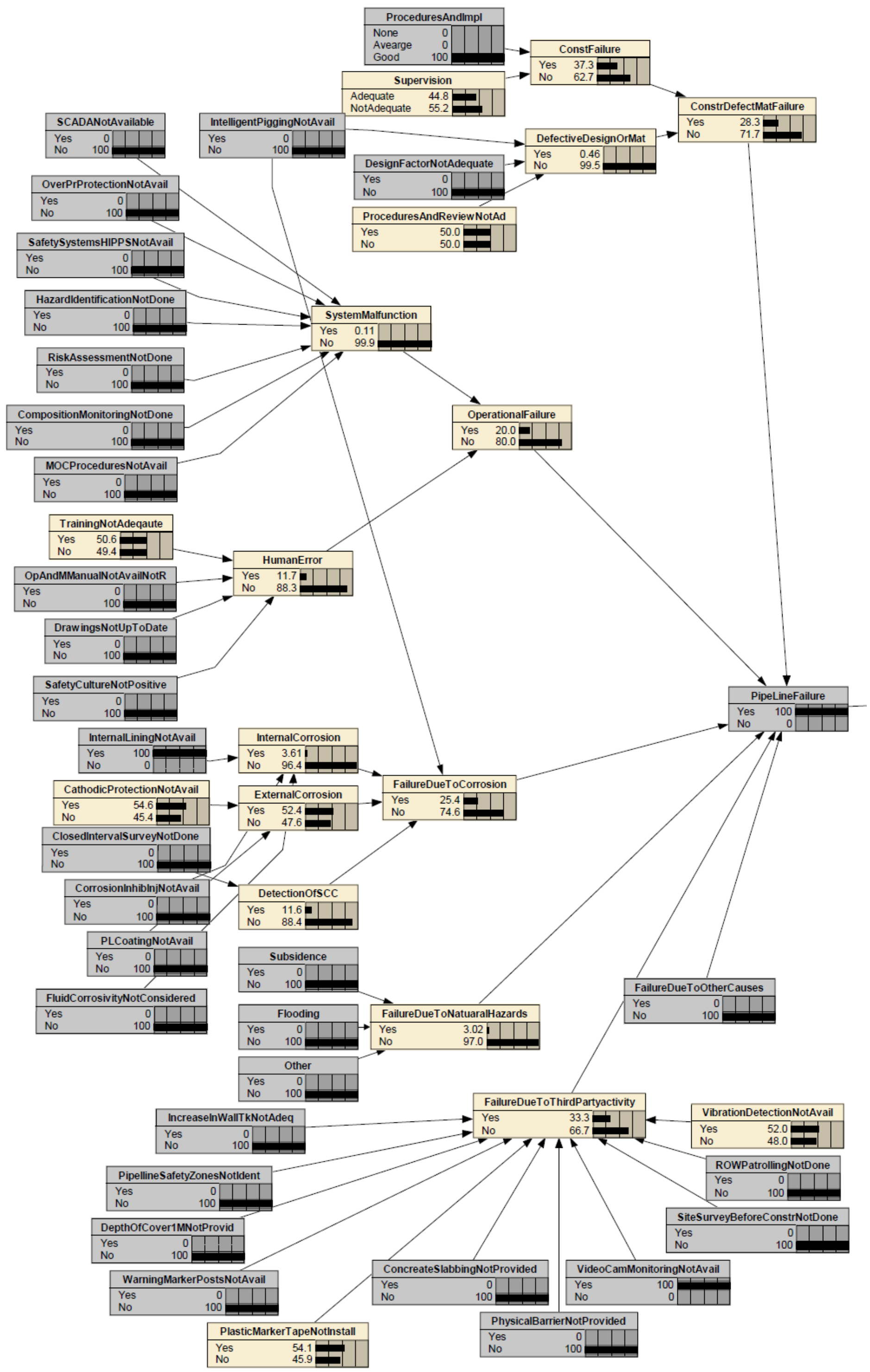


Figure 5.4 BN for confirmed loss of containment for pipeline

5.5 Sensitivities

Apart from the above, sensitivity of other nodes to the query node also can be found out from the network. All BN software have the feature of analyzing the network for sensitivity of one node to node (Please see section 3.4). For Netica®, this involves selecting the target node and then the parent nodes for which the sensitivity has to be analyzed. For the given situation, sensitivity analysis of other nodes to Pipeline failure node is given in Figure 5.5.

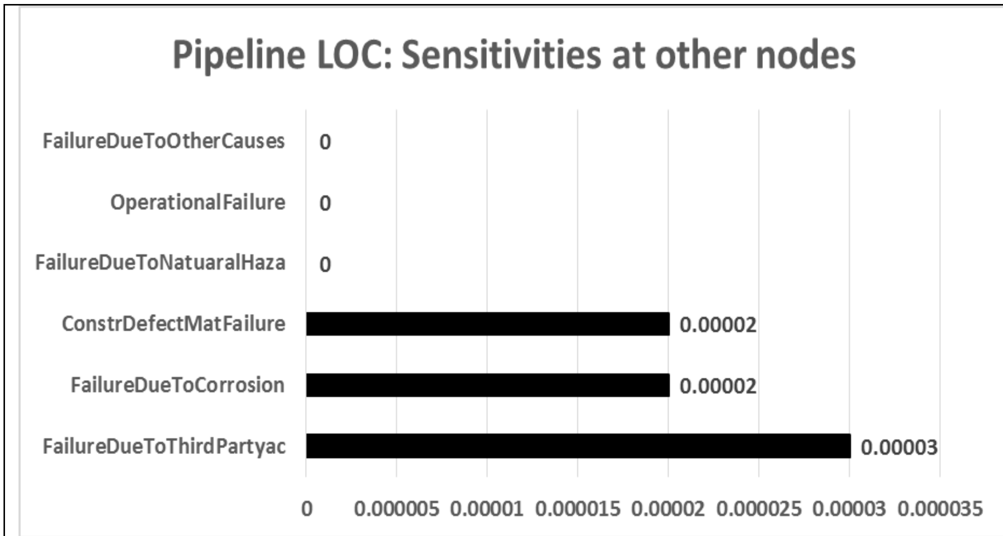


Figure 5.5. Sensitivity of other nodes to Pipeline LOC

5.6 Event Tree for pipeline loss of containment

The eventual consequences of a pipeline loss of containment will be jetfire, Vapor Cloud Explosion or flashfire back to source or no ignition (toxic gas dispersion) or a combination of the above. Main safety barriers preventing escalation of a loss of containment to the above scenarios are gas detection and Emergency Shutdown (ESD) actions. They are depicted in the BN in Figure 5.6. Since Netica®'s BN does not display more than 4 digit decimal, they have been separately generated and shown in as blue boxes in the Figure 5.6. As can be seen, with the safety barriers in place and with current average value of pipeline failure (0.00033 failures /year) the occurrence of hazardous consequences are quite low.

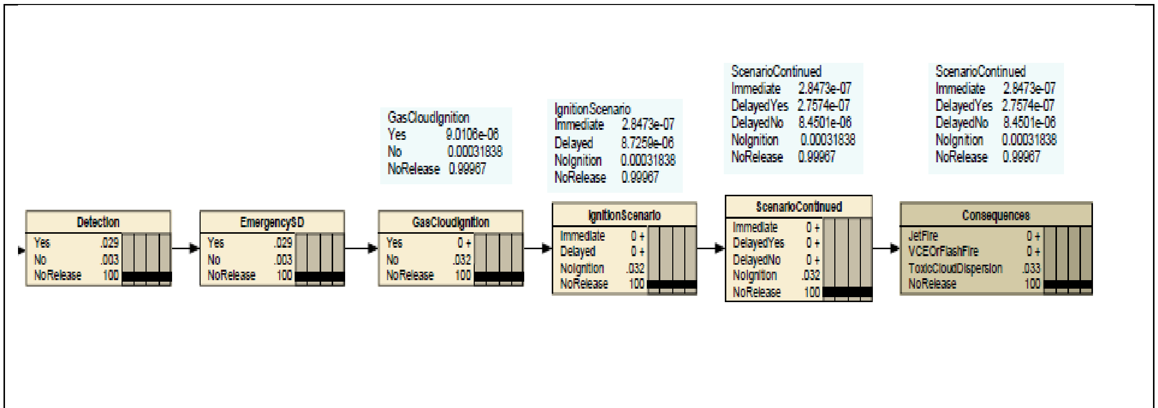


Figure 5.6. Event tree for gas pipeline LOC

5.7 Case Study using the BN for pipeline: Natural gas pipeline, Andhra Pradesh, India

5.7.1 Background:

Gas Authority of India (GAIL) Tatipaka-Kondapalli 18 inch pipeline built in 2001 to carry natural gas from ONG wells to Lanco Power plant had leaked sometime around 27 July 2014 near Nagaram village, East Godavari district in Andhrapradesh, leading to ignition and vapor cloud explosion. There were 22 fatalities, several injuries and considerable business loss. Government of India through ministry of oil constituted an internal enquiry. The inquiry committee's report is not available in the public domain; however only certain key findings of the same have been made known [66]. According to press reports the main causes of the accident have been noted as "lack of systems approach".

5.7.2 Key findings:

- The pipeline is supposed to carry dry natural gas. Yet there was no equipment (separators) to take out liquids in the line.
- The line had several leaks earlier which were controlled by temporary measure of clamps.
- The line was corroded and there was recommendations for injecting corrosion inhibitor, which was not done.

- People has reported smell of gas earlier several times which went unheeded by the authorities.
- The report concluded 'inadequate systems approach' for the accident.

5.7.3 Application of the BN model:

The BN pipeline model can be tuned to see the situation by conducting a hindsight review of the impact of parent nodes on other parameters. The nodes states have been given the values that are thought to be the most likely situation before the loss of containment of the pipeline. They are given in Table 5.6 along with notes. All the values can be changed based on information about actual situation when it is known.

Table 5.6 Details of nodes & states for case study: Pipeline failure at AP, India

Main causal factor	Parent Nodes (Sub causes)	States	Probability %	Notes
Construction Defect / Mat. Failure				All state values are given based on general industry practice.
Construction Failure	Procedures And Implementation	None	0	
		Average	0	
		Good	100	
	Supervision	Adequate	100	
		Not Adequate	0	
Defective Design or Material	Design Factor Not Adequate	Yes	0	
		No	100	
	Procedures And Review Not Adequate	Yes	100	
		No	0	

Table 5.6 Details of nodes & states for case study: Pipeline failure at AP, India				
Main causal factor	**Parent Nodes (Sub causes)**	**States**	**Probability %**	**Notes**
	Intelligent Pigging Not Available	Yes	50	Assumed in the absence of information
		No	50	
Operational Failure				All state values are given based on general industry practice.
System Malfunction	SCADA Not Available	Yes	50	Assumed in the absence of information
		No	50	
	Over Pr. Protection Not Available	Yes	0	
		No	100	
	Safety System HIPPS Not Available	Yes	0	
		No	100	
	Hazard Identification Not Done	Yes	100	
		No	0	
	Risk Assessment Not Done	Yes	100	
		No	0	
	Composition Monitoring Not Done	Yes	100	
		No	0	
	MOC Procedure Not Available	Yes	100	
		No	0	

Table 5.6 Details of nodes & states for case study: Pipeline failure at AP, India				
Main causal factor	**Parent Nodes (Sub causes)**	**States**	**Probability %**	**Notes**
Human Error	Training Not Adequate	Yes	100	
		No	0	
	Op & Maint. Manual Not Available or Reviewed	Yes	100	
		No	0	
	Drawings Not Up to date	Yes	50	Assumed in the absence of information
		No	50	
	Safety Culture Not Positive	Yes	100	
		No		
Failure Due To Corrosion				All state values are given based on general industry practice.
Internal Corrosion	Internal lining not Available	Yes	100	
		No	0	
	Corrosion Inhibitor Inj. Not Available	Yes	100	
		No	0	
	Fluid corrosivity not considered	Yes	100	
		No	0	
External Corrosion	Cathodic Protection Not Available	Yes	50	Assumed in the absence of information
		No	50	
	Pipeline Coating Not Available	Yes	0	

Table 5.6 Details of nodes & states for case study: Pipeline failure at AP, India				
Main causal factor	**Parent Nodes (Sub causes)**	**States**	**Probability %**	**Notes**
		No	100	
Detection of SCC	Closed Interval Survey Not Done	Yes	50	Assumed in the absence of information
		No	50	
Failure Due To 3rd Party Activity				All state values are given based on general industry practice.
	Increase In Wall thickness Not Adequate	Yes	0	
		No	100	
	Pipeline Safety Zones Not Adequate	Yes	100	
		No	0	
	Depth of Cover 1 M Not Available	Yes	0	
		No	100	
	Warning Marker Posts Not Avail	Yes	50	
		No	50	
	Plastic Marker Tape Not Installed	Yes	0	
		No	100	
	Concreate Slabbing Not Provided	Yes	100	
		No		
	Physical Barrier Not Provided	Yes	50	Assumed in the absence of information

Table 5.6 Details of nodes & states for case study: Pipeline failure at AP, India

Main causal factor	**Parent Nodes (Sub causes)**	**States**	**Probability %**	**Notes**
		No	50	
	VideoCam Monitoring Not Provided	Yes	100	
		No		
	Site Survey Before Construction Not Done	Yes	50	Assumed in the absence of information
		No	50	
	ROW Patrolling Not Done	Yes	100	
		No	0	
	Vibration Detection Not Available	Yes	100	
		No	0	
Failure Due To Natural Hazards	Subsidence	Yes	0	All state values are given based on general industry practice.
		No	100	
	Flooding	Yes	0	
		No	100	
	Other	Yes	0	
		No	100	
Failure Due to other Causes		Yes	0	All state values are given based on general industry practice.
		No	100	

5.7.4 Bayesian Network for the case study

When the node state values in BN are given the inputs as in Table 5.5 and simulated, it is seen that the percentage probability of pipeline failure has increased to 0.054, which is considerably higher than the current state in the industry. Please see Figure 5.7. A comparison of the values are given in Table 5.7 to illustrate this point.

Table 5.7 Comparison of GAIL pipeline state with industry averages

Parameter	GAIL pipeline	Industry average (EGIG)
Failure frequency	5.4 x 10-4	3.3 x 10-4

With the above probability of LOC, the chance of a jet or flash fire is still low (4.32 x 10-07 for jet fire and 4.18 x 10-07 VCE or flash fire) provided the safety barrier, that is, gas detection is in operation. Please see Figure 5.8 for post release LOC scenario with safety barriers in operation.

However, when this is combined with the failure of the key safety barrier for detection of the gas release it can be seen that the probability of a fire is very high.

The probability goes up to 0.0016 for jet fire and 0.0015 for Vapor Cloud Explosion(VCE) or flash fire from the average of 4.32 x 10-07 for jet fire and 4.18 x 10-07 VCE or flash fire respectively when the detection barrier is working (Please see Figure 5.9). Thus failure of gas detection in time played a major part in amplifying the incident to a major accident.

Clearly the pipeline was operating in a high risk situation. Had this been noticed in time, the accident could have been avoidable.

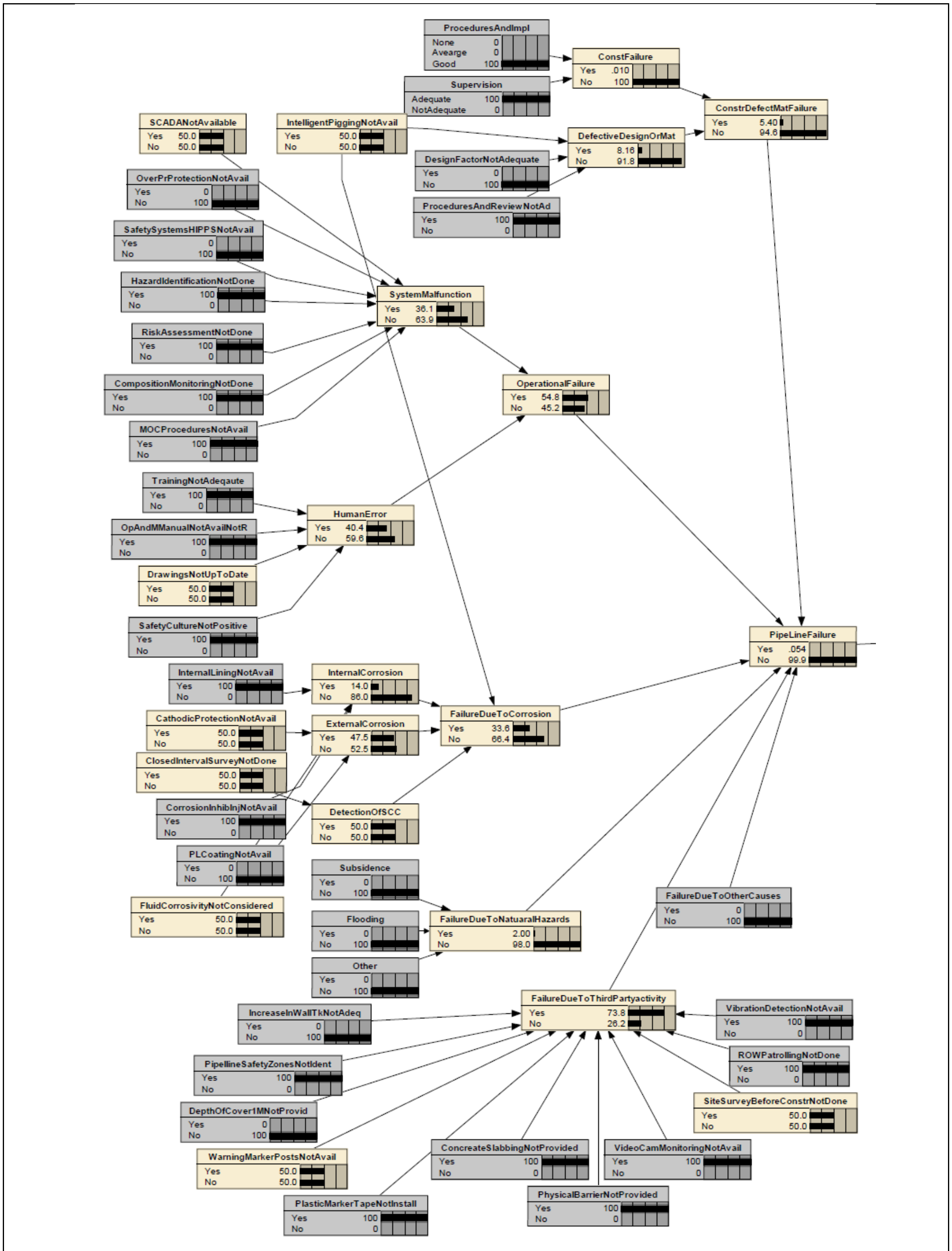


Figure 5.7. BN for GAIL pipeline-conditions before failure

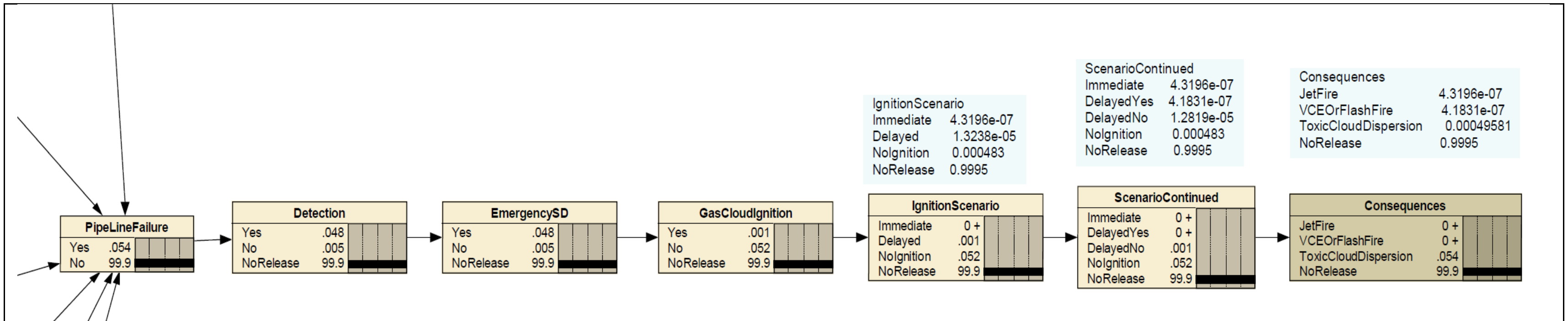


Figure 5.8. BN for Event tree: Post release scenario with safety barrier in operation

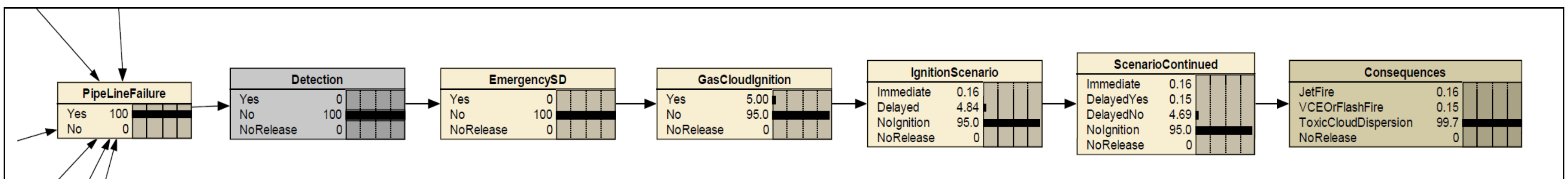


Figure 5.9. BN for Event tree: Post release scenario- Failure of safety barrier

5.8 Chapter summary

This chapter presents the BN for causes, mitigation measures employed to counter those causes, its interrelationships and post event scenarios for LOC of hydrocarbon pipeline. Pipeline failure data are available in public domain and the same have been analyzed to find out the main causes and sub-causes of LOC. Further, the mitigation measures employed to counter these causes are investigated. It is noted that data regarding the same are mostly not available. Industry practice and expert opinion have been incorporated for the above. The causes, sub-causes and mitigation measures have been converted to BN for LOC of the pipeline. The usage of NoisyOR distribution is described. Sensitivities and BN for Event Tree (post LOC) are also given. A case study of a natural gas pipeline failure that happened in Andhra Pradesh has been included to illustrate the predictive nature of the BN.

Next chapter takes up BN for hazards of hydrocarbon storage tanks namely Floating and Cone roof tanks.

6 Bayesian Network for loss of containment in hydrocarbon storage tank

6.1 Storage tank basics

Large inventory of hydrocarbon is stored in atmospheric storage tanks. In fact a group of such tanks poses a high level of risk. Over the years the design, operation and maintenance of atmospheric storage tanks have considerably improved. However accidents like Buncefield [12] and IOC Jaipur [11] still happen. Figure 6.1 shows a typical hydrocarbon atmospheric storage tanks known as Floating roof tank.

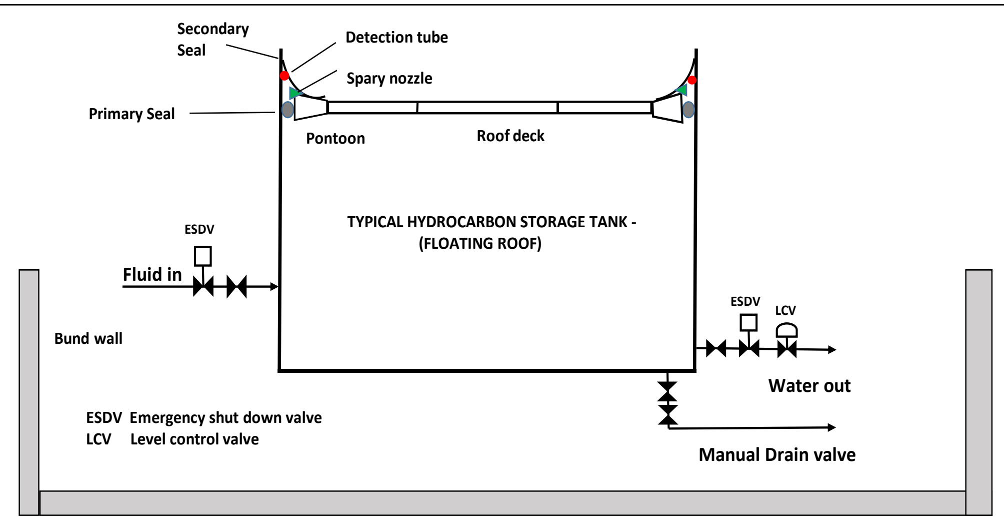


Figure 6.1 Schematic diagram of Floating roof tank

In Floating roof tank the roof deck floats on the liquid. Sealing between the tank wall and the deck is achieved by providing rim seal-primary seal (made of flexible polyurethane or similar material) and an additional secondary seal between the pontoon portion of the deck and tank wall.

The protective safety barriers are the ESDV provided at the inlet and outlet of liquid lines, which are activated when a set of process conditions including high-high level of the liquid in the tank reach predefined values. Also any fire starting on the top of rim seal area is detected by a linear heat detector tube triggering an automatic foam outflow through the spray nozzles.

On the other hand the Cone roof tank has a fixed conical roof and thus has gas space above the liquid level. A gas blanket with control system is provided to ensure a positive pressure on the gas space. Figure 6.2 shows the schematic diagram of a Cone roof tank.

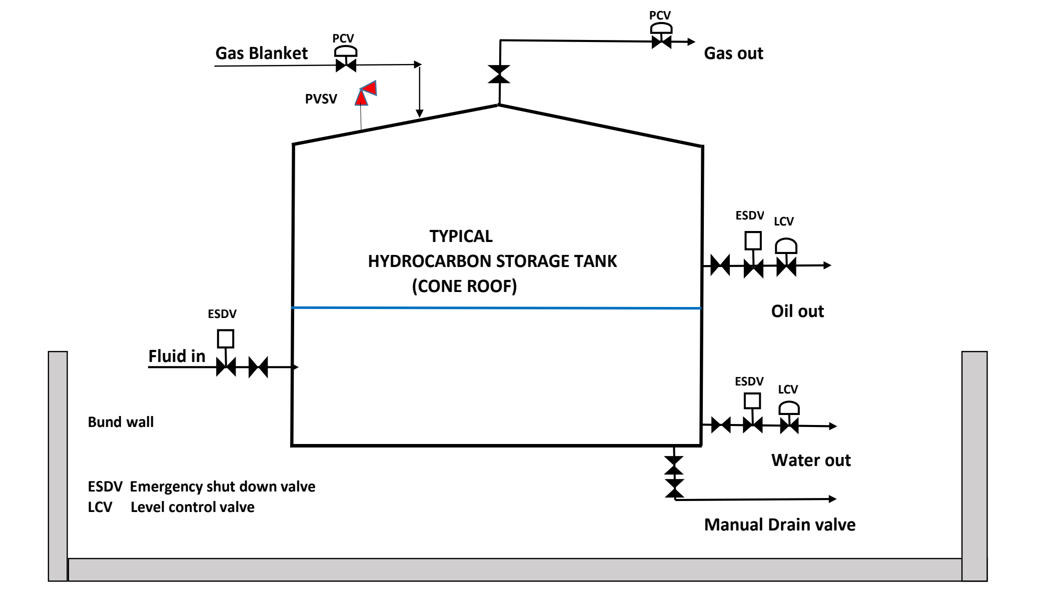


Figure 6.2 Schematic diagram of Cone roof tank

Protective devices include ESDVs at inlet and outlet lines that will act automatically to close on fulfilling a set of process conditions including high-high level in the tank. The Pressure vacuum valve (PVSV) provided on roof is the safety barrier to prevent over-pressurization as well as vacuum inside the tank.

6.2 Causal factors for loss of containment

Since BN requires causal factors for loss of containment in hydrocarbon storage tanks, the same were finalized on the basis of findings from [55] [56] [57] [58] [59] [60] [67]. Accident investigation reports for Buncefield [12] and Indian Oil Corporation's Jaipur Tank farm accident [11] also provided useful inputs. Key casual factors are grouped under the following headings and form the key nodes in the BN [68] [69] [70] [71] [72] [73] [74]. Same is given in Table 6.1

Table 6.1 Key causal factors for storage tank failures

Nodes for key causal factors:	No. of parent nodes
1. Quality of design	21
2. Quality of Maintenance & Inspection	8
3. Quality of construction	4
4. Quality of Equipment selection	7
5. Quality of Risk Assessments	3
6. Quality of Systems & Procedures	12
7. Quality of Human & Organizational Factors	7
8. Lightning strike	-
9. Catastrophic tank failure	3

Each of the above causal nodes have been parameterized as Poor (0.3 to 0.5), Average (0.5 to 0.7) and Good (0.7 to 1).

Each of the key causal factors in Table 6.1 are child nodes of several parent nodes, which are root causes influencing the key nodes. Details of the parent nodes and its states are given in subsequent sections.

The relative probabilities of effects have been arrived at by combining the above key causes and intermediate causes suitably using NoisyOr distribution. The last effect node is arrived at by converting the relative probability to the generic average probability values given in the references given in Table 3.6

6.3 Methodology for development of BN and evaluation

The parent nodes in Table 6.1 have states with manual binary inputs effectively meaning 'Not fulfilling a requirement' 0% or 'Fulfilling a requirement' 100%. These are then combined in the each of the key casual factor nodes by using Normal distribution to bring in the probabilistic nature of the factors. Mean of the distribution is the average of all the parent nodes. Thus if any of the parent node's state changes, it will be reflected in the state value of the child (effect) node.

An overview of the causal factors; one level preceding the key causal factors and 3 levels downstream of the key causal factors are shown in Figure 6.3 below along with the Tables and Figures where data on the same are detailed.

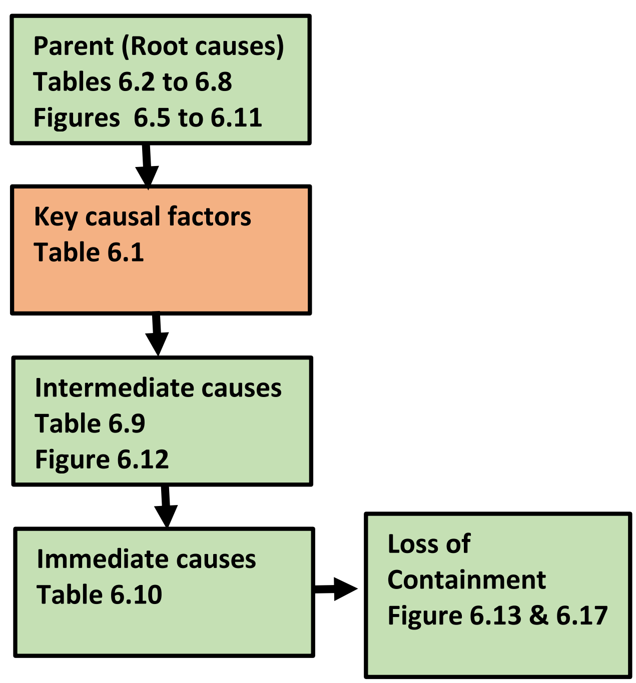


Figure 6.3. Overview of analysis of causal factors for LOC for storage tank

BN has been developed separately for Floating roof and Cone roof tank, since there are certain differences in the design and operation of these tanks. Cone roof tanks as shown in Figure 6.2 do not have a rim seal. It has a gas space that is contained and pressurized with hydrocarbon gas to ensure positive pressure. Pressure Vacuum safety relief valves are fitted on to the roof as protection against overpressure as well as vacuum conditions inside the tank.

Event Trees and its equivalent BN have been developed separately for Floating and Cone roof tanks. An overview of the same is given in Figure 6.4 below:

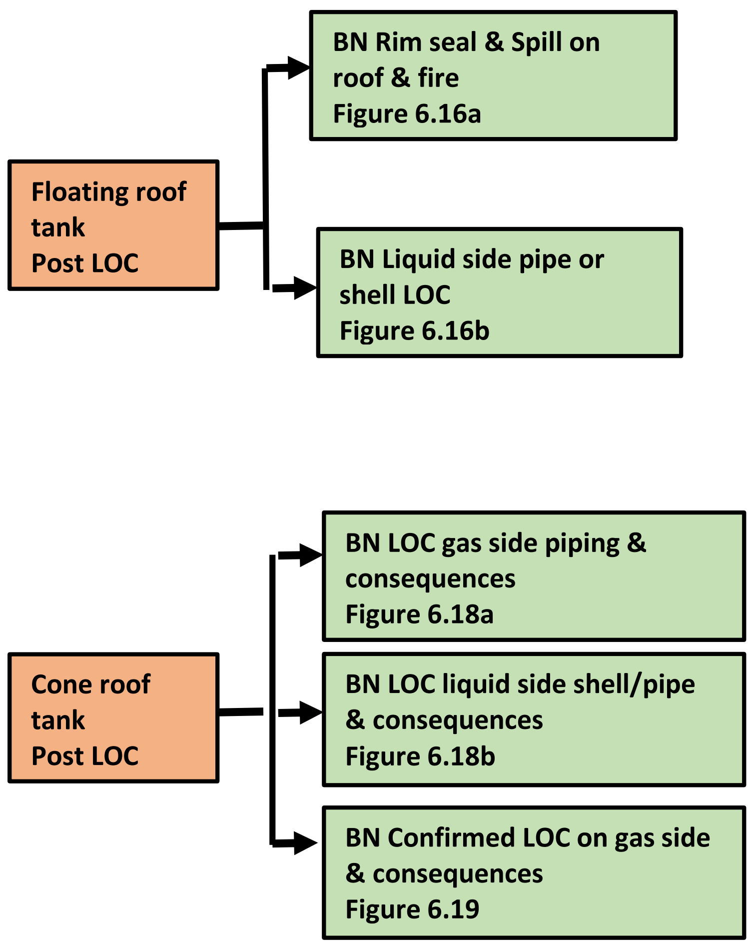


Figure 6.4. Overview of analysis of post LOC for Floating and Cone roof tanks

6.4 BN for Loss of containment in Floating roof tank

Following gives description of each of the key casual factors listed in Table 6.1, its parents (influencing factors) and the related BN.

6.4.1 Quality of Design

Table 6.2 describes this node, its parents (factors affecting this node) and its states along with the parameterization method.

Table 6.2 Details of the parent nodes of Quality of Design

Sl. No.	Main node and its parent nodes	Node full form	States	Parameterization method	Description
1	**QOfD**	**Quality of design**	Poor Average Good	Calculated. Normal distribution. (Mean: average of all parent nodes 1.1 to 1.21. SD = 0.1)	
1.1	EStdsDesignChk	Adherence to Engineering standards and regulations & Design checks	Part Full	Calculated NoisyOr distribution	This node is having 6 further parents with states No / Yes --Manual input node. They are: Following all relevant Stds, Drains double valving, automatic tank level monitoring, Remote isolation valves, Anti-rotation device, Double seal for Floating roof.
1.2	OFProtection	Overflow protection	Adequate Not adequate	Manual. Input node	Automatic valve provided to cut off supply in case of overfill
1.3	SelStTank	Selection of storage tank type	Incorrect Correct	Manual. Input node	Selection of the type of storage i.e. fixed or floating, is based on the Flash point of the liquid.
1.4	SInS	Site Inspection and study	Not adequate Adequate	Manual. Input node	Topographical and other relevant information about the site is critical.

Table 6.2 Details of the parent nodes of Quality of Design

Sl. No.	Main node and its parent nodes	Node full form	States	Parameterization method	Description
1.5	SD	Safe distances	Not adequate Adequate	Manual. Input node	Best practices allow certain minimum distances between tanks to be fixed. However generally this is confirmed by the risk assessment.
1.6	BDC	Bunds / Dikes capacities	Not adequate Adequate	Manual. Input node	Dike capacity are generally 1.25 times the tank capacity. But when there are more than one tank within a dike, the situation has to be analyzed on case to case basis.
1.7	BFR	Bund fire resistance	Poor Good	Manual. Input node	Integrity of Bund/Dike wall which is the secondary containment is important and provision with valve for proper Bund draining
1.8	FireSVal	Fire safe valves	Not provided Provided	Manual. Input node	Valves within Bund wall shall be fire safe.
1.9	CD	Capacity definition of tank	Not clear	Manual. Input node	There must be clarity in capacity definition of tanks capacity mentioned in the design documents. Usually it is the

Table 6.2 Details of the parent nodes of Quality of Design

Sl. No.	**Main node and its parent nodes**	**Node full form**	**States**	**Parameterization method**	**Description**
			Clear		working capacity between Low level to high level control bank.
1.10	LPD	Lightning protection design	Not adequate Adequate	Manual. Input node	
1.11	FPSD	Fire protection and fire protection system design	Not adequate Adequate	Manual. Input node	Including cooling water & foam systems for Floating (with dams) and Cone Roof tanks
1.12	PipingFP	Piping fire proofing	Not provided Provided	Manual. Input node	All piping within Bund wall shall be adequately fireproofed.
1.13	FGDS	Fire and gas detection system	Not provided Provided	Manual. Input node	Hydrocarbon detection. Linear heat detection for Rim seals.
1.14	CCTV	Closed circuit TV	Not provided Provided	Manual. Input node	
1.15	StatEl	Static electricity prevention	Not considered Considered	Manual. Input node	Velocity of all fluid movement into the tank, out of the tank and within the tank must be analyzed. Accumulation of static change must be prevented either by design or procedures. Proper Bonding & earthing.

Table 6.2 Details of the parent nodes of Quality of Design

Sl. No.	Main node and its parent nodes	Node full form	States	Parameterization method	Description
1.16	MatSel	Material selection	Not adequate Adequate	Manual. Input node	Correct metallurgy of the tank and components are essential. Usually internal fiberglass lining is also provided.
1.17	TempMon	Temperature monitoring	Not provided Provided	Manual. Input node	
1.18	ESDSIF	Emergency Shut down valve as per Safety Instrumented Function requirements	Not provided Provided	Manual. Input node	ESDV valve shall be provided at the inlet and out of tanks and its SIL level as per ISA 61508 must be analyzed by LOPA.
1.19	ElectHazAreaClass	Electrical area classification	Not adequate Adequate	Manual. Input node	Accurate Electrical hazardous area classification is required.
1.20	TertiaryContainment	Tertiary containment	Not considered Considered	Manual. Input node	Tertiary containment must be considered. In both Buncefield and Jaipur the secondary containment failed.
1.21	FaultTD	Fault tolerant design	Not considered Considered	Manual. Input node	Automation of operations must be a prime objective with adequate back up and plan for human intervention. In Buncefiled the automatic shut off valve did not

Table 6.2 Details of the parent nodes of Quality of Design

Sl. No.	Main node and its parent nodes	Node full form	States	Parameterization method	Description
					work and in Jaipur the loss of containment that became uncontrollable during the transfer operations was the triggering point of the accident

The nodes in Table 6.2 and its cause and effect connectivity's and have been translated to a BN as shown in Figure 6.5

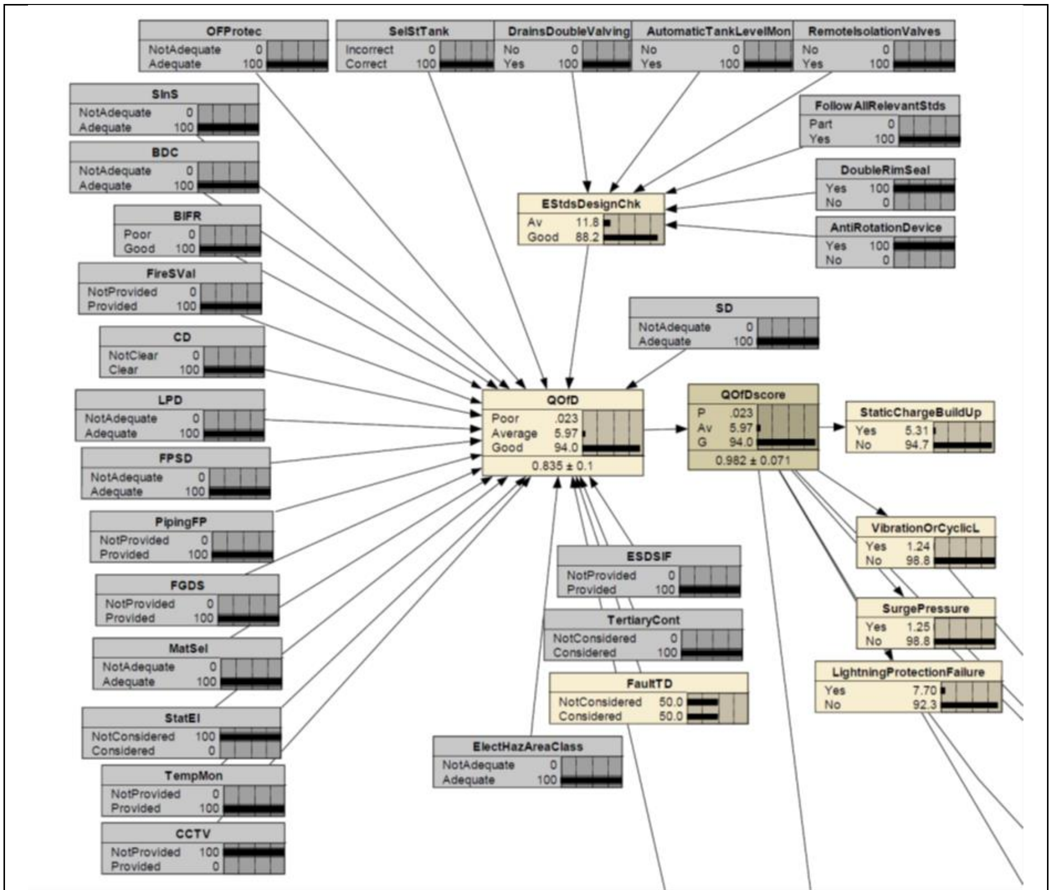


Figure 6.5 BN for the node 'Quality of Design'.

As can be seen from Figure 6.5, all the 21 root causes have been linked to the key causal factor node 'Quality of design' (QOfD). Normal distribution at the node 'QOfD' (Quality of Design) combines the parent nodes as per the equation below:

P (QOfD | BDC, BIFR, CD, EStdsDesignChk, FireSVal, FGDS, CCTV,FPSD, LPD, SD, SInS, MatSel, SelStTank, OFProtec, PipingFP, TertiaryCont, FaultTD, ESDSIF, StatEl, TempMon, QOfSysProcScore, ElectHazAreaClass) =

NormalDist (QOfD, avg (BDC, BIFR, CD, EStdsDesignChk, CCTV, FireSVal, FGDS, FPSD, LPD, SD, SInS, MatSel, SelStTank, OFProtec, PipingFP, TertiaryCont, FaultTD, ESDSIF, StatEl, TempMon, QOfSysProcScore, ElectHazAreaClass), 0.1) (Eqn.6.1)

Of the above all sub causes have binary states except ‘EStdsDesignChk’ which is defined by an equation using NoisyOr distribution given in Eqn 6.2

p (EStdsDesignChk | DrainsDoubleValving, AutomaticTankLevelMon, RemoteIsolationValves, DoubleSealForFR, AntiRotationDesignFR, FollowAllRelevantStds) =

NoisyOrDist (EStdsDesignChk, 0.00001, DrainsDoubleValving, 0.20, AutomaticTankLevelMon, 0.20, RemoteIsolationValves, 0.20, DoubleSealForFR, 0.20, AntiRotationDesignFR, 0.20, FollowAllRelevantStds, 0.70) (Eqn 6.2)

Given the condition of the states for each of the parent nodes, the probability values for Quality of Design is calculated in percentages as Poor = 0.023, Average = 6.00, Good = 94.0 (Poor, Average and Good categorization is on the basis of the value of Normal distribution between 0.3 to 0.5, 0.5 to 0.7 & 0.7 to 1 respectively)

6.4.2 Quality of Maintenance and inspection

The Table 6.3 showing the parent nodes, its description and parameterization methods for the main casual factor node Quality of Maintenance and inspection is given below. The corresponding BN in Figure 6.6.

Table 6.3 Details of parent nodes for Quality of Maintenance & inspection

Sl. No.	Node name	Node full form	States	Parameterization method	Description
1	RI	Routine inspection	Yes No	Manual	Planned routine inspection
2	PRFTest	Proof testing	Yes No	Manual	Regular testing of components &

Table 6.3 Details of parent nodes for Quality of Maintenance & inspection					
Sl. No.	**Node name**	**Node full form**	**States**	**Parameterization method**	**Description**
					systems including overfill protection system
3	PreVent	Preventive maintenance	Yes No	Manual	Scheduled preventive maintenance
4	ProEq	Protective equipment	Yes No	Manual	Usage of protective equipment during maintenance
5	ExPrEq	Explosion proof equipment	Yes No	Manual	Usage of explosion proof equipment
6	HotWr	Hot work permit	Yes No	Manual	Established hot work permit system in tank area in accordance with relevant standards.
7	Training	Training	Yes No	Manual	Providing training for staff
8	WComChk	Work completion check	Yes No	Manual	A verification system for checking completion of work as per established procedures

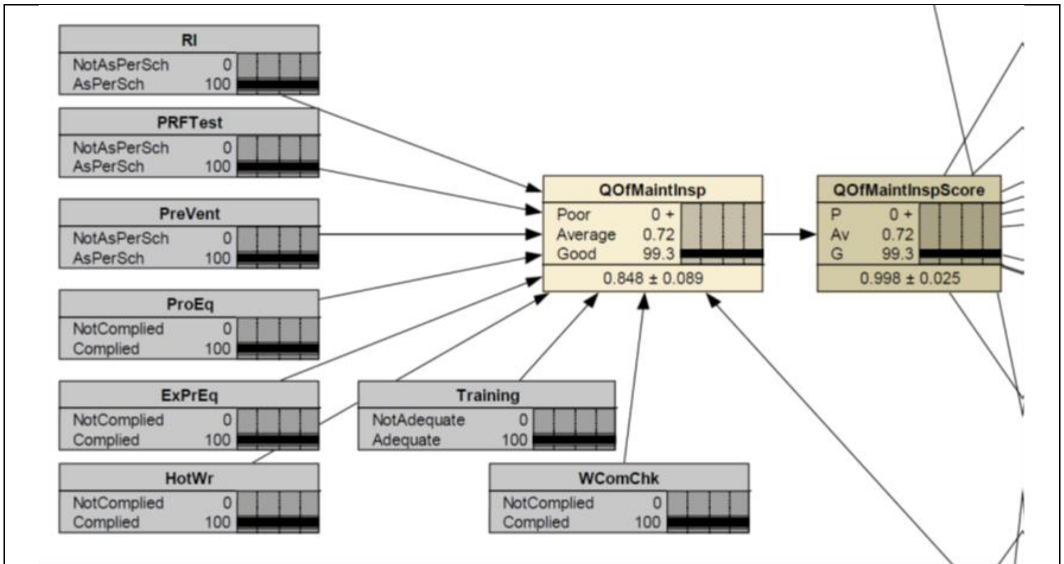


Figure 6.6 BN for 'Quality of Maintenance & inspection'

Figure 6.7 shows the direct connection of the 8 influencing factors on the node 'Quality of Maintenance and Inspection' (QOfMaintInsp0.

Equation for node 'Quality of Maintenance & inspection' is given below:

p (QOfMaintInsp | RI, PRFTest, PreVent, ProEq, ExPrEq, HotWr, Training,

WComChk, QOfSysProcScore) =

NormalDist (QOfMaintInsp, avg (RI, PRFTest, PreVent, ProEq, ExPrEq, HotWr,

Training, WComChk, QOfSysProcScore) , 0.1) (Eqn. 6.3)

6.4.3 Quality of construction

Table 6.4 below gives the description for the parents influencing the main causal factor Quality of construction followed by BN in Figure 6.7.

Table 6.4 Details of parent nodes of Construction

Sl. No.	Node name	Node full form	States	Parameterization method	Description
1	ContrQuality	Contractor Quality	Poor Average Good	Normal distribution	Quality of the contractor for executing the work

Table 6.4 Details of parent nodes of Construction					
Sl. No.	**Node name**	**Node full form**	**States**	**Parameterization method**	**Description**
2	Supervision	Supervision	Not Adequate Adequate	Manual	Adequacy of construction supervision
3	ConstCertPr	Construction certification procedures	Not implemented Implemented	Manual	Procedures for certifying completion of construction
4	TestingReq	Testing requirements	Not complete Complete	Manual	Completion of testing requirements

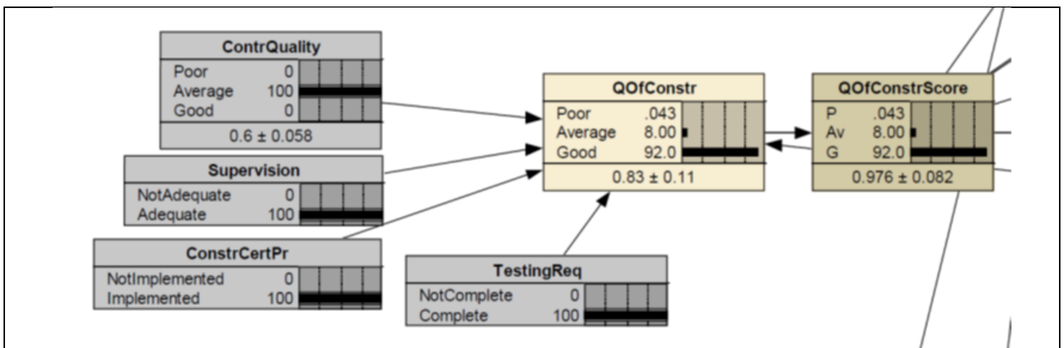


Figure 6.7 BN for 'Quality of construction'

Equation for node 'Quality of construction is given in Eqn. 6.4

p (QOfConstr | ContrQuality, Supervision, ConstrCertPr, TestingReq, QOfSysProc) =

NormalDist (QOfConstr, avg (ContrQuality, Supervision, ConstrCertPr, TestingReq, QOfSysProc) , 0.1) (Eqn. 6.4)

6.4.4 Quality of Equipment selection

Table 6.5 indicates the parent nodes for Quality of Equipment selection. Figure 6.8 shows the corresponding BN.

Table 6.5 Details of parent nodes of Quality of Equipment selection					
Sl. No.	**Node name**	**Node full form**	**States**	**Parameterization method**	**Description**
1	LiProtS	Lightning protection system	Not industry practice Industry practice	Manual	Lightning protection system selection should be as per industry practice
2	ESDVSys	Emergency Shut Down valve & system	Proven Not Proven	Manual	ESDV design alone is not enough, the system selected must be proven and fit for the purpose.
3	IsoVType	Isolation valve type	Not operator friendly Operator friendly	Manual	The isolation valve has a critical function. Its failure probability must be evaluated with respect to operator actions.
4	ROV	Remote operated valve	Not fire safe Fire safe	Manual	ROV provided must be fire safe as per relevant standards.
5	ComplianceWithElecHaz	Compliance with Electrical Hazardous area classification	Not complied Complied	Manual	All equipment shall comply with appropriate Electrical hazardous area classification
6	TherExForLiquid	Thermal expansion for liquid	Not provided Provided	Manual	If there is possibility of locked up liquid in above ground piping, thermal expansion must be considered and designed in.
7	QfSysProc	Quality of Systems and procedures	Poor, Average, Good	Input from another calculated node	--

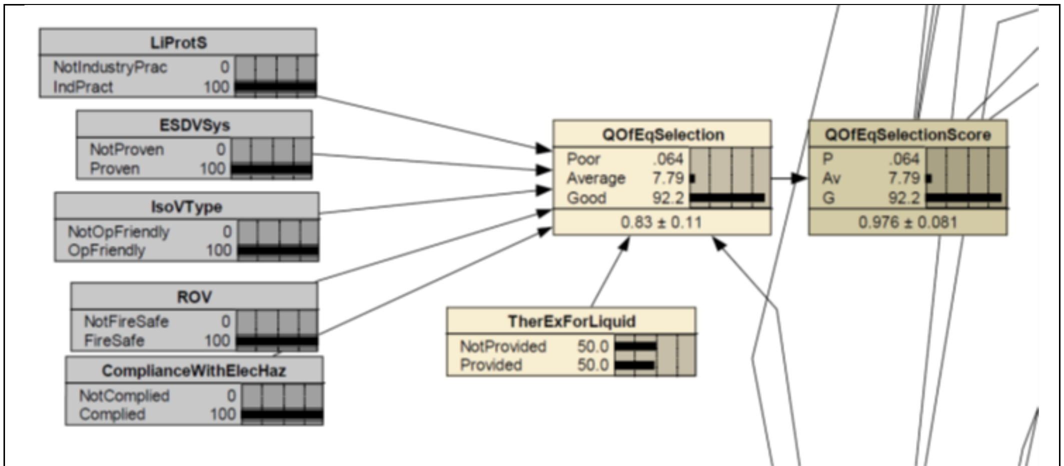


Figure 6.8. BN for ‘Quality of Equipment selection’

Equation for node ‘Quality of ‘Equipment selection’ given below:

P (QOfEqSelection | LiProtS, ESDVSys, IsoVType, ROV, TherExForLiquid,

QOfSysProcScore, ComplianceWithElecHaz) =

NormalDist (QOfEqSelection, avg (LiProtS, ESDVSys, IsoVType, ROV,

TherExForLiquid, QOfSysProcScore, ComplianceWithElecHaz) , 0.1)

(Eqn.6.5)

6.4.5 Quality of Risk assessments

Table 6.6 below gives the parent nodes and description for the main causal factor Quality of Risk assessments followed by BN in Figure 6.9

Table 6.6 Details of parent nodes of Quality of Risk assessments

Sl. No.	Node name	Node full form	States	Parameterization method	Description
1	HAZID	Hazard identification	Poor Quality Good Quality	Manual	Quality of Hazard identification study
2	HAZOP	Hazard & operability studies	Poor Quality Good Quality	Manual	Quality of Hazard & operability study
3	RA	Risk assessments	Poor Quality Good Quality	Manual	Quality of risk assessment studies

Table 6.6 Details of parent nodes of Quality of Risk assessments					
Sl. No.	**Node name**	**Node full form**	**States**	**Parameterization method**	**Description**
4	QOfSysProc	Quality of Systems and procedures	Poor, Average, Good	Input from another node	There must be evaluation of quality of risk assessments

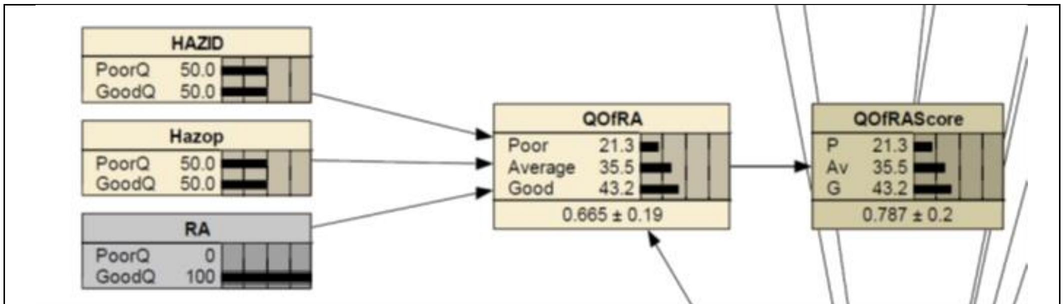


Figure 6.9 BN for 'Risk assessments'

Node 'QOfRA' contain the equation Eqn. 6.6

P (QOfRA | HAZID, RA, Hazop, QOfSysProcScore) =

NormalDist (QOfRA, (0.24* HAZID + 0.24* RA + 0.24 * Hazop + 0.28 *QOfSysProcScore) , 0.1) (Eqn. 6.6)

Here the mean of the Normal distribution is weighted average of the sub-causes (parents)

6.4.6 Quality of Systems and procedures

Table 6.7 below gives the parent nodes and description for the main causal factor Quality of construction followed by BN in Figure 6.10

Table 6.7 Details of parent nodes of Quality of Systems and procedures					
Sl. No.	**Node name**	**Node full form**	**States**	**Parameterization method**	**Description**
1	EnggControlsRev	Engineering controls review	Not implemented Implemented	Manual	Review procedures for quality control of engineering work
2	SOPReview	Standard operating procedures review	Not available Available	Manual	Regular review of operating procedures
3	EmergencyResposneDrills	Emergency response drills	Not available Available	Manual	Periodic emergency response drills and review
4	OpStaffTraining	Operating staff training	Not conducted Conducted	Manual	Training program for operating staff
5	AdherenceToMOC	Adherence to management of change	Not complied Complied	Manual	Procedures for management of change and adherence to the same
6	AuditForPSM	Audit for process safety management	Not conducted Conducted.		Audit procedures and audit exercises on regular basis
7	ProtocolForCRManning	Protocol for control room manning	Not available Available	Manual	Protocol for manning the control room
8	DDUUpdateSystem	Drawings and documentation update system	Not available Available	Manual	Ongoing system for updating of drawings and documentation
9	IsolationProcedures	Isolation procedures	Not available Available	Manual	Established procedures for isolation and adherence to the same
10	DrainingProcedures	Draining procedueres	Not available Available	Manual	Established procedures for isolation and adherence to the same

Table 6.7 Details of parent nodes of Quality of Systems and procedures					
Sl. No.	**Node name**	**Node full form**	**States**	**Parameterization method**	**Description**
11	PeriodicUpdateRA	Periodic update of Risk assessments	Not complied complied	Manual	Scheduled update of risk assessments
12	QOfHOF	Quality of Human and organizational factors	Poor Average Good	From another node	

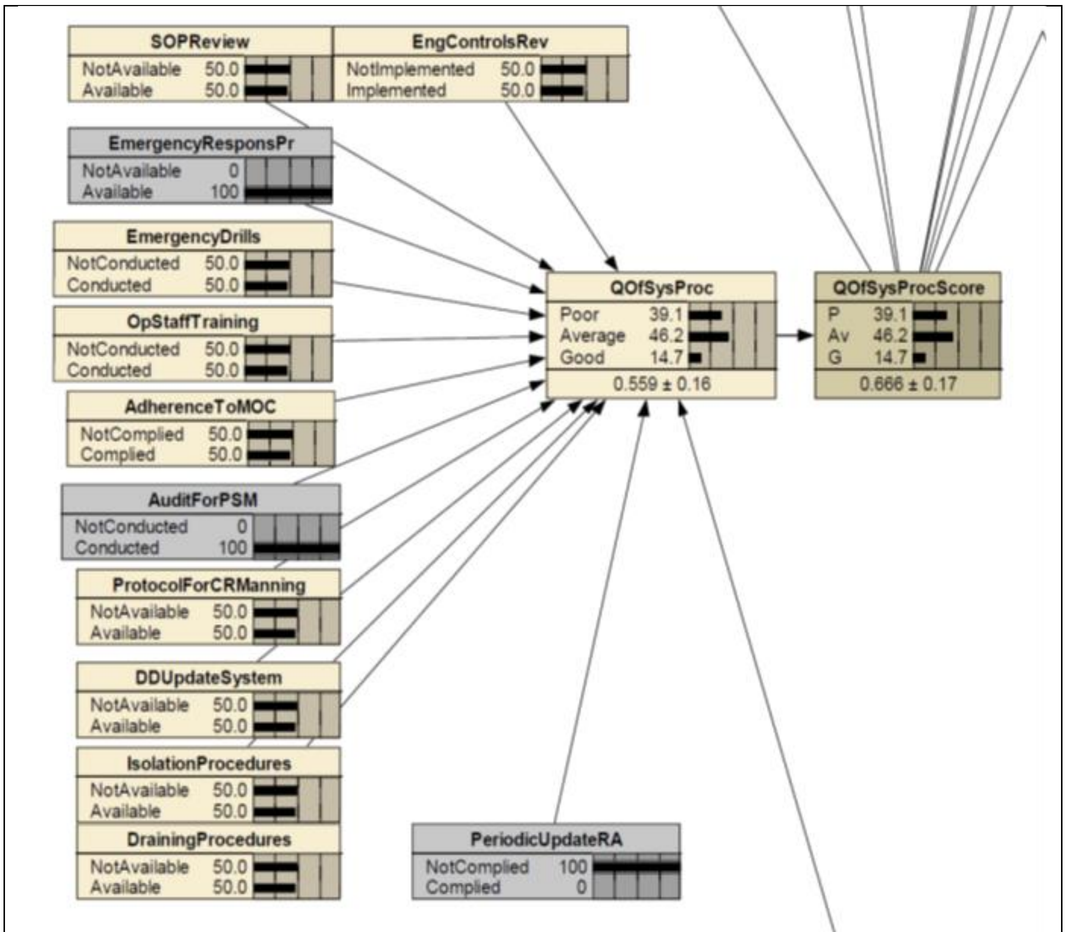


Figure 6.10 BN for 'Quality of Systems and procedures'

Equation for the node 'QOSysProc' is given below:

P (QOfSysProc | EngControlsRev, SOPReview, EmergencyResponsPr, EmergencyDrills, OpStaffTraining, AdherenceToMOC, AuditForPSM, ProtocolForCRManning, DDUpdateSystem, PeriodicUpdateRA, IsolationProcedures, DrainingProcedures, QOfHOF) =

NormalDist (QOfSysProc, avg (EngControlsRev, SOPReview, EmergencyResponsPr, EmergencyDrills, OpStaffTraining, AdherenceToMOC, AuditForPSM, ProtocolForCRManning, DDUpdateSystem, PeriodicUpdateRA, IsolationProcedures, DrainingProcedures, QOfHOF), 0.1) (Eqn. 7.7)

6.4.7 Quality of Human and Organizational factors

Table 6.8 and Figure 6.11 gives details of parent nodes for Quality Human and Organizational factors and the corresponding BN, respectively.

Table 6.8 Details of parent nodes of Quality of Human and Organizational factors

Sl. No.	**Node name**	**Node full form**	**States**	**Parameterization method**	**Description**
1	VisibilityPSM	Visibility of Process Safety Management (PSM)	Not visible Visible	Manual	Process safety management must be visible to the staff for its effectiveness
2	UnderstandingPSM	Understanding PSM	Poor Good	Manual	PSM is often confused with personal and construction safety even at senior management levels.

Table 6.8 Details of parent nodes of Quality of Human and Organizational factors

Sl. No.	Node name	Node full form	States	Parameterization method	Description
3	KwPotRisks	Knowledge of potential risks	Poor Good	Manual	Risk awareness of personnel is important.
4	QualifiedPer	Qualified personnel	Not available Available	Manual	Personnel must have the required technical qualifications
5	RRDefPSM	Roles and responsibility definitions for PSM	Not assigned Assigned	Manual	PSM hierarchy must have their roles and responsibility clearly defined
6	SelForSC	Selection of personnel for safety critical operations	Wrong choice Correct Choice	Manual	Personnel for safety critical operations must be assessed for suitability
7	Safety Culture	Safety culture	Pool Positive	Manual	A positive, risk aware safety culture is a basic requirement for promoting safe practices.

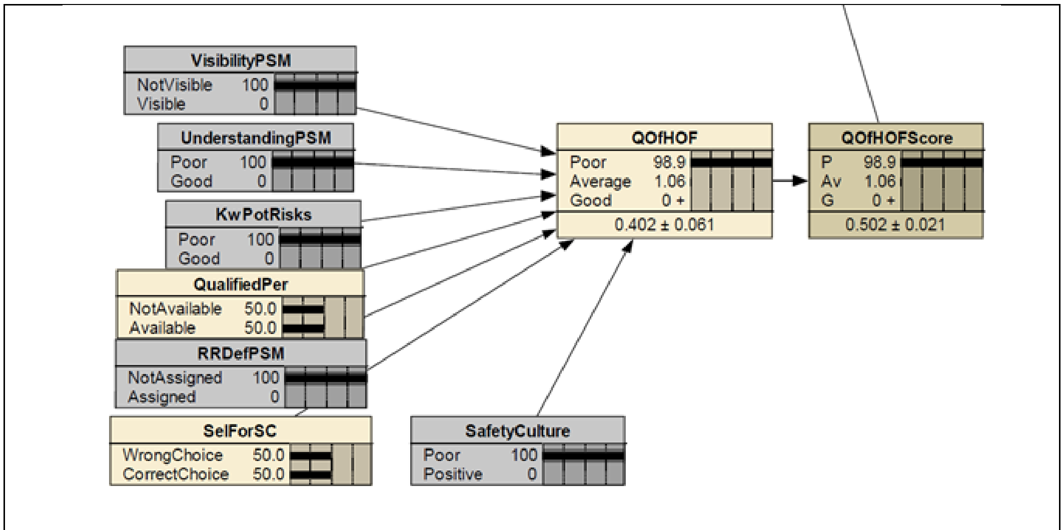


Figure 6.11. BN for 'Quality of Human and Organizational factors'

Equation 6.8 provides the relationship between the parent nodes and child node as Normal distribution with mean as the average of all parent nodes with a Standard deviation of 0.1.

P (QOfHOF | VisibilityPSM, UnderstandingPSM, KwPotRisks, QualifiedPer, RRDefPSM, SelForSC, SafetyCulture) =

NormalDist (QOfHOF, avg (VisibilityPSM, UnderstandingPSM, KwPotRisks, QualifiedPer, RRDefPSM, SelForSC, SafetyCulture) , 0.1) (Eqn. 6.8)

6.4.8 Intermediate causes

Each of the key causal factors further influence downstream intermediate causes which form the immediate causes for a failure. Certain key causal factors impact more than one intermediate factor. They are listed in Table 6.9.

Table 6.9. Intermediate factors		
Sl. No.	**Key causal factor**	**Impacted intermediate downstream factors**
1	Quality of design	Static charge build up
		Vibration or cyclic loading
		Surge pressure
		Lighting protection failure
2	Quality of Construction	Weld failure
		Tank internal lining failure
		Liquid side piping failure
3	Quality of maintenance and inspection Quality of equipment selection	Tank outlet valve leak
		Liquid side piping failure
		Corrosion
		Liquid control system failure
		ESDV failure
4	Quality of QRA	Liquid side piping failure
		Excessive liquid transfer
5	Quality of systems and procedures	Incorrect valve operation
		Improper work on tank
		Tank outlet valve leak

6.4.9 Other Root causes:

They include lightning strike, catastrophic tank failure due to natural causes, foundation subsidence and external impact.

The intermediate and immediate causes and failure of components are given in Figure   which shows the relevant portion of the BN.

6.4.10 Bayesian Network for loss of containment scenarios for Floating roof tank

The 9 key causal factors in Table 6.1, 63 root causes for the same, intermediate downstream causes plus the failure nodes given in Table 6.9 and their interrelationships are combined in a BN for different LOC scenarios for Floating roof tank. Portion of full BN showing the same is given in Figure 6.12 below. NoisyOr distribution or weighted average equations have been used for the effect (child) nodes to define the conditional probability tables.

Full BN for LOC of Floating roof tank is given in Figure 6.13.

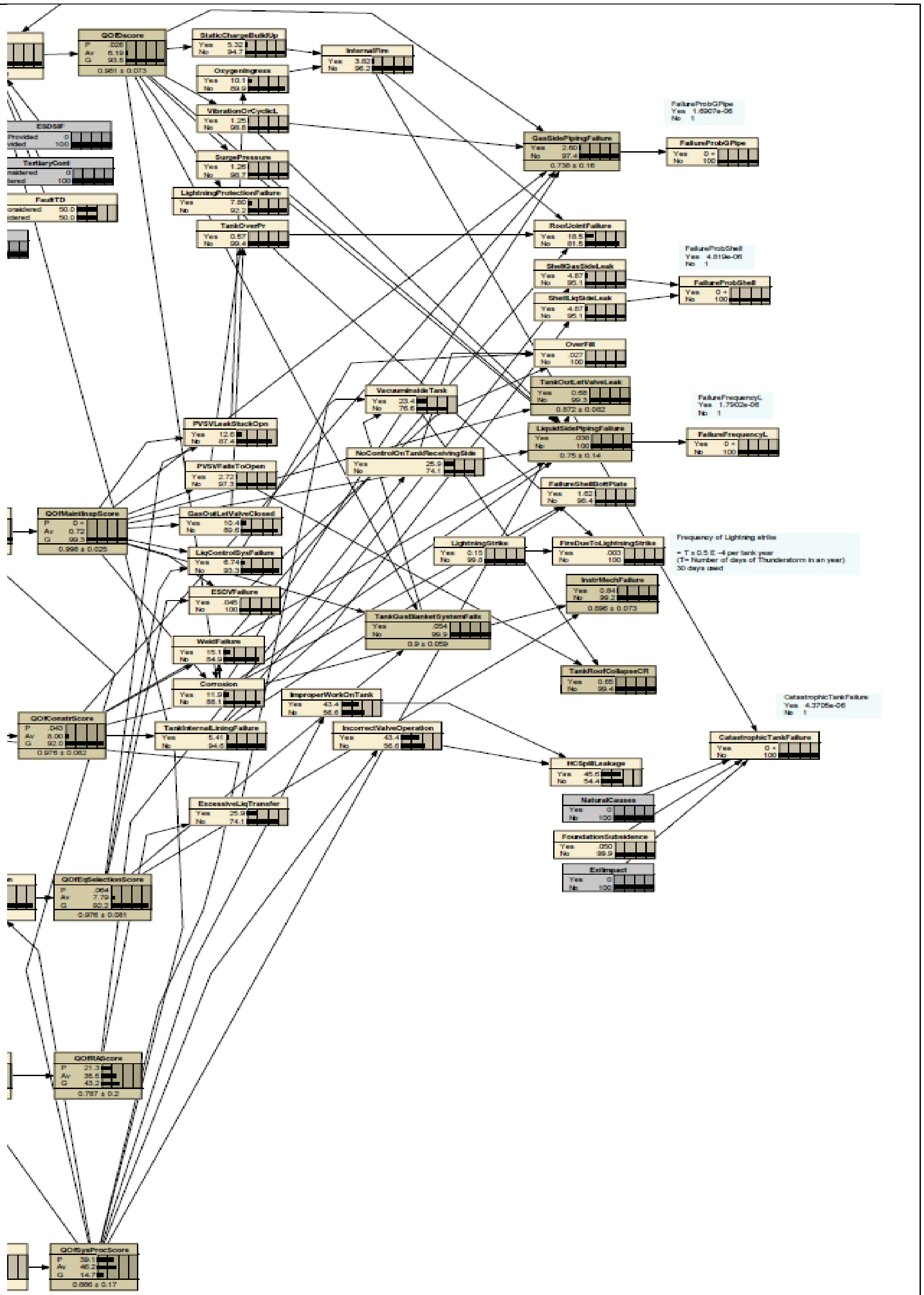


Figure 6.12. Portion of BN showing Intermediate and immediate causes and their interrelationships

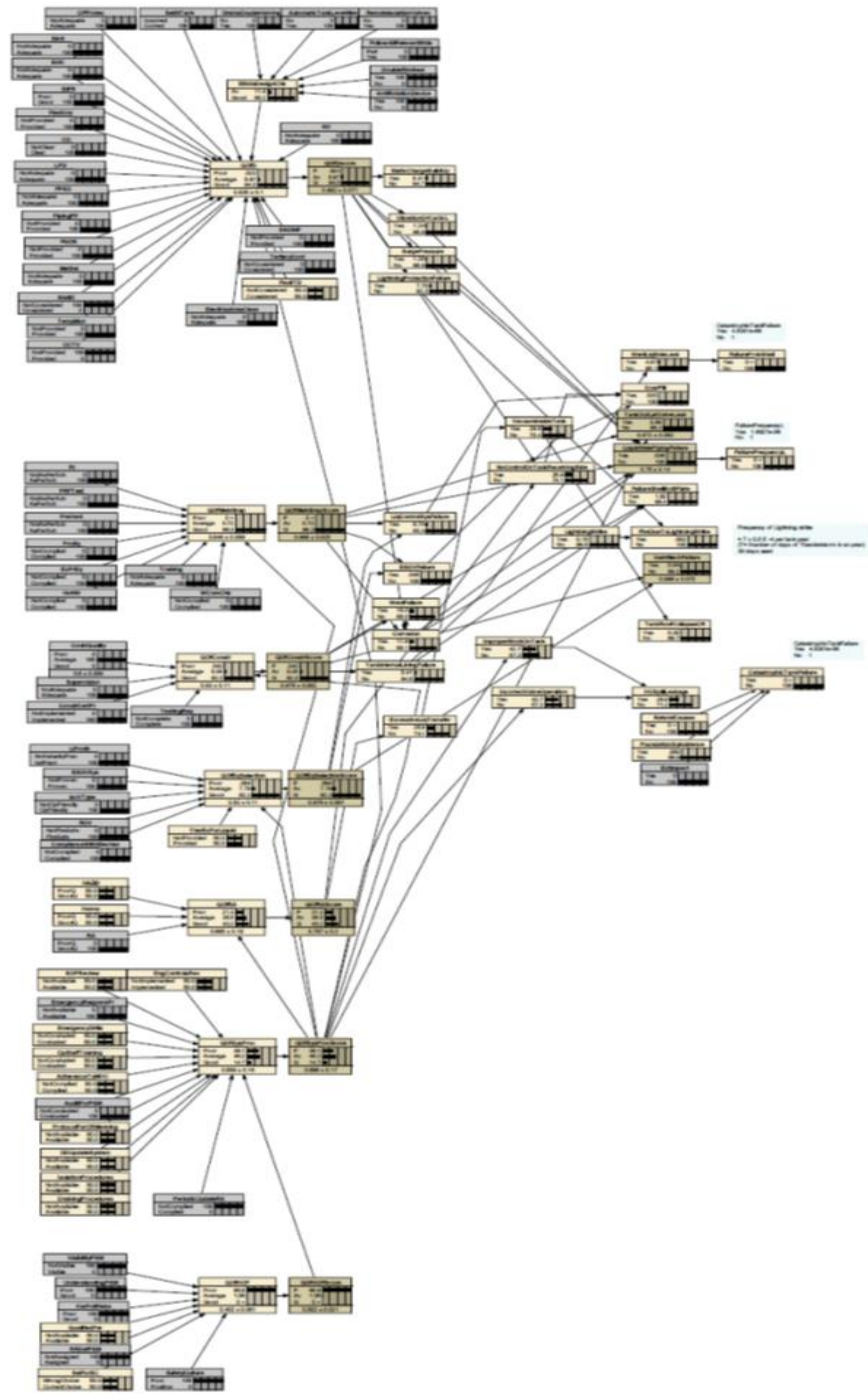


Figure 6.13. Full BN for loss of containment scenarios for Floating roof tank

The cause and effect relationships of the final, its predecessor (as applicable) and its immediate parent nodes are shown in BN in Figure 6.14. The conditional probability table and notes of the same are given below in Table 6.10:

Table 6.10. Conditional Probability Table for final effect nodes

Final effect node name and its parent nodes in ( )	Conditional Probability Table	Notes
FailureProbShell (ShellLiqSideLeak)	FailureProbShell: Yes No ShellLiqSideLeak 1e-4 0.9999 Yes 0 1 No	The CPT converts the relative probability to average generic probability@
ShellLiqSideLeak (TankInternalLiningFailure)	ShellLiqSideLeak: Yes No TankInternalLiningFailure 0.9 0.1 Yes 0 1 No	Probability of failure of tank internal lining directly affects the probability of shell leak
OverFill (NoControlOnTankReceivingSide, LiqControlSysFailure, ESDVFailure)	p (OverFill | NoControlOnTankReceivingSide, LiqControlSysFailure, ESDVFailure) = NoisyOrDist (OverFill, 0.0000001, NoControlOnTankReceivingSide, 0.0005, LiqControlSysFailure, 0.001, ESDVFailure, 0.0020)	The relationship is defined by NoisyOr distribution

Table 6.10. Conditional Probability Table for final effect nodes

Final effect node name and its parent nodes in ( )	Conditional Probability Table	Notes
TankOutLetValveLeak (QOfMaintInspScore, QOfSysProcScore)	TankOutLetValveLeak (QOfMaintInspScore, QOfSysProcScore) = 0.50* QOfMaintInspScore + 0.50*QOfSysProcScore	The weighted equation defines the relationship of parents (causes) with effect.
FailureFrequencyL: (LiquidSidePipingFailure)	FailureFrequencyL: Yes No LiquidSidePipingFailure 0.005 0.995 Yes 0 1 No	The CPT converts the relative probability to average generic probability@
LiquidSidePipingFailure (Corrosion, SurgePressure, VibrationOrCyclicL, QOfDscore, QOfMaintInspScore, QOfConstrScore)	LiquidSidePipingFailure (Corrosion, SurgePressure, VibrationOrCyclicL, QOfDscore, QOfMaintInspScore, QOfConstrScore) = (0.35 *Corrosion + 0.05* SurgePressure + 0.05* VibrationOrCyclicL + 0.25* QOfDscore + 0.20* QOfMaintInspScore + 0.10* QOfConstrScore)	Liquid side piping failure is defined by NoisyOr distribution of its causes.

Table 6.10. Conditional Probability Table for final effect nodes

Final effect node name and its parent nodes in ( )	Conditional Probability Table	Notes
FailureShellBottPlate (TankInternalLiningFailure)	FailureShellBottPlate: Yes No TankInternalLiningFailure Corrosion 0.9 0.1 Yes Yes 0.1 0.9 Yes No 0.05 0.95 No Yes 0 1 No No	Failure of tank bottom plate is defined by the CPT of its parent nodes
FireDueToLightningStrike: (LightningProtectionFailure)	FireDueToLightningStrike: Yes No LightningStrike LightningProtectionFailure 0.1 0.9 Yes Yes 0.01 0.99 Yes No 0 1 No Yes 0 1 No No	CPT table defines the relationship

Table 6.10. Conditional Probability Table for final effect nodes

Final effect node name and its parent nodes in ( )	Conditional Probability Table	Notes
TankRoofCollapse (VacuumInsideTank)	TankRoofCollapse: Yes No VacuumInsideTank 0.01 0.99 Yes 0 1 No	Tank roof collapse is directly dependent on the vacuum condition inside the tank
CatastrophicTankFailure (NaturalCauses, FoundationSubsidence, ExtImpact)	P (CatastrophicTankFailure | NaturalCauses, FoundationSubsidence, ExtImpact) = NoisyOrDist (CatastrophicTankFailure, 0.0000045, NaturalCauses, 0.000008, FoundationSubsidence, 0.00006, ExtImpact, 0.00001)	NoisyOr distribution is used to define the relationship between the parent and causal nodes

@These relative probabilities has been transformed to an average failure frequency probabilities based on the values indicated in the published literature [59] for loss of containment. [The generic frequencies for LOC for atmospheric storage tank and for pipes is of the order of 5 x 10-6 and 2 x 10-6 per meter per year respectively. (Table 3.5 and 3.7 of [59]). This is done to provide certain measure of judgement about the variation from current average when casual factors are changing.

6.4.11 Sensitivities

Sensitivity of other nodes to a target node can be analyzed in a BN. Figure 6.14- indicates sensitivity of other nodes to shell side leak and Figure 6.15 shows sensitivity of other nodes to failure frequency (probability) of liquid side LOC.

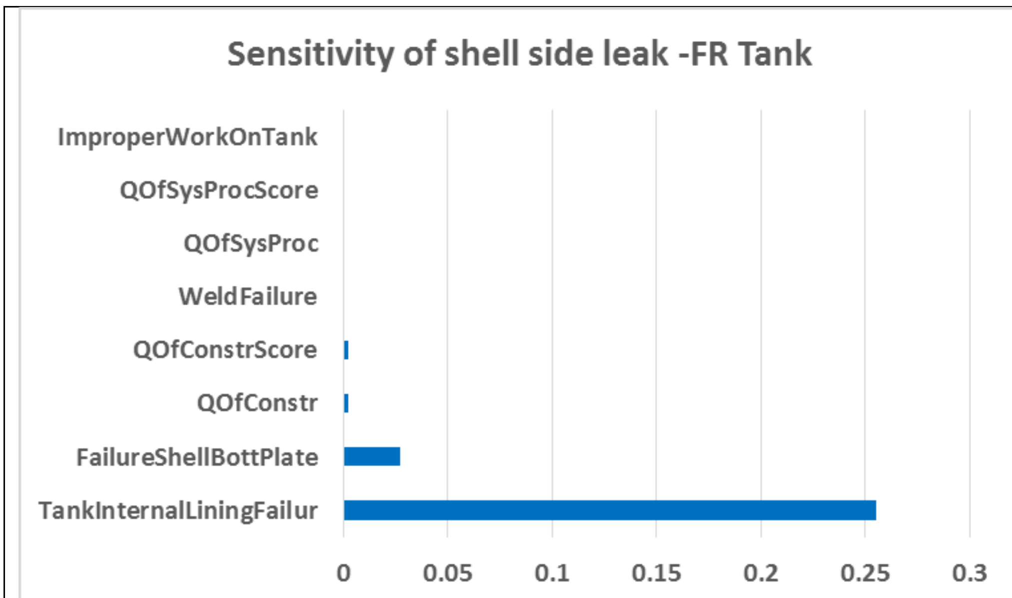


Figure 6.14. Sensitivity of nodes to a leak on shell side –FR Tank

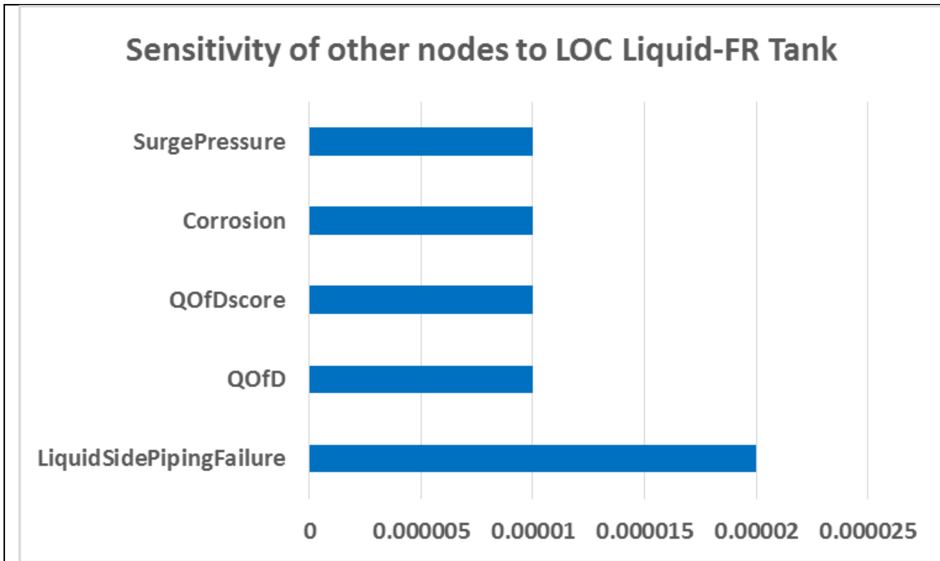


Figure 6.15. Sensitivity of nodes to a Failure Liquid side–FR Tank

6.5 Event Tree for the post loss of containment scenario in Floating roof tank

BN equivalent of Event trees for the post LOC scenario for Floating roof tank is given below based on LASTFIRE [55]. The scenarios are

i. Rim seal fire
ii. Spill on roof
iii. Shell or liquid side piping

The scenarios are shown in Figures 6.16 a and Figure 6.16 b below:

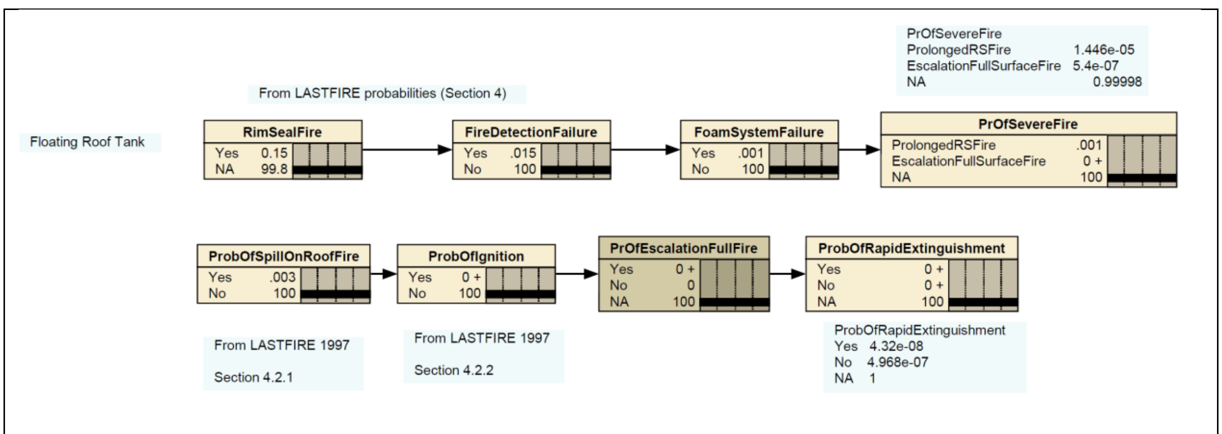


Figure 6.16a. BN for the post loss of containment: Rim seal & Spill on roof. FR tank

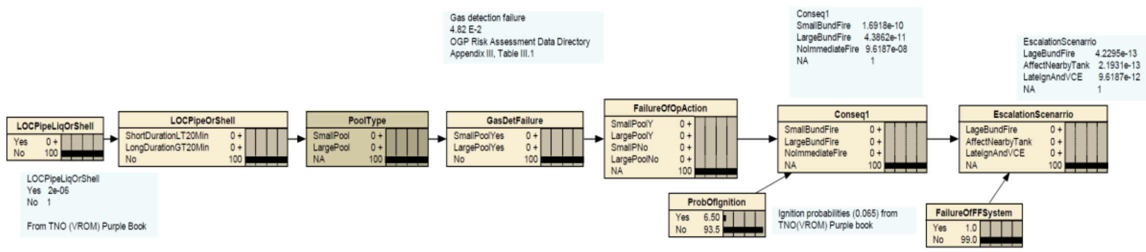


Figure 6.16b BN for [post loss of containment: Liquid side (Pipe or shell). FR tank

6.6 BN for Loss of containment in Cone roof (CR) tank

As can be seen from Figure 6.2, Cone roof tank has a gas space and blanketing gas keep the space under positive pressure. Therefore a node has been added to take care of this aspect. All other nodes, CPT and equations remain the same as in Floating roof tank. The BN is for Cone roof tank is given in Figure 6.17.

The equation for the added node ‘GasSidePipingFailure’ is given in equation 6.9

GasSidePipingFailure (Corrosion, VibrationOrCyclicL, QOfDscore,

QOfMaintInspScore, QOfConstrScore) =

(0.35* Corrosion + 0.10* VibrationOrCyclicL + 0.25*QOfDscore + 0.10*

QOfMaintInspScore +0.10*QOfConstrScore) (Eqn. 6.9)

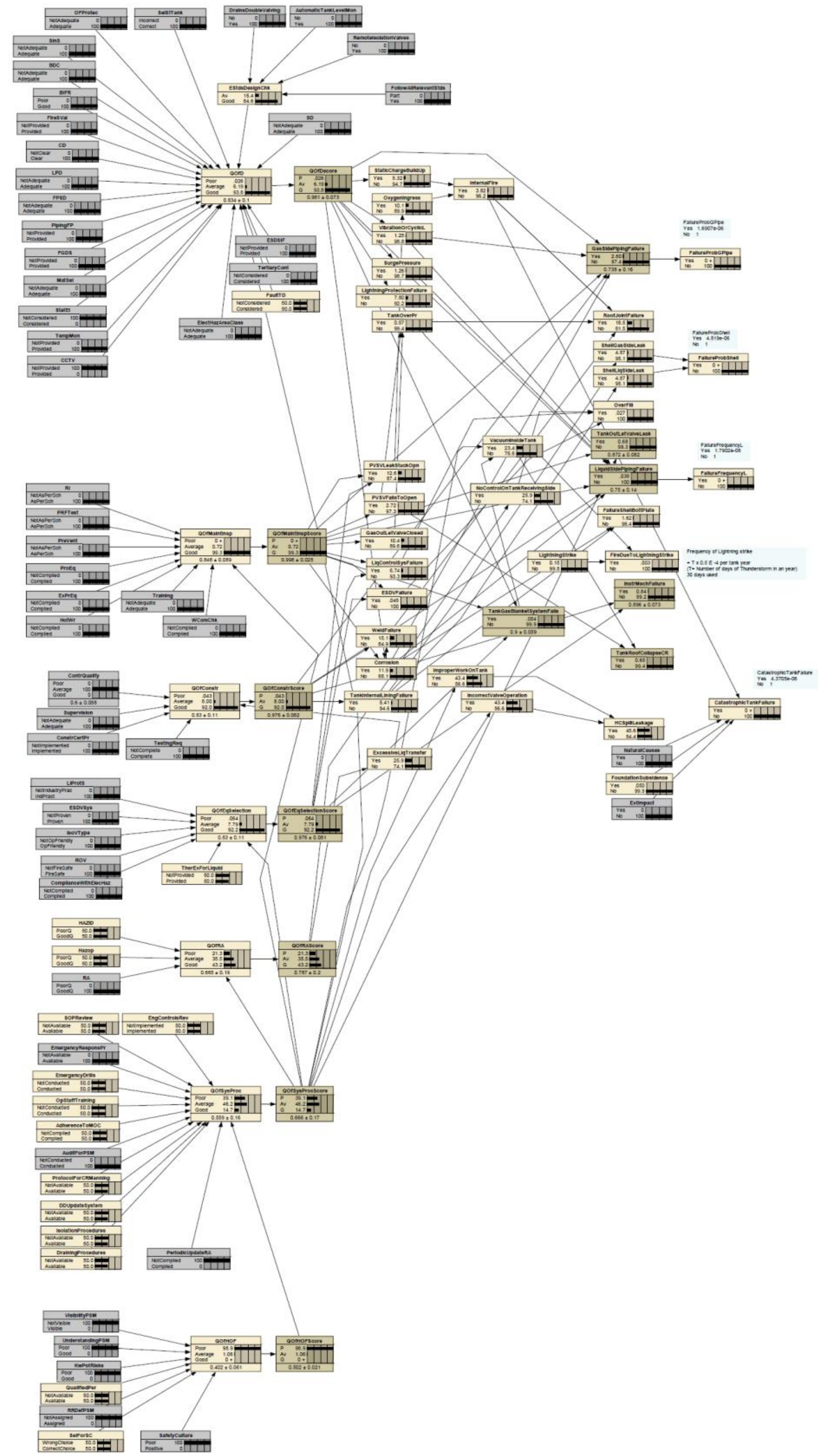


Figure 6.17. BN for Cone roof tank

Next difference is in the LOC scenario. In Cone roof tank there is a probability of LOC for gas side either on gas piping side or on shell side (gas). The BN equivalent of Event trees for LOC on gas side piping and shell side (gas) are given in Figure 6.18 a & b. As can be seen, with generic probabilities for LOC, the consequences are very low. However, when there is a confirmed LOC on the gas side (yes =100%), the probability of a consequences namely; jet fire, Vapor Cloud Explosion (VCE) and toxic gas dispersion increases. This is shown in BN given in Figure 6.19, with LOC of gas 100%.

6.7 Chapter summary

The probability of loss of containment in the shell side or that on the liquid side for Floating roof and Cone Roof tanks have been described in detail in the preceding sections. The causal factors have been analyzed in four levels. Key causal factors and its root (parent) causes, followed by downstream effects of the key causal factors namely intermediate, immediate causes and failure of components. The BN showing the interrelationships between the above have been developed. The casual factors and its mitigation measures are taken from published literature as well as from industry practice and experts' opinion. The relationships embedded in the CPTs capture the probabilistic nature of the relationships.

Event trees for post LOC and its equivalent BN are also developed separately for Floating and Cone roof tanks. For Floating roof, rim seal fire and spill on the roof and fire due to LOC have been given separately. For Cone roof 3 BNs are given, one for post LOC for gas side and another for liquid side. Additionally a BN for a confirmed gas LOC is given to illustrate the how the probability of fire increases on a confirmed gas leak. The models serves as a status for the risk levels in atmospheric storage tank installation. Whenever actual data about the site becomes available, it can be entered in to the model to see the impact of the same on the probability of LOC.

BN for compressor damage is discussed in the next chapter.

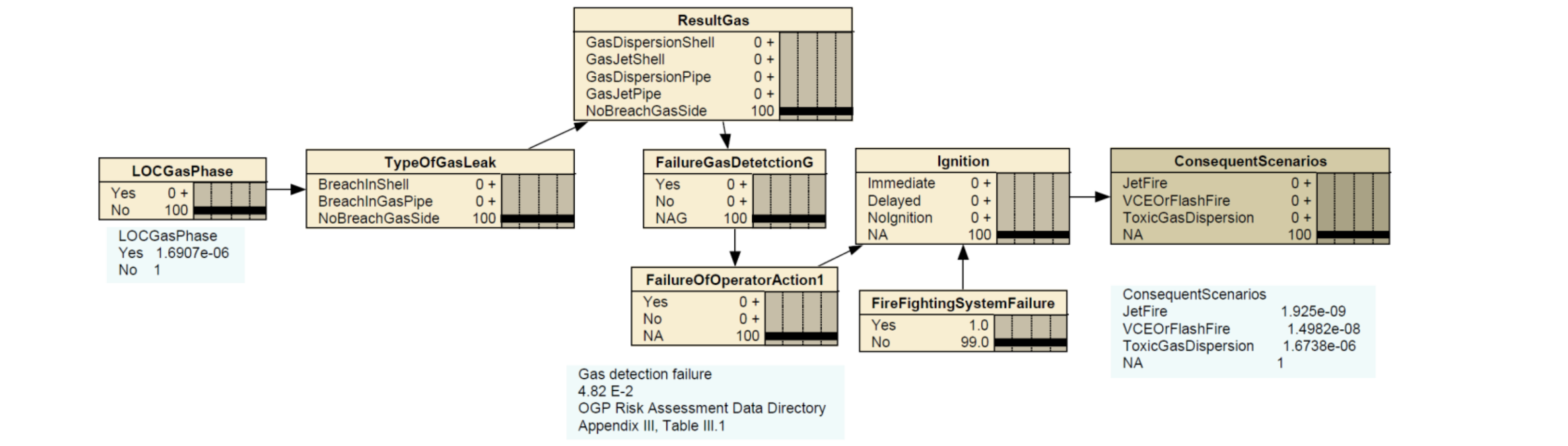


Figure 6.18 a. BN equivalent for Event tree –post LOC on gas side piping-Cone roof tank

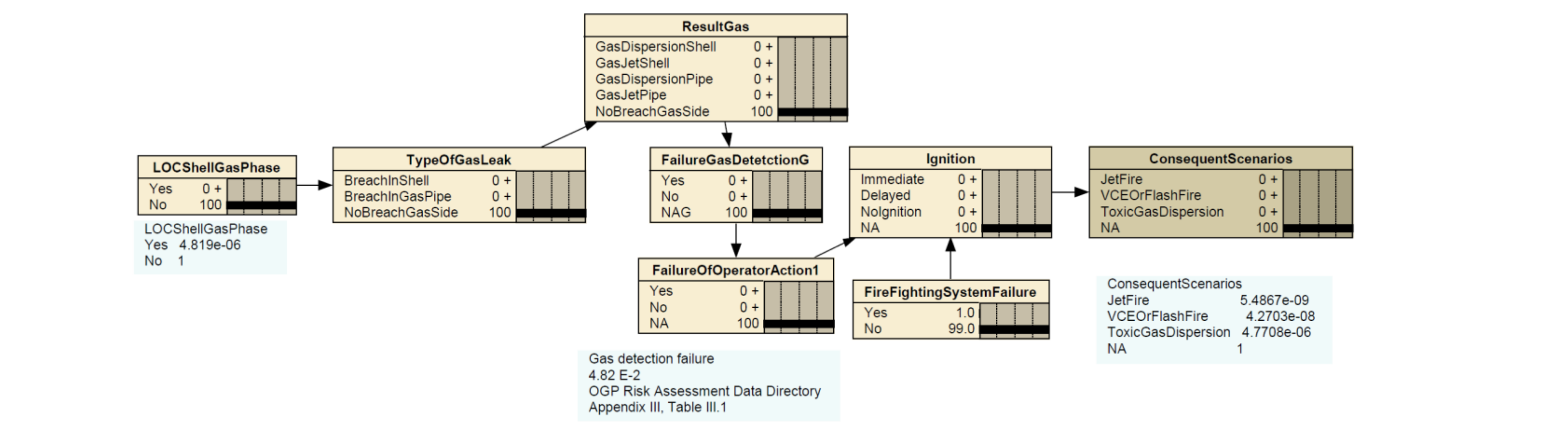


Figure 6.18 b. BN equivalent for Event tree –post LOC on Shell gas side-Cone roof tank

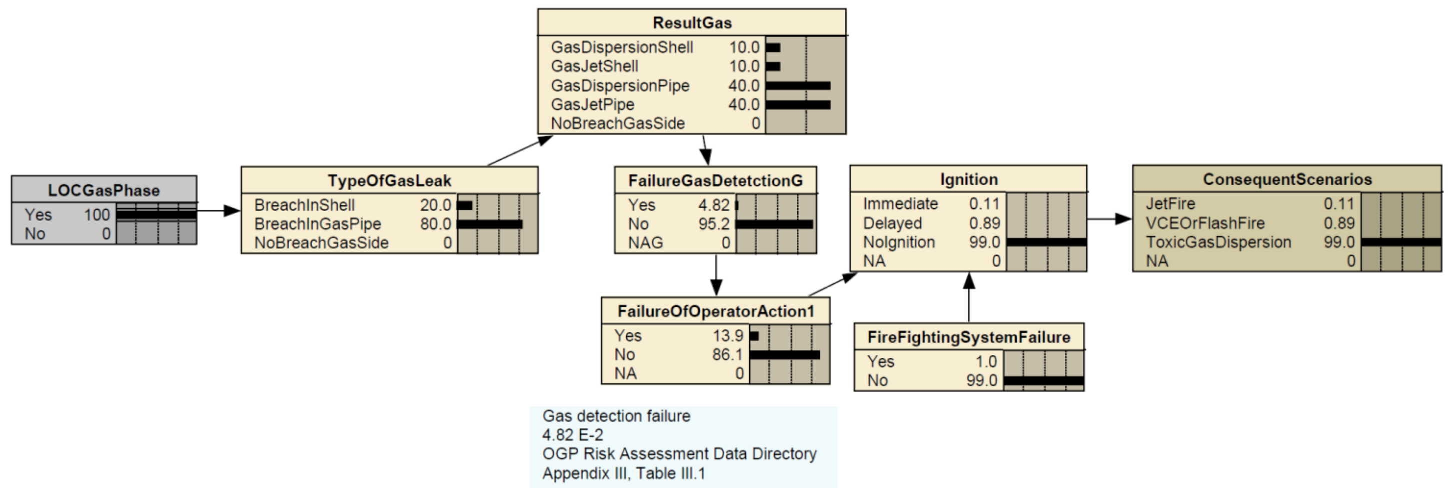


Figure 6.19. BN equivalent for Event tree –confirmed LOC (= 100%) on gas side-Cone roof tank

7. Bayesian Network for compressor damage

Centrifugal compressor is one of the most commonly used rotating equipment in oil and gas industry. The function of compressor is to increase the pressure of the gas from inlet to outlet. A general schematic of the protective barriers in the compressor system is depicted in Figure 7.1. The automatic emergency shutdown and safety blowdown system is triggered when predefined abnormal conditions are reached by a set of process variables.

7.1 Compressor failure modes:

OREDA [48] lists compressor failure modes as per Table 7.1 given below:

Table 7.1Failure Modes for Centrifugal compressor

Sl. No.	**Failure Modes**
1	Abnormal instrument reading
2	Breakdown
3	Erratic output
4	External leakage –Process medium
5	External leakage –Utility medium
6	Fails to start on demand
7	Fails to stop on demand
8	High output
9	Internal leakage
10	Low output
11	Minor in-service problems
12	Noise
13	Other
14	Overheating
15	Parameter deviation
16	Spurious trip
17	Structural deficiency
18	Unknown
19	Vibration

7.2 Compressor failure rates

As seen from the Table 7.1, only external leakage of process medium will result in a loss of containment for which OREDA [48] has given a mean failure rate of 10.26 per 10-6 hours or 8.99 x 10-2 failures per compressor year. On the other hand, HSE UK report Item FR 3.1.3 [60] frequency rates for Rupture as 2.9 x 10-6 per compressor year and 2.7 x 10-4 for small holes 25mm to 75mm. It is worthwhile to note that one of the main causes for compressor failure in industry, that is liquid carry over is not mentioned by either databases, but is clearly highlighted by consultants Barringer [75]. It could be that such invisible root cause is not reported properly to the databases.

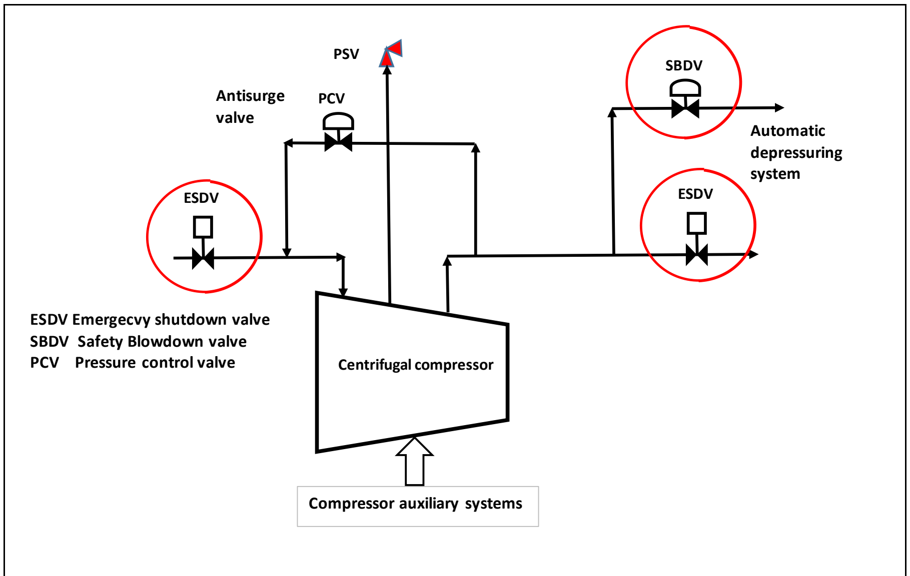


Figure 7.1 Diagram for compressor layer of protection

For the purpose of this study the following causes and sub causes have been used in the BN. Expert opinion has been elicited for developing the influence factors for compressor damage. These causes and sub causes along with the mitigating factors are mapped into BN. The table of causal factors and the corresponding BN for compressor failure is given below in Table 7.2 and Figure 7.2 respectively

Table 7.2. Main and sub causal factors for compressor damage

Sl. No.	**Main causal factor**	**Sub causal factors. (Parent nodes)**	**Notes: All sub-causal factors (Parents nodes) are modeled as Normal distribution with parameters noted below. Ranges of states 'Yes' & 'No' are also indicated**
1	Overpressure in compressor	1.1 Downstream blockage 1.2 Failure of valve to flare 1.3 Failure of high pressure shutdown of ESDV	Mean=0.08, SD=0.1, Yes (0.01-0.025), No (0.025-0.99) Mean=0.15, SD=0.1, Yes (0.01-0.06), No (0.06-0.99) Mean=0.04, SD=0.01, Yes (0.001-0.002), No (0.002-0.99)
2	Failure of Anti surge valve		Mean=1.16 e-4, SD=0.0001, Yes(1e-6-3e-6), No (3e-6-0.001)
3	Intermediate2	3.1 PSV Failure 3.2 PSV undersized	Mean=0.005, SD=0.001, Yes (0.001-0.0012), No(0.0012-0.99) Mean=0.05, SD=0.1, Yes (0.01-0.02, No (0.02-0.99)
4	Liquid carryover	4.1 Suction demister design inadequate 4.2 Liquid slugs in inlet gas 4.3 Failure of control system 4.4 Failure of high liquid level trip 4.5 Failure of operator action	Mean=0.15, SD=0.01, Yes (0.01-0.06, No (0.06-0.99) Mean=0.15, SD=0.1, Yes (0.01-0.06, No (0.06-0.99) Mean=0.12, SD=0.1, Yes (0.01-0.045, No (0.045-0.99) Mean=0.09, SD=0.01, Yes (0.01-0.025, No (0.025-0.99) Mean=0.11, SD=0.1, Yes (0.01-0.04, No (0.04-0.99)
5	Gas seal	5.1 Liquid carry over 5.2 Excessive vibration	Mean= avg(Sub-causes 4.1 to 4.5), SD=0.1, Yes (0.01-0.3), No (0.03-0.99) Mean=0.0004, SD=0.01, Yes (1e-4-8e-4), No (8e-4-0.99)
6	Lube oil system failure	6.1 Failure of Lube oil system 6.2 Failure of operator action	Mean=0.006, SD=0.1, Yes (0.001-0.008), No (0.008-0.99) Mean=0.11, SD=0.1, Yes (0.01-0.04, No (0.04-0.99)
7	Foreign object entry	7.1Temporary strainers 7.2 Lack of procedure for removal /verification	Manual entry, Yes (0.75), No (0.25) Manual entry, Yes (0.10), No (0.90)
8	Change of Operating conditions		Manual input. Binary (Yes or No)
9	Thrust bearing failure		Manual input. Binary (Yes or No)

Table 7.2. Main and sub causal factors for compressor damage			
Sl. No.	**Main causal factor**	**Sub causal factors. (Parent nodes)**	**Notes: All sub-causal factors (Parents nodes) are modeled as Normal distribution with parameters noted below. Ranges of states ‘Yes’ & ‘No’ are also indicated**
10	Coincident Mechanical & Acoustic frequencies		Manual input. Binary (Yes or No)

As seen above all the respective sub causes have been combined in each of the main causal factors using Normal distribution with suitable mean, Standard Deviation (SD) and ranges, except the last factor ‘Coincident Mechanical & Acoustic frequencies’ which has a manual input.

These causal factors and its mitigation measures have been modeled as a BN in Figure 7.2

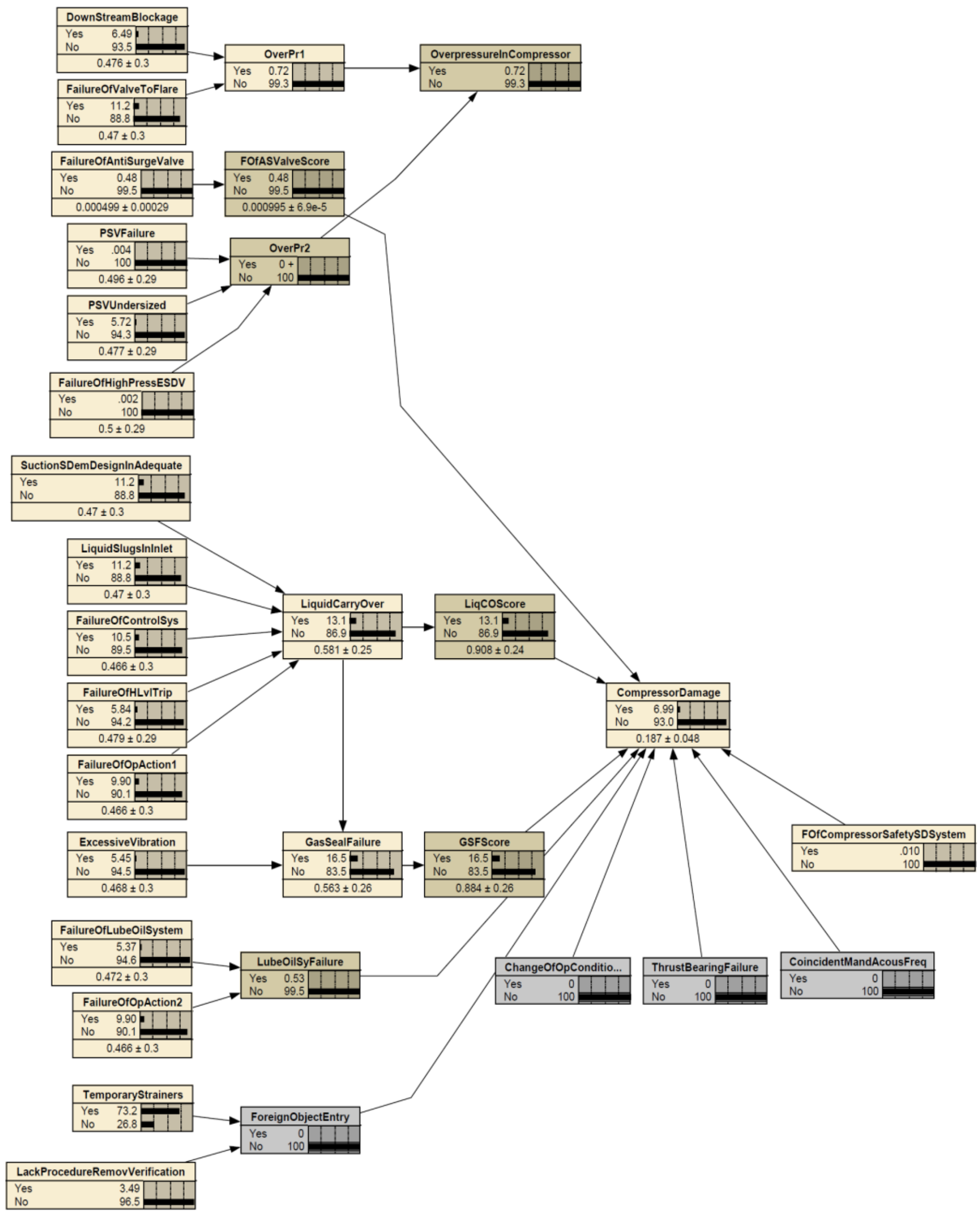


Figure 7.2 BN diagram for compressor damage

7.3 Findings from the BN for compressor damage

The BN in Figure 7.2 represents cause and effect relationships of the variables involved in the damage scenarios of a centrifugal compressor. Various predictive and diagnostics mode can be simulated on the BN. For the given set of probability values shown in Figure 7.2, the probability of compressor damage is calculated as 0.0699.

Now if we suspect that the suction scrubber and demister design is inadequate, the corresponding node 'SuctionSDemDesignInAdequate' can be made 100% and the probability of liquid carry over and compressor damage goes up to 22.3 and 10.2 from 13.1 to 6.99 respectively.

Inadequate design and presence of liquid slugs at the inlet will increase the probability of liquid carry over and compressor damage still higher to 38.2 and 15.8 which in relative scale (that is almost a 3 times increase in probability of liquid carry over and 2 times increase in compressor damage) which is not an acceptable situation. See Figure 7.3

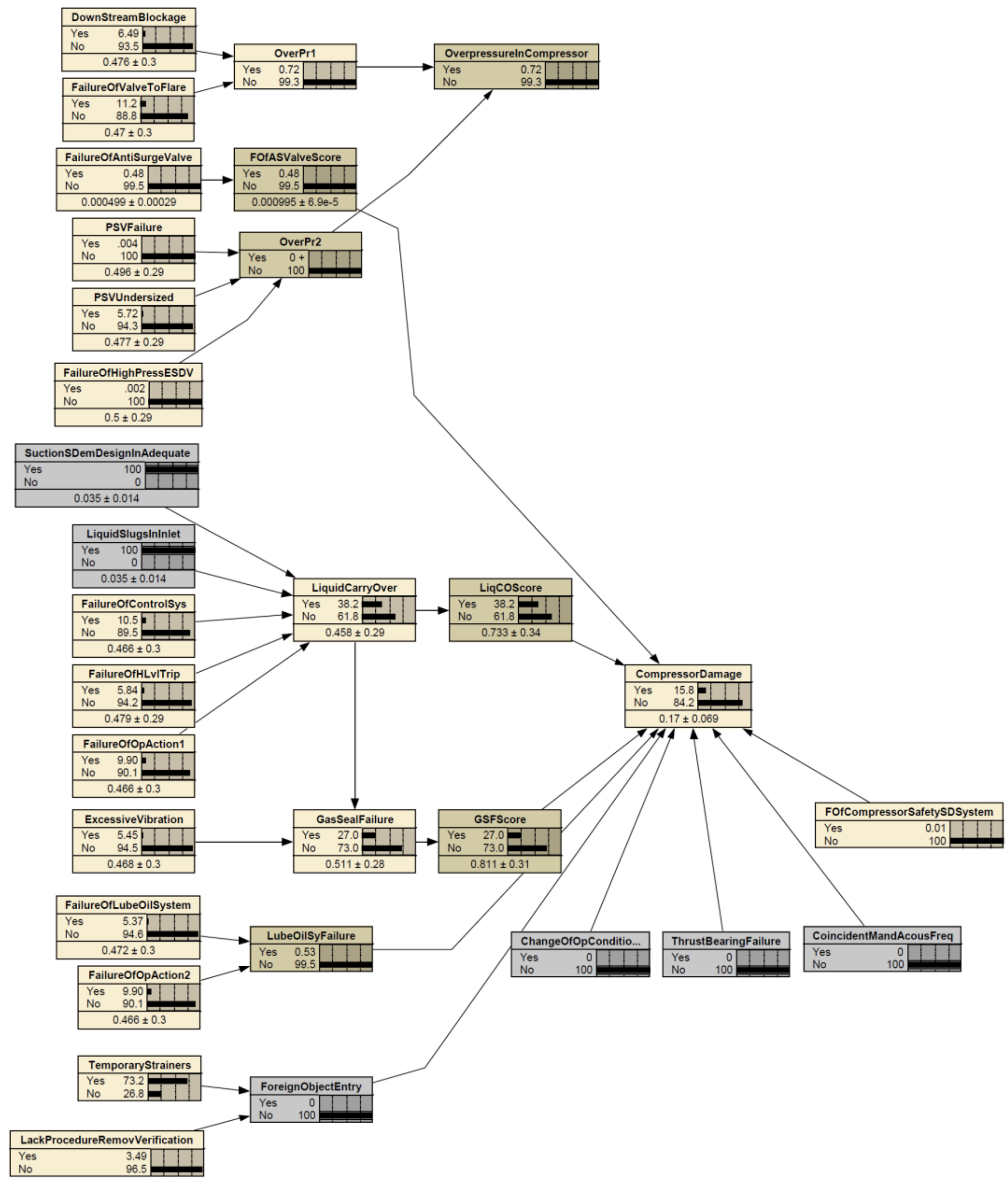


Figure 7.3 BN diagram for compressor damage- predictive mode: Suction scrubber design inadequate AND liquid slugs at inlet

The BN can be run on diagnostic mode. Given the prior probabilities, it is observed that there is liquid carry over and we want to know which is the most contributing factor is. The node “LiquidCarryOver’ is made 100%. BN computes the probabilities of the root causes backwards. This is shown in Figure 7.4. It is seen that the probability of failures of the parent nodes as well as other nodes have gone up.

The main contributors to the effect “LiquidCarryOver’’ as can be ascertained from the BN, in the decreasing order of probability are: ‘Failure of operator action’, ‘Liquid slugs at inlet’, ‘Failure of control system’, ‘Suction scrubber Demister design inadequate’ and ‘ Failure of High level trip’. Such diagnostic mode simulations are a valuable tool to understand the root causes of several abnormal situations in a process system.

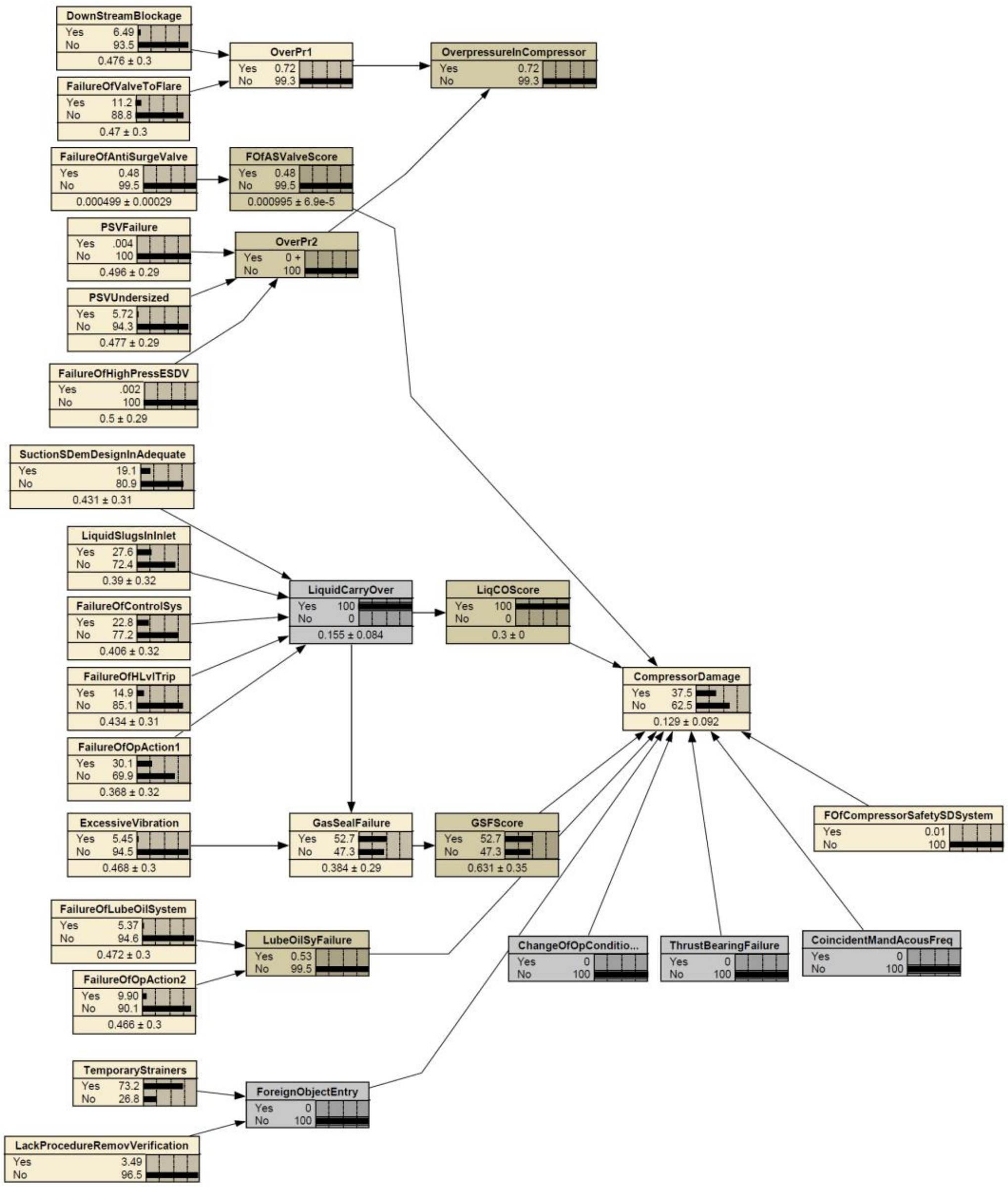


Figure 7.4 BN diagram for compressor damage: Diagnostic mode-change in probabilities of root causes when there is evidence of Liquid carry over

7.4 Sensitivity of Compressor damage node to parent nodes

To summarize the impact of parent nodes on the effect node 'CompressorDamage' a sensitivity analysis was performed. Results are shown in Figure 7.5. The analysis results indicates that failure of operator action followed by liquid slugs at the inlet have the greatest influence on the probability of Compressor damage.

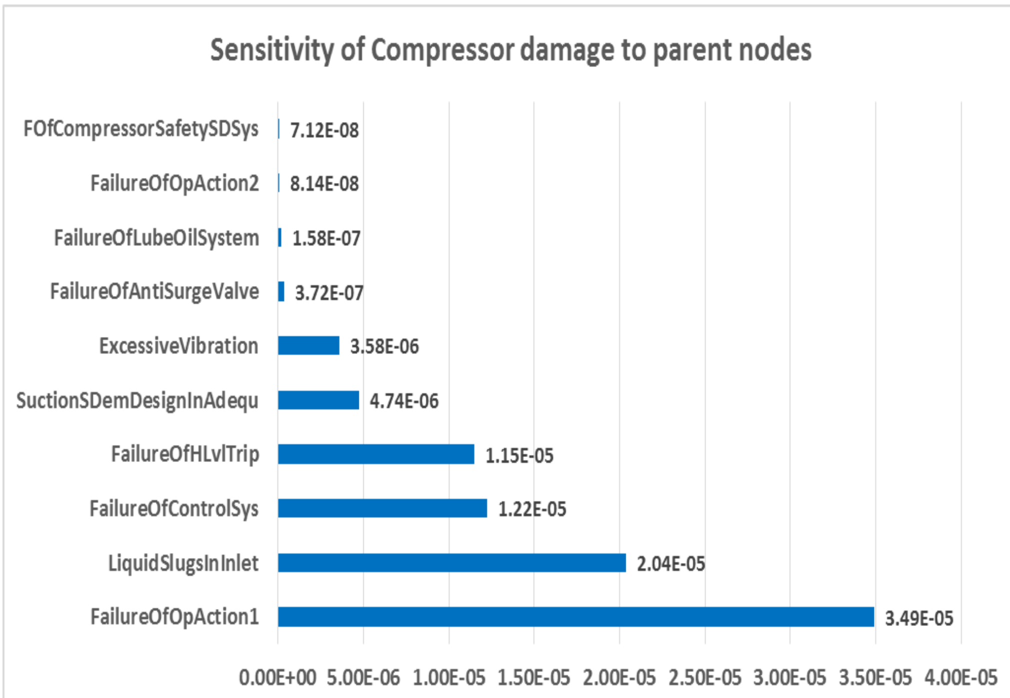


Figure 7.5 Sensitivity of causes in BN for compressor damage

7.5 Loss of containment and consequences

Loss of containment from compressor is usually taken as failure of associated piping and leak from the machine itself, which is very rare.

For average/high reactive gas release, the probability of immediate ignition is 0.2 for release rates below 10 kg/s, 0.5 for release rates between 10 and 100 kg/s and 0.7 for higher than 100 kg/s. Delayed ignition is supposed to occur if the flammable cloud meets an onsite ignition source or if it crosses the site boundary. TNO – VROM –Purple book, Table 4.5 [59]. The BN for LOC for compressor is given in Figure 7.6. A pin hole release rate is taken to illustrate the scenarios.

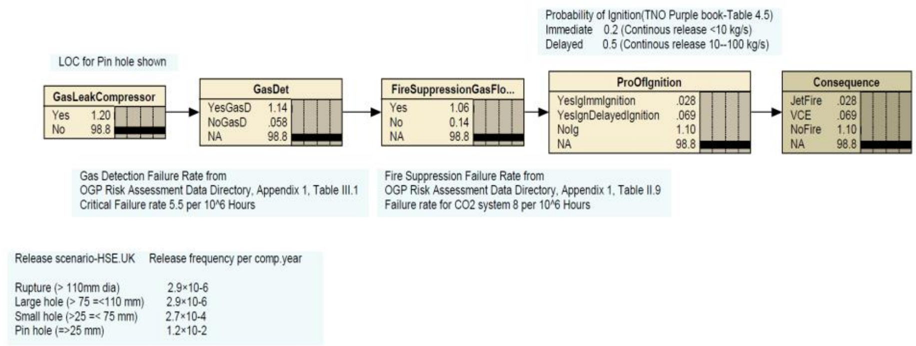


Figure 7.6 BN diagram for LOC from compressor

7.6 Chapter summary

BN for compressor damage is developed in this chapter. Main causes that result in major damages of the compressor have been ascertained from industry reports and expert opinion. Sub causes or root causes for these main causes are further listed. Their inter-relationships are given in the Table and converted to BN. Use of BN for predictive and diagnostic reasoning is described. Further 'Sensitivity of findings' from Netica indicates that presence of liquid slugs at the compressor inlet and failure of operator action constitutes the most possible cause for a major damage. Event Tree and its equivalent BN is also shown.

Comparison of QRA and BN is described in the following chapter.

8. Comparison between Quantitative Risk Assessment (QRA) and Bayesian Networks in analyzing risk

In order to compare conventional QRA and BN, results of both need to be known. BN results have been already presented and therefore QRA methodology need to be applied to a similar scenario to compare the results. A case study of Floating roof tank hazards is selected to conduct a typical industrial QRA study. To see the comparison with BN method for risk assessment, the BN earlier developed is populated with the data to see the failure frequency of LOC and post LOC scenarios.

8.1 Measuring risk: QRA method

Risk is defined as a function of hazard, hazard frequency and hazard consequences.

In QRA method measuring risk consists of the following steps. The method is described in detail in [6].

8.1.1 Failure or Loss Of Containment frequency estimation

i. Identifying accident scenarios. For major hazards it will be loss of containment. Usually a parts count of the subsystems that are isolatable is conducted and it is assumed that there are different types of leaks occurring in these items. A small leak of 10 mm diameter, leak of 20 mm, 50 mm and 150 mm diameters and a full rupture of equipment or pipe are usually considered. For tanks and vessels, catastrophic failure is included.

ii. Finalizing the frequency of the releases and catastrophic failures

8.1.2 Consequence analysis: this consists of two parts.

i. Calculation of the rate of releases through each of the leaks are computed. Source term models are used for the same.

ii. Computing consequences of the releases; that is either pool fire, jet fire, flash fire / vapor cloud explosion or toxic gas dispersion or a combination as applicable.

iii. Converting the consequences to impacts on humans (loss of life) and property (asset damage) using suitable data or probit equations.

8.1.3 Risk calculation:

Risk is presented generally as any of the following:

a. Location specific individual risk (LSIR): Location specific individual risk provides a measure of hazard associated with different geographic locations within a facility. The assumption is that each target location is permanently inhabited by a single individual. The calculated risks are given as risk contours.

b. Cumulative frequency Vs. Number of fatalities (F-N): F-N curve also called Societal risk is a plot of the cumulative frequency of events resulting in N or more fatalities against N. F will be a decreasing function of N.

Since the main objective here is a comparison with BN, the final risk calculation is limited to Location specific individual risk (LSIR), which will serve to illustrate the calculation methodology.

Main difference between traditional QRA and BN approach is in the first two steps that is; in scenario identification and failure frequency analysis. The third steps (consequence analysis) is common to both methods. Risk calculation has certain differences between the two methods. A detailed comparison is presented in Table 8.1.

Table 8.1 Comparison between traditional QRA and Bayesian Network methods				
Sl. No.	**Parameter**	**QRA**	**BN approach**	**Notes**
1	Scenario (Hazard) identification	Identified generally as loss of containment from leaks of various hole sizes in pipes and failures of vessel or tank.	BN can include LOC due to leaks from holes in piping, failures of vessels & tanks plus any other credible scenarios including failure of Human and Organizational Factors (HOF)	
2	Failure (LOC) frequencies	Usually taken from published sources (See Table 4.1). Site specific data is not available in most of the cases.	In the BN, initial failure frequencies are taken from published sources. These frequencies are updatable easily to include data and observations at site.	
3	Causal factors for hazard scenarios (LOC)	Once credible scenarios are finalized, causal factors are not considered for analysis.	Causal factors are considered including non-technical factors like Human and Organizational Factors (HOF). Cause & effect mechanisms are the most important aspects of BN. Intermediate causes as well as root causes can be modeled in BN.	Frequencies of occurrence of causal factors are included as fixed values or more realistically as probability functions in BN. For example NoisyOr distribution can describe the effect of many causes far better than a fixed number.
4	Failure (LOC) frequency update for a specific facility	Not usually available. The calculations will have to be repeated with another set-without much basis-which requires time and effort.	Because BN includes causal factors for intermediate causes and root causes, failure frequencies can be updated realistically based on the probability of occurrence of the causal factors.	The probabilities for root causes are combined in a probabilistic manner using Boolean logic or other suitable probability distribution.(see Section 6.4)
5	Common cause failures	Almost never considered	Can be considered easily based on the BN logic.	BN basically represents a Bow-Tie diagram, with left side Fault Tree diagram, and right side Event Tree diagram with the LOC

Table 8.1 Comparison between traditional QRA and Bayesian Network methods

Sl. No.	**Parameter**	**QRA**	**BN approach**	**Notes**
				event in the middle. Therefore examining the same for Common causes failures is easy.
6	Expert opinion	Not usually included	Can be suitably included.	Expert opinion can be included using suitable parameters.
7	Safety barriers	Not included explicitly. Credit for the safety barriers is taken in the form of factors to modify the failure frequencies in a deterministic manner.	Modeled explicitly. Barrier failures and its frequencies are part of the Fault & Event Tree mapped in to BN. Causes of barrier failures can be included. Please see [31]	Deterioration of safety barriers (which is usually the cause for escalation of minor accidents) can be reflected in BN by using appropriate equations.
8	Modifications in a facility and its impact	Addition of an equipment or system is usual during operational phase & could affect the risk profile, but this will require revising the QRA. Almost never done in practice.	Changes to an equipment or system can be included in BN and its effect can be analyzed.	For example adding a reliable Gas detection system will provide a safety barrier , which can be easily added in BN.
9	Including other hazard scenarios	When QRA is done for a total facility, generally other scenarios that have hazard potential like Lightning strike or overfill (in the case of tanks) are generally not considered unless specifically identified during hazard identification. (Generally only hazards thought to be	BNs can be developed for such specific cases with all relevant cause and effect mechanisms that can provide a quick and easy assessment of a risk situation. This is possible because BN can analyze all effects and its causes in visually clear manner.	

Table 8.1 Comparison between traditional QRA and Bayesian Network methods

Sl. No.	Parameter	QRA	BN approach	Notes
		having highest possibility are analyzed).		
10	Finding the most likely causes for an event	Not possible within the QRA framework	BN is a model of all cause and effect relationships with probability values. Therefore it can be run in diagnostic mode to see which nodes (parents) are the highest contributors to an event node (child) that is selected in the BN.	Diagnostic mode is a powerful tool to visualize which is having the largest influence in a causing an accident.
11	Transparency of the model	Not very transparent. Specialist assumptions are not always stated.	The model is transparent, visually appealing and the cause and effect mechanism is easily understandable. Experts knowledge can be captured and placed in the model	People who has knowledge about the system can quickly appreciate and learn the model's cause and effect relationship and fine-tune it to represent the real situation.
12	Application area	Most of QRAs in the industry are oriented to spatial aspects of risk assessment that is, for Land Use Planning or for specifying safe spacing criteria.	BN can be used for the same and also for understanding specific risks as noted above.	If the BN for a system is fine-tuned and kept up to date, it can be used for understanding the risk profile of a system at any time.
13	Consistency of result	Wide variations are possible from different analysts for the same system. Example is the ASSURANCE project [64].	Since the model is transparent and all assumption are known, variations are minimum from different analysts.	
14	Use during operational phase of a facility	QRAs done during design stage are usually not available during operational phase of a facility.	BN model is a live model that can take data on near misses or accident precursors during the operational life of a plant	Risk profile changes during operational period of a facility due to various reasons. To reflect

Table 8.1 Comparison between traditional QRA and Bayesian Network methods				
Sl. No.	**Parameter**	**QRA**	**BN approach**	**Notes**
				this is very difficult in QRA but possible in BN.
15	Sensitivities	Sensitivity of the results to failure frequency, ignition probability, spillage area, population distribution and vulnerability criteria can be investigated in QRA in a deterministic manner by redoing the calculation with lower and upper bound values for the selected failure frequencies. But the basis for such values are questionable.	In addition to the sensitivities calculations (possible under QRA), BN can compute realistically with sound technical basis, the sensitivity of all causal factor nodes (parent nodes) to an effect node (child node) very easily.	Such analysis enables priorities to be assigned mitigating specific causal factors and in maintenance and testing of safety barriers.

8.2 Case study: QRA of a typical Floating Roof tank hazards

The Floating roof tank parameters in this case study are modeled similar to the IOC Jaipur Gasoline tank that leaked and caused a major accident. However, it must be recognized that there are limitations in predicting such disasters. Another point to note is that QRA case study described in the following section is a typical analysis used in the industry. It does not have any bias arising from the knowledge about IOC Tank farm fire. (No hindsight bias).

8.2.1 Case study: Typical Quantitative Risk Assessment (QRA) for a Floating Roof Tank

Example of QRA

Following sections summarize a typical QRA study done during design and installation of hydrocarbon storage tank.

As noted under section 8.1 QRA consists of two parts, failure frequency assessment and consequence modelling. Of the above, consequence assessment is common to the conventional method of QRA and Bayesian approach. Therefore the failure frequency calculation in a typical industrial QRA is presented first in the following sections to highlight the variance with Bayesian approach. A typical atmospheric storage tank storing Motor gasoline have been chosen for QRA. Table 8.2 gives a brief description of the parameters of the QRA study-.

Part 1: Failure frequency assessment

Failure frequency assessment of the components/parts identified during the hazard identification phase

Equipment under consideration: Hydrocarbon storage tank (Floating roof) containing petroleum product Motor Spirit (MS or gasoline), its bund wall and associated piping inside the bund wall.

Table 8.2 Parameters of the Floating Roof tank storing Motor Spirit (MS)		
Sl. No.	Parameter	Description
1	Size & capacity of tank	Diameter 24 M, Height 15 M, working capacity 6110 m3.
2	Site location	Assumed to be sufficiently away from populated areas as per original design. Only building in the vicinity; within 1 km radius is the Tank Farm operations control room
3	Tank safety features	High-high level: Automatic closure of MOVs at inlet and outlet Low-low level: Trips connected pumps to avoid pump damage.
4	Tank operations	By operation of a tank isolation system consisting of two Motor operated valves (MOV), first valve near to the tank nozzle (MOV: gate valve) followed by the second MOV) with a bleed valve in between MOVs has local and remote (from control room) operations facility. (3 push buttons: open, pause and close) as well as a hand wheel for manual operation. MOV to close in case of power failure. Tank level was ascertained by manual tank dip reading. (Similar to the tank at IOC Jaipur tank operations before the accident). Tank is assumed to contain the product at all times
5	Drainage system	Any leaks from valves, flanges, instruments, drain points as well as rain water will be channeled to a pit located within the bund wall area. The liquids from this pit can be diverted to oily water system or to storm water drain through valves provided outside the bund wall. These valves are normally closed.
6	Fire protection system	Typical fire protection system assumed consisting of 2 fire water tanks, 3 fire water main pumps (diesel operated) two jockey pumps (diesel operated), foam system and spray rings around the tanks for cooling purpose. Fire water system will provide protection for 4 hours as stipulated by Indian standards (Oil India Safety Directorate-OISD)
7	Manpower for operations (typical)	3 shifts: 1 officer plus 3 operators per shift –No dedicated operator in control room (similar to IOC Jaipur before the accident). General (day time) shift had more operating staff including officers and operators totaling approximately 20.

a. Hazard scenarios with respect to the tank are listed below:

Isolatable parts of the tank system are the tank, its associated pipework and bund wall. Therefore the following major hazards have been identified since the analysis is concerned only with major hazards. Table 8.3 lists the hazard scenarios identified.

Table 8.3 Hazard scenarios identified for the tank

Scenario	Causes
Loss of containment	Overfilling of product leading to settlement of the roof at the top, spillage due to insufficient number of tank valves opening / more opening / malfunction of the control system / wrong line up.
	Overflow due to reverse flow from other connected tanks
	Leakage of tank shell due to corrosion or external impact
	Leakage of associated piping due to corrosion or external impact
	Failure of Motor operated valves
Release of vapors	Fast lowering of roof during operations
	Tank roof collapse due to high rate of out flow
Tank top fire	Lightning
	Fire due to leakage from appurtenances including foam injection pipe
	Failure of tank shell cooling system of the tank, in case of fire in adjacent tank leading to overheating and fire.
Boil over	Possible if there is water layer at the bottom of the tank during a prolonged tank fire

Notes:

Of the above scenarios, the following were taken up for QRA study in line with typical industrial QRAs.

1. LOC from piping; studied by assessing the leaks of
   i. 10 mm leak diameter (piping)
   ii. 20 mm leak diameter (piping)
   iii. 50 mm leak diameter (piping)
   iv. Full bore rupture: taken as 100 mm

LOC from piping leaks may lead to pool fire due to immediate or delayed ignition of the hydrocarbon vapors.

2. LOC from tank shell considering 20, 50, 100 mm holes: LOC from these leaks could lead to pool fire due to immediate or delayed ignition of the hydrocarbon vapors.
3. Full surface tank top fire
4. Overflow frequency is considered, but found to be of low probability when compared to other failure frequencies and therefore not taken up for consequence modelling.

LOC events for valve leakage will be subsumed in the events considered for leak from piping.

Boil over is a rare phenomenon and depends on many factors and is not usually considered in a typical QRA.

b. Event trees for hazard scenarios

Typical event tree for a 50 mm piping leak is given below in Figure 8.1. Similar event trees have been developed for 10mm, 20 mm leaks and 100 mm (full bore failure).

Description: 50 mm leak on associated piping

Initaiting event	Immediate ignition	Delayed ignition	Conseqences	Frequency/yr
	yes		jet fire & pool fire	4.00E-02
1.40x10-6	4.00E-02			
	no	yes	flash fire & pool fire	2.72x10-7
	9.60E-01	2.0x10-1		
		no	no ignition	1.09x10-6
		8.0x10-1		

Hazard scenario	**LOC due to a 50 mm leak from tank shell or associated pipework**	
Failure	**50 mm leak**	
Releae rate. Kg/s	**13**	1.78E-02 m3/s
Ignition probbaility	**4.00E-02**	

Figure. 8.1. Event tree for 50 mm leak in process piping

c. Failure frequencies and their sources

c.1 Leaks from pipes

Summary of the initiating event probabilities and consequence probabilities are given in Table 8.4. The overall initiating event frequencies are taken from the E&P Forum [58]. The total frequency has been distributed to the representative hole sizes selected by considering information presented in Cox (Table 18.1, page 39 [76] and TNO [59].

Table 8.4 Hole size failure frequency for process piping leakage

Failure type	Initiating frequency	Jet & pool fire	Flash & pool fire	No ignition
10 mm leak	5.40×10^{-5}	5.40×10^{-7}	1.07×10^{-5}	4.36×10^{-5}
20 mm leak	7.20×10^{-5}	2.16×10^{-6}	6.98×10^{-5}	5.59×10^{-5}
50 mm leak	1.40×10^{-6}	4.20×10^{-8}	2.72×10^{-7}	1.09×10^{-6}
Full bore rupture	3.60×10^{-7}	1.08×10^{-8}	6.98×10^{-8}	2.80×10^{-7}

c.2 Leaks from storage tank

Frequencies for atmospheric storage tank leakage are given in Table 8.5. They have been taken from UK HSE Failure Rate and Event Data for use within Risk Assessments [60] and OGP Risk Assessment Data Directory, Storage incident Frequencies, Report N. 434-3 [68].

Table.8.5 Hole size failure frequency for Atmospheric Storage Tanks

Hole size mm	Failure rate per tank per year
20	2.1×10^{-3}
50	4.2×10^{-4}
100	2.8×10^{-4}
Rupture	5.0×10^{-6}

c.3 Full surface fire frequency for Floating roof tank is taken as: 1.2×10^{-4} per tank year - OGP Report 434-3 [68]. It is also observed that data from LASTFIRE is 3×10^{-5} per tank year [55]

Bund failure frequencies are given in Table 8.6. Data is from OGP Report 434-3 [68] and LASTFIRE project [55].

Table 8.6 Bund fire event frequency data	
Bund type	Frequency
Small bund fire	9×10^{-5} per tank per year
Large bund fire	6×10^{-5} per tank per year

c.3 Overfill frequency calculations (from confidential source)

$$f\ overfill$$
$$= f_{base}\ X\ MFQuality\ X\ MFLevel\ Gauging\ X\ MFAutoshut\ X\ MFAttend\ X\ No.\frac{fills}{yr}\ Eqn.(8.1)$$

f_{base} = Base frequency = 1×10^{-4} events per tank fill/year/tank

MFQuality = Adjustment for the quality of the facility’s overfill management systems

MFLevel Gauging = Adjustment for level gauging

MFAuto shut = Adjustment for automatic shut down

MF Attend = Adjustment for attendance at automatic tank fill operations

No. fills / yr = From LOPA studies and operational data

Table 8.7 & Table 8.8 show the adjustment factors used in the overfill frequency calculations.

Table 8.7 Adjustment for level gauging	
Type of level gauging	Modifying factor
Two stage independent level gauging	0.5
Instrumental level gauging	0.8
Ground level gauging	1

Table 8.8 Adjustment for automatic shutdown	
Shutdown system	Modifying factor
Automatic	0.1
Manual	1

Based on the above calculations the overfill frequency was estimated as 1.89×10^{-5}.

The most important assumption in the QRA is that ‘all equipment on the proposed site will be designed, built and operated to the required standards and will comply with all legislations”.

Part 2. **Consequence models**

As noted earlier, consequence modeling, its effect and risk calculations are common to both approaches. However for illustrating the calculation methodology and a full comparison of both conventional QRA and Bayesian approaches, summary of the full QRA is presented.

A. Fire due to leakage from holes in pipes

As depicted in Event tree in Figure 8.1, the major consequence of LOC from leaks in process piping within bund wall is a pool fire. Thermal radiation from such pool fires are modelled using the point source model given in the spreadsheet in CCPS, Guidelines for Chemical Process Quantitative Risk Assessment (CPQRA) [6]; an example calculation for a leak of 50 mm from a pipe is given in Table 8.9. Such calculations have been done for 10 mm, 20 mm and full bore failure taken as 100 mm.

Table.8.9 Example calculation for thermal radiation from pool fire at a distance of 100 m. Leak from 50 mm hole in pipe

Example 2.30: Radiation from a Burning Pool		
Input Data:		
Liquid leakage rate:	0.070484	m**3/s
Heat of combustion of liquid:	43700	kJ/kg
Heat of vaporization of liquid:	360	kJ/kg
Boiling point of liquid:	342	K
Ambient temperature:	310	K
Liquid density:	738	kg/m**3
Constant heat capacity of liquid:	2.5	kJ/kg-K
Dike diameter:	73.5	m
Receptor distance from pool:	100	m
Relative humidity:	25	%
Radiation efficiency for point source model:	0.35	
Calculated Results:		
Modified heat of vaporization:	440	kJ/kg
Vertical burning rate:	1.26E-04	m/s
Mass burning rate:	0.093087	kg/m**2-s
Maximum pool diameter:	26.67	m
Diameter used in calculation:	26.67375	m
Area of pool:	558.80	m**2
Flame H/D:	1.62	
Flame height:	43.12	m
Partial pressure of water vapor:	1578.29	Pa
Point Source Model:		
Point source height:	21.56	m
Distance to receptor:	128.50	m
View factor:	4.82E-06	m**(-2)
Transmissivity:	0.67	
Thermal flux at receptor:	2.58	kW/m**2

Plot of the radiation profile for leaks from 10 mm, 20 mm and 100 mm are given in Figure 8.2.

100 mm is for full bore failure. Radiation of 1.58 kw/m2 is the design value for thermal flux at which personnel can be continuously exposed.

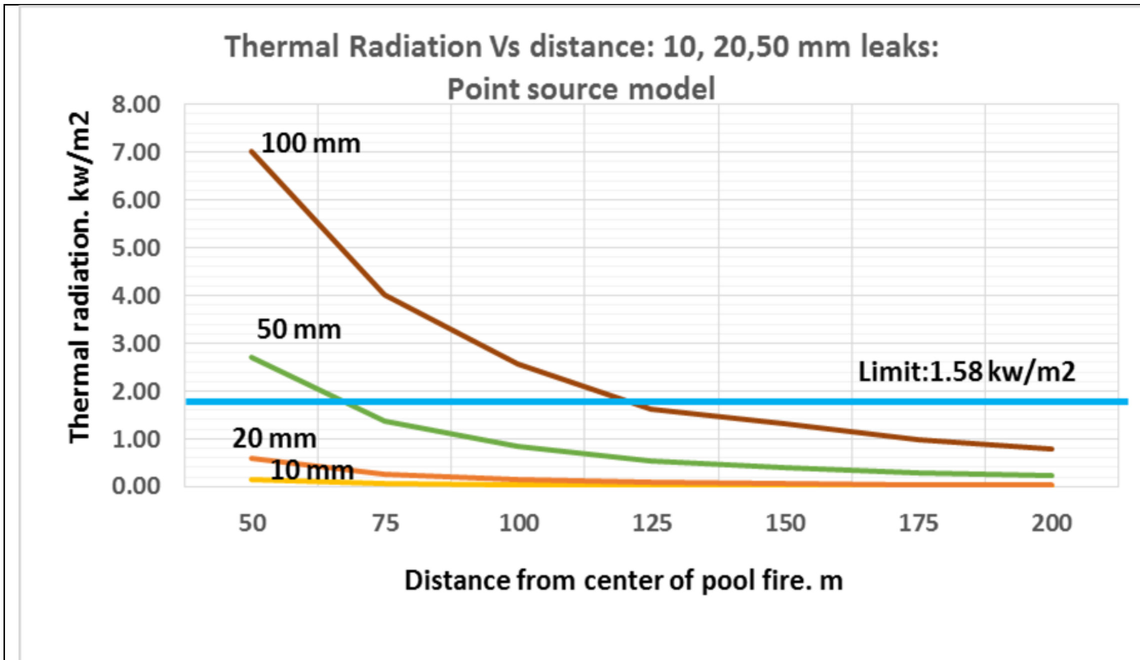


Figure 8.2.Thermal radiation Vs. Distance for pool fire: Leaks from 10, 20, 50 & 100 mm

B. Full surface tank fire

Full surface fire heat flux for MS tank is calculated by using the spreadsheet method (version 1805.0) provided freely in Internet by US Nuclear Regulatory Commission (NUREG) [77].
(www.nrc.gov/.../nuregs/.../05.1_Heat_Flux_Calculations_Wind_Free.xls**).**

Results of the same is plotted in the graph shown in Figure 8.3. Related data is given in Table 8.10.

Table 8.10 Thermal radiation from tank full surface fire

	Point source model	m	ft
	Tank diameter	24.00	78.72
	Tank Dike dimension	30.00	100.00
Distance between fire and target L	**Distance from center of fire to edge of target R**	**Thermal radiation**	
m	**m**	**kw/m2**	**Btu/ft2-sec**
50	61.98	7.88	0.69
75	86.97	4.00	0.35
100	111.97	2.41	0.21
125	136.96	1.61	0.14
150	161.96	1.15	0.10
175	186.95	0.87	0.08
200	211.94	0.67	0.06

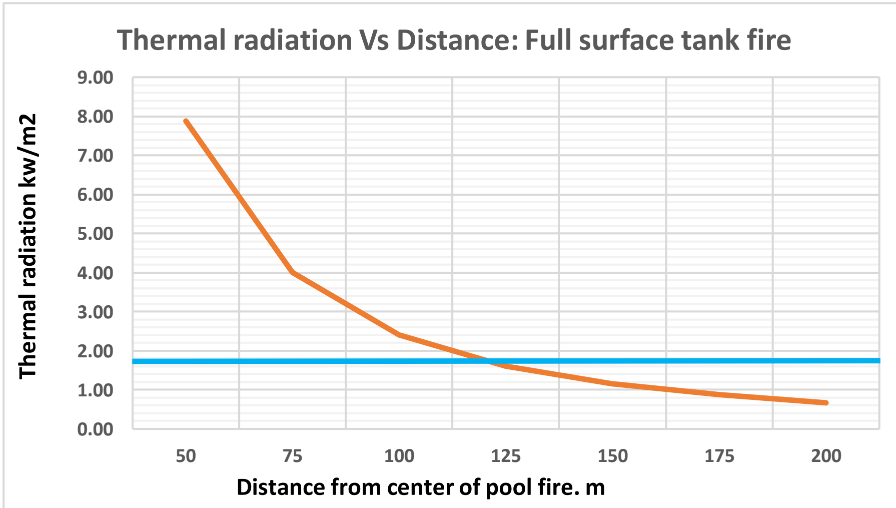


Figure 8.3 Thermal radiation from full surface tank fire

C. Thermal radiation effects.

C.1 Fire due leak from holes in pipes

Impact of radiation due to a fire inside the bund wall caused by leaks in pipes is found to be negligible because of limited duration assumed (within feasible and practical limits) for the leaks.

C.2 Full surface fire of tank

Total engulfment of personnel by a tank top fire is not a possibility and therefore excluded. Other effects depend strongly on the time exposed and protective clothes worn. Data in Table 8.11 below is from OGP Risk Assessment Data Directory Report No 434-14.1 March 2010, titled Vulnerability of Humans. [78].

Table 8.11 Effects of thermal radiation from OGP [52]

Thermal Radiation (kW/m^2)	Effect
35	Immediate fatality (100% lethality)
20	Incapacitation, leading to fatality unless rescue is effected quickly
12.5	Extreme pain within 20 s; movement to shelter is instinctive; fatality if escape is not possible. Outdoors/offshore: 70% lethality Indoors onshore: 30% lethality*
6	Impairment of escape routes
4	Impairment of TEMPSC embarkation areas

* People indoors are only vulnerable if they have line-of-sight exposure to thermal radiation, hence a lower lethality than for people outdoors.

From the above data it can be taken that from a distance of about 75 m from the center of the tank, the personnel with adequate protective clothing have to take cover within 20 secs. For continuous exposure with light clothing a minimum distance of 110 m is recommended. Fatalities are estimated to be very low.

D. Vapor cloud explosion (VCE)

D.1 Vapor cloud explosion blast pressure

Prolonged release of hydrocarbon liquid will lead to vaporization of gaseous components from the pool resulting in formation of a vapor cloud mass. Depending on the time duration and weather conditions this vapor cloud can be within the flammability limit. For Motor Spirit the flammability concentration limit is from 1.2% to 7.4% by volume with air. If the vapor within this limit finds an ignition source, a VCE will result. Generally industrial QRAs in the past did not consider VCE due to pool fire evaporation. But the events in Buncefield and IOC Jaipur indicates that such an event is possible. The calculations involved are complex and are outside the framework of objectives of the study. Therefore an order of magnitude calculation is presented for the consequences of a VCE blast and its overpressure scenarios.

i. TNT Equivalent calculations

The calculations are based on the spreadsheet method provided in CCPS Guidelines for CPQRA [6]. The method uses the TNT equivalent method similar to the method used in M. B Lal committee report on IOC Jaipur Tank farm accident [11].

The calculations assume a leak of Motor Spirit from 50 mm hole at the rate of 20.70 kg/s for a duration of 1200 secs (20 min). Properties of n-Hexane has been assumed. The spreadsheet is given in Table 8.12

Table 8.12 TNT equivalence calculations [6]

TNT Equivalent Calculation: CCPS -Guidelines for CPQRA: Examle 2.20						
Heat of combustion.Hexane		btu/lb	19246.00	W: Equivalent mass of TNT lb		
Assumed explosion efficieny η			0.05	η : empirical explosion efficiency		
Assumed EcTNT		btu/lb	2000.00	M : mass of hydrocarbon lb		
$W = \frac{\eta\, M\, Ec}{ETNT}$		Eq 2.2.1		Ec : Heat of combustion of flammable gas. btu/lb ETNT: heat of combustion of TNT~2000 . btu/lb		
Release rate: 50 mm leak	Time before blast	LOC quantity	Vaporized fraction	Vaporised Mass		TNT Equivalent
kg/s	s	kg		kg	lbs	kg
20.70	1200.00	24840.00	0.08	1987.20	4381.78	956.14

ii. Blast overpressure calculations

Blast overpressure from explosion is calculated using the equivalent TNT and is based on the spreadsheet given in CCPS, Guidelines for CPQRA. Example 2.20 [6]. The spreadsheet is given in Table 8.13.

Table 8.13. Calculation of blast pressure from TNT equivalent vapor mass

Example 2.20: TNT Equivalency of a Vapor Cloud				
Input Data:				
TNT Mass:		956	kg	
Distance from blast:		177	m	<– Trial & error distance to get overpressure
Calculated Results:				
Scaled distance, z:		17.9675	m/kg**(1/3)	
Overpressure Calculation:			(only valid for z > 0.0674 and z < 40)	
	a+b*log(z):		1.479625	
	Overpressure:		6.94	kPa
			1.006516	psig
Impulse Calculation:			(only valid for z > 0.0674 and z < 40)	
	a+b*log(z):		1.072434	
	Impulse:		17.60068	Pa s
Duration Calculation:			(only valid for z > 0.178 and z < 40)	
	a+b*log(z):		0.808651	
	Duration:		5.754677	ms
Arrival Time Calculation:			(only valid for z > 0.0674 and z < 40)	
	a+b*log(z):		1.52606	
	Arrival time:		44.026	ms

iii. Blast pressure effects

Blast overpressure damage levels are known. Typical damage levels and overpressure limits from M. B Lal Committee Report on IOC Jaipur accident investigation [11] is given below in Table 8.14.

Table 8.14. Blast overpressure and damage levels

Blast Overpressure (psi)	Damage level
5.0	Major structural damage; fatal to people indoors
3.0	Oil Storage tank failure
2.5	Ear drum rupture
2.0	Repairable damage: light structures collapse
1.0	Window Panes shatter: light injuries

The effect of blast overpressures on personnel are summarized in Table 8.15. The data is from HIPA4. [79]. (New South Wales Govt. Dept. of Planning, “Hazardous Industry Planning Advisory Paper No 4. Risk Criteria for Land Use Safety Planning, January 2011 (HIPA4)

Therefore the distances for each of the above blast pressure levels were calculated using the method given in spreadsheet Example 2.20 of CCPS [6] for the overpressures shown in Table 8.15. Typical calculation is given in Table 8.16. Summary of the results; that is, the distances at which the overpressures corresponding to personnel vulnerability, is given in Table 8.17.

Table 8.15. Blast pressure effects on personnel

The probability of fatality for individuals exposed to overpressure were defined for various levels of overpressure, as described below. The probabilities were based on guidance provided within HIPAP4.

Explosion Overpressure	Effect	Probability of Fatality (Outdoors)
7 kPa (1 psi)	Probability of injury is 10%. No fatality	0%
21 kPa (3 psi)	20% chance of fatality to a person in a building	0%
35 kPa (5 psi)	50% chance of fatality for a person in a building and 15 % chance of fatality for a person in the open	15%
70 kPa (10 psi)	100% chance of fatality for a person in a building or in the open	100%

References:

- New South Wales Government, Department of Planning, "Hazardous Industry Planning Advisory Paper No. 4, Risk Criteria for Land Use Safety Planning", January 2011 (HIPAP4).

Table 8.16. Overpressure calculation [6]

Example 2.20: TNT Equivalency of a Vapor Cloud				
Input Data:				
TNT Mass:		806	kg	
Distance from blast:		160	m	<-- Trial & error distance to get overpressure.
Calculated Results:				
Scaled distance, z:		17.1926	m/kg**(1/3)	
Overpressure Calculation:			(only valid for z > 0.0674 and z < 40)	
	a+b*log(z):		1.453772	
	Overpressure:		7.33	kPa
			1.063384	psig
Impulse Calculation:			(only valid for z > 0.0674 and z < 40)	
	a+b*log(z):		1.026351	
	Impulse:		18.36675	Pa s
Duration Calculation:			(only valid for z > 0.178 and z < 40)	
	a+b*log(z):		0.74234	
	Duration:		5.680077	ms
Arrival Time Calculation:			(only valid for z > 0.0674 and z < 40)	
	a+b*log(z):		1.49968	
	Arrival time:		41.807	ms

Table 8.17. Distances and overpressures for Vapor Cloud Explosion		
Distance from blast	**Overpressure**	
m	psig	Pa
56	5.0	34473.80
78	3.0	20684.28
88	2.5	17236.90
104	2.0	13789.52
177	1.0	6894.76

From Table 8.17, it is seen that an overpressure of 5 psig occurs at about 56m from the source and from Table 8.15, from last column ‘probability of fatality (outdoors)’ is 15%.

Part 3. Estimation of risk

For a typical Atmospheric Storage Tank containing Motor Spirit the following approach has been taken ascertain an order of magnitude estimation.

Individual Risk Per Annum (IRPA)

CCPS Guidelines for CPQRA [6] defines individual risk as “Individual risk contours show the geographical distribution of individual risk. The contours show the expected frequency of an event capable of causing the specified level of harm a specified location, regardless of whether or not anyone is present at that location to suffer harm. Thus, individual risk contour maps are generated by calculating the individual risk at every geographic location assuming that somebody will be present and the subject to the risk of 100% of the time (i.e. annual exposure of 8760 hours per year)”.

Calculation of Individual risk per annum

$$\text{IRx,y} = \sum_{i=1}^{n} IR\ x, y, i \qquad \text{Eqn. (8.2)}$$

Where

IRx,y = the total individual risk of fatality at a geographical location x, y (chances of fatality per year)

IRx,y,i = the total individual risk of fatality at a geographical location x, y from incident outcome case i (chances of fatality per year)

n= the total number of outcomes cases considered in the analysis

$$IR_{x,y,i} = f\,P_{f,i} \qquad \text{Eqn. (8.3)}$$

Where

f = frequency of incident outcome case i , from frequency analysis (per year)

Pf,i = Probability that an incident outcome case i, will result in a fatality at location x,y from consequence and effect models.

Simplified approach is taken for the study here and assumptions are listed in CCPS Guidelines for CPQRA [6]. Weather conditions are assumed to be stable.

A. Individual risk for thermal radiation.

Summary of the calculations based on the above and plots are given in this section

A.1 Harm to personnel on site

For a tank full surface fire, the thermal radiation at a distance of 75 m is 4 kw/m2, which is the safe distance where all personnel has to take cover within 20 secs. At this distance around the tank the Individual Risk Per Annum (IRPA) for harm to people is calculated as 1.2x10-04 which is obtained by multiplying ((1.2x10-04 -from Part 1 C3) by 1 (Probability of fatality) taking the probability of ignition as 1. Risk contour for the same is given in Figure 8.4.

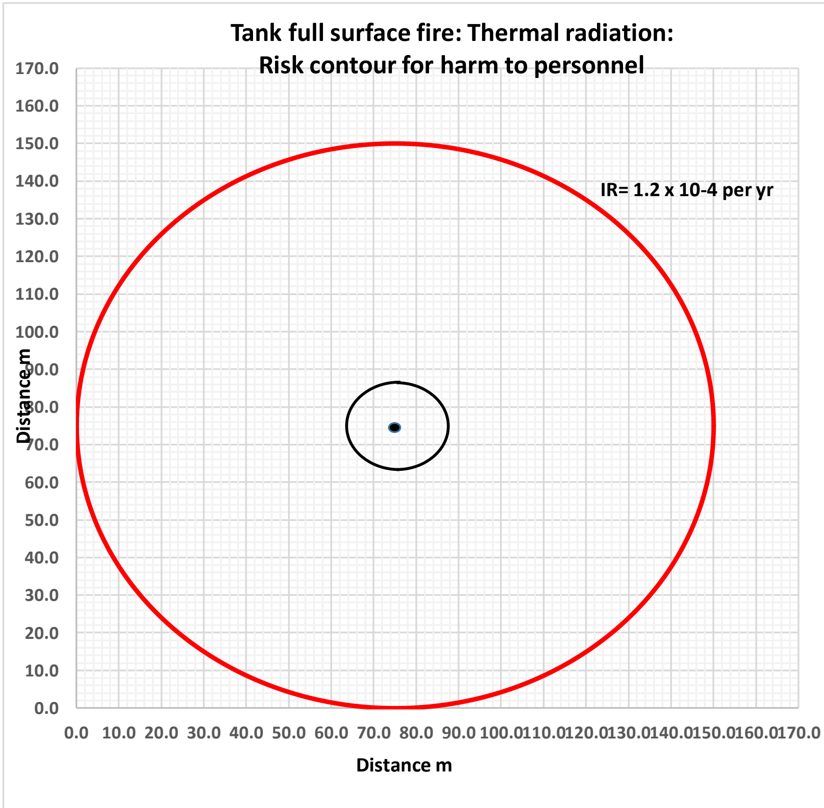


Figure 8.4 Tank full surface fire. Risk contour for harm to personnel

A.2 Safe distance for continuous exposure

Safe distance from a tank on full surface fire is calculated as 110 m, where personnel can be continuously exposed (less than a heat flux of 1.58 kw/m2). Probability of fatality is 10-4. Risk is calculated as 1.2 X 10-8 which when compared to general tolerable risk of 1 X10-6 is acceptable. Same is shown in Figure 8.5.

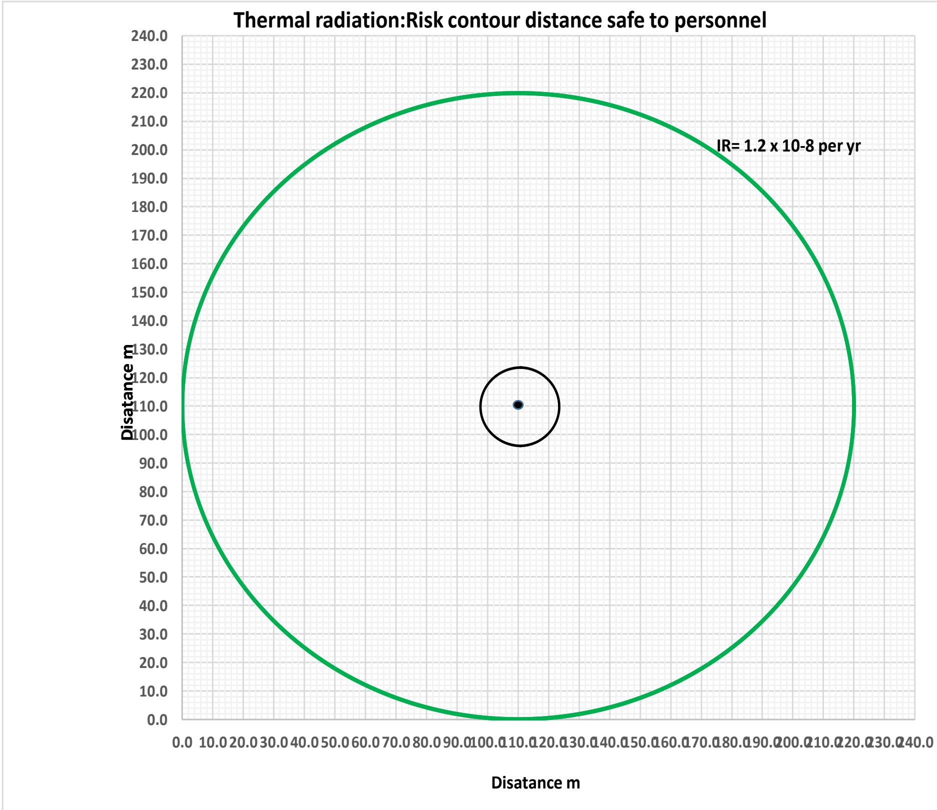


Figure 8.5 Tank full surface fire. Distance safe for personnel

B. Vapor Cloud Explosion (VCE)

For a vapor cloud explosion there is 15% probability of fatality at a distance of about 56 m (Table 9.16). The IRPA for VCE is calculated as 0.9 x 10-5 (6 x 10-5 (from Part 1-Table 9.6) x 0.15). Plot for the same is given in Figure 8.6.

Safe distance

From all of the above outcomes of distances it can be concluded that a minimum safe distance for personnel exposure on a normal basis should be beyond 110 m.

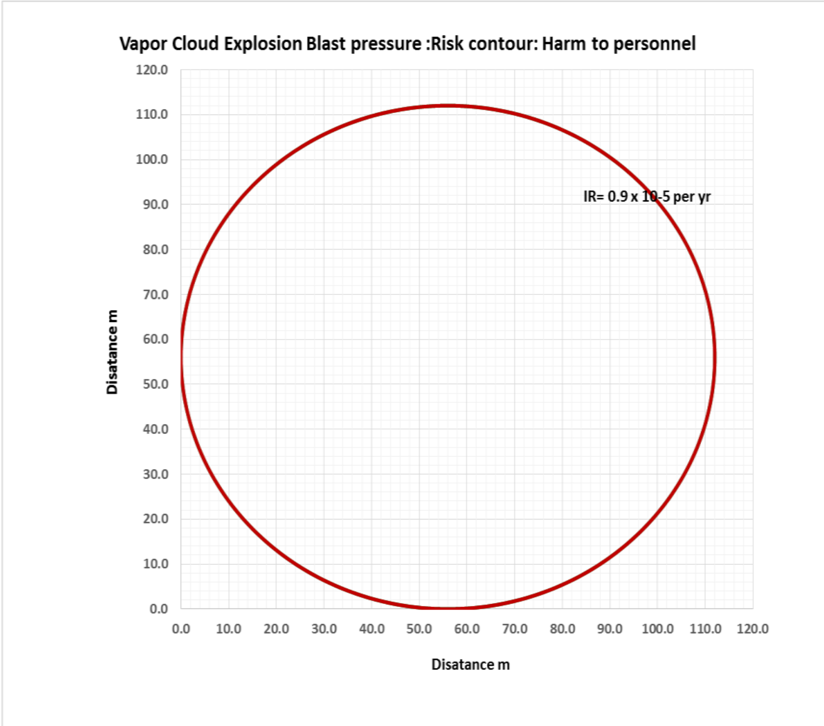


Figure 8.6 Vapor Cloud Explosion. Risk contour

8.3 Case study: Hazards of a Floating Roof tank using Bayesian Network

Following presents case study for hazards of a Floating Roof tank using BN. In the subsequent sections the risk profile of the tank at the pre-accident situation of IOC Jaipur fire is described. This is done to see the predictability of the model. Summary is given below:

The BN model for Floating roof tank described in section 6.2 contains the probability values in a normal 'Good" situation when the facility is assumed to be designed, constructed, operated and maintained with compliance to all codes and standards, complying mostly all the required systems and procedures, average quality of risk assessments and average score in quality of Human and Organizational Factors. The values for the node states in 'Good" state is reproduced below in 4th column in Table 8.18 below. The values are from BN Figures 6.3 to 6.10.

Next step involved revising the probability values of the parent nodes to have a predominantly 'Poor' state for the main causal factors. When the BN is simulated with these values a risk picture of what can be 'a worst case' emerges. The 5th column titled 'Poor' state values contain results from such values. It can be seen that for all the key causal factors, the state of 'Poor' is very high and consequently the probability of LOC is also very high.

To access the realistic situation at the facility, the last step is to revise the probability values of the parent nodes of the same BN model based on the pre-accident conditions similar to those existing at IOC Jaipur. The pre-accident conditions probabilities are assigned based on the Lal investigation committee report [11]. BN simulated with the site situation produced values of the key casual factors listed in the last column of the Table 8.18.

8.3.1 Summary of Investigation committee findings

IOC Fire Accident Investigation Report [11] notes the critical factors that resulted in the accident as:

i. Loss of primary containment of Motor Spirit (Petrol)

ii. Loss of secondary containment

iii. Incapacitated Operating Personnel

iv. Inadequate mitigation measures

v. Shortcomings in design and engineering specifications of facilities and equipment

vi. Absence of Operating Personnel from site and also from vital operational area

Root cause parameters in BN were changed based on the above findings. The values calculated by BN for these conditions (pre-accident situation) is given in Table 8.18 last column, which basically gives an idea about the risk situation existing in the facility during that time.

Table 8.18. BN values for Good & Poor and pre-accident conditions before the accident

	Node name	**Node states**	**'Good' state values. Probability % (From Figs 6.3 to 6.10)**	**'Poor' state values. Probability %**	**Values before accident. Probability %**
1	Quality of design	Poor	0.023	99.9	43.0
		Average	5.97	0.10	50.7
		Good	94.0	0.0	6.29

Table 8.18. BN values for Good & Poor and pre-accident conditions before the accident					
	Node name	**Node states**	**'Good' state values. Probability % (From Figs 6.3 to 6.10)**	**'Poor' state values. Probability %**	**Values before accident. Probability %**
2	Quality of Maint. & Inspection	Poor	0	99.9	99.7
		Average	0. 72	0.061	0.27
		Good	99.3	0.0	0.0
3	Quality of construction	Poor	0.043	99.9	45.2
		Average	8.0	0.56	35.7
		Good	92.0	0.0	19.1
4	Quality of equipment selection	Poor	0.064	99.9	81.6
		Average	7.79	0.082	17.8
		Good	92.2	0.0	0.6
5	Quality of risk assessments	Poor	21.3	70.5	92.6
		Average	35.5	24.2	7.40
		Good	43.2	5.34	0.044
6	Quality of Systems & procedures	Poor	39.1	100.0	100.0
		Average	46.2	0.044	0.044
		Good	14.7	0.0	0.0
7	Quality of organizational factors	Poor	98.9	99.8	99.8
		Average	1.06	0.16	0.16
		Good	0.0	0.0	0.0
	Failure Probability. Shell		**4.86 E-06**	**2.0 E-05**	**1.0 E-05**
	Failure probability Liquid side.		**1.80 E-06**	**3.2 E-03**	**2.9 E-03**

From the Table 8.18, it can be seen that the facility was operating very near to the 'Poor' state meaning that probability a LOC was very high when compared to normal state of such type of facilities.

8.3.2 BN for Event tree

It is interesting to see the BN simulated values for a post LOC on liquid side for a Floating Roof tank. The generic probability values from industry references have been used in the BN shown in Figure 8.7

Three cases have been simulated in BN and given in Figures 8.7, 8.8 and 8.9:

1. With probability of LOC values available from references namely 2.0 E-06.
2. With a confirmed LOC from pipe or shell, small pool, fire and failure of operator action.
3. With a confirmed LOC from pipe or shell, large pool, fire and failure of operator action.

The BN for post LOC (Figure 8.7) from pipe or shell shows that the probability of fire inside the bund is relatively quite small due to the safe guards preventing an escalation of a small fire. The probability values are from the LASTFIRE report [55].

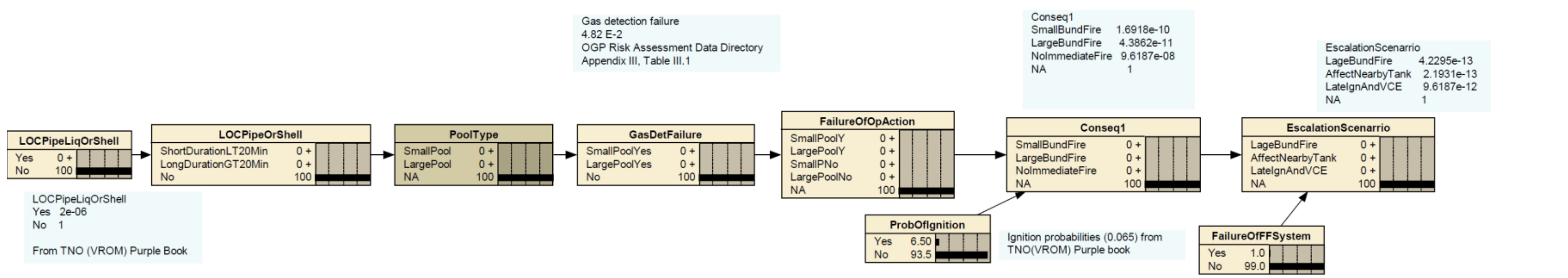


Figure 8.7 BN for Event tree for post LOC or liquid from pipe of shell side-FR tank

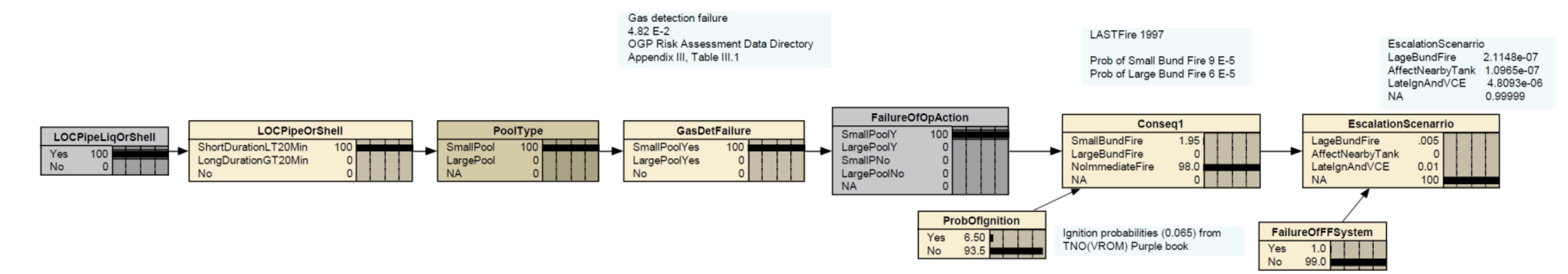


Figure 8.8 BN for Event tree for post LOC of liquid from pipe or shell side-FR tank with failure of Opertor action for small pool fire

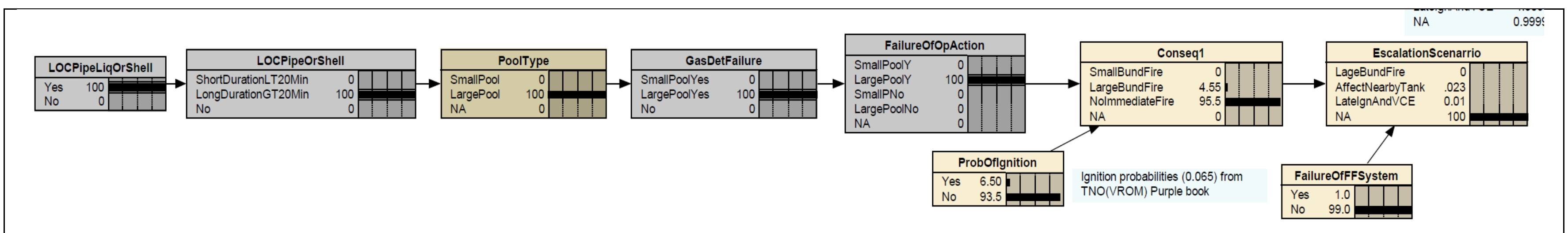


Figure 8.9 BN for Event tree for LOC of liquid from pipe of shell side-FR tank with failure of Operator action for Large pool fire

But when there is a confirmed LOC (100%) as shown in Figure 8.8 and no operator action on a small bund fire, the probability of fire escalating to large bund fire is very high. From a value of 2.11 E-07 it has jumped to 0.005%. See Figure 8.8 last node ‘EscalationScenario’.

Similarly when there is prolonged release liquid, a large pool is formed and if there is delayed ignition, this could result in massive evaporation of volatile compounds and Vapor cloud explosion. This is shown in Figure 8.9 last node ‘EscalationScenario’, which shows the probability of fire affecting nearby tank is 0.23% (AffectNearbyTank=0.023) and late ignition and VCE ‘LateIgAndVCE’ as 0.01%).
These predictions are not possible with traditional QRA methods.

8.3.3 Computing of risk values with BN

When the BN simulated with generic values for the failure frequencies as used in the QRA (Section 8.2), the Individual Risk Annum (IRPA) and risk contour will be the same as in QRA. However, when these values change based on site specific data and conditions, the BN calculates revised probabilities. When these are used the IRPA will change. The revised IRPA based on the updated situation is calculated as follows:

i. Full surface tank fire

Causal factors for a full surface tank fire are rim seal fire, fire from a spillage on the roof or heat impact from large bund fire in nearby tank-LASTFIRE report. [55]
If there is confirmed LOC for a longer duration greater than 20 minutes, in the Bund area, and failure of protective barriers of Gas detection and operator action to control a large pool within the Bund area, the probability of it affecting a nearby tank goes up from a negligible 1.0965 E-07 to 0.00023 (2.3 E-04). Please see Figure 8.9 last node.
Therefore the probability of full surface fire will be 2.3 E-04 instead of 1.2 E-04. This will result in an IRPA of 2.3 E-04. This is shown in Figure 8.10, which shows that the IRPA has gone up to nearly double than earlier predicted by QRA at 75 m from the tank.
This represents a higher risk to personnel than the earlier value of 1.2 E-04.

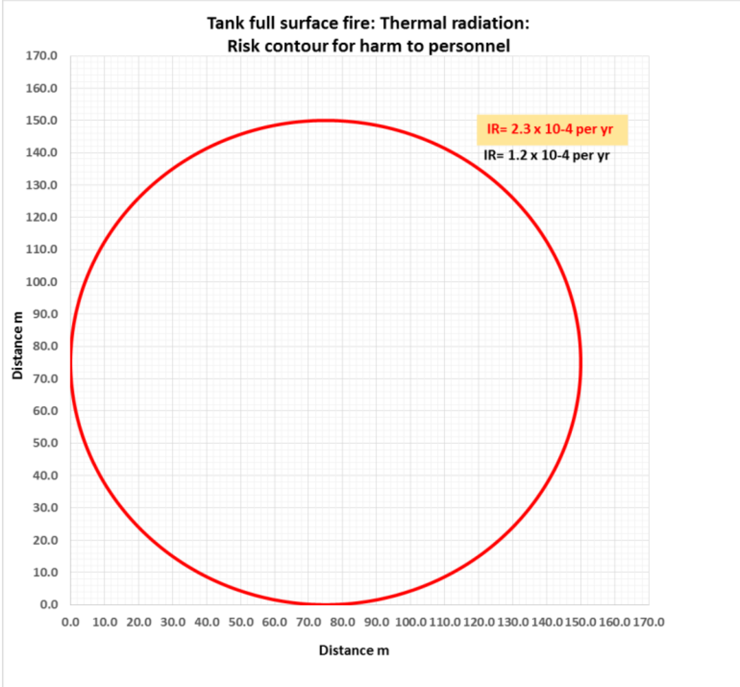


Figure 8.10 Tank full surface fire. Higher risk level to personnel at 75 m

8.3.4 What happened at IOC Jaipur Tank Farm: Predictability of BN

Without going in to details, in a very concise summary, what happened at IOC Jaipur tank farm was a prolonged loss of containment of Gasoline without any control action to mitigate it, for a time longer than normally expected-about more than an hour. The secondary containment failed, as well as the firefighting system. In fact the Gasoline spread through storm water drains also. So even if operator wanted to do something, nothing was possible. All that could have been done was to pump and spread foam on to top of this massive pool from a foam truck (if available). But the vapor cloud had already started forming.

Meanwhile about 700,000 to 800,000 kg of Gasoline spread as a massive pool. It did not catch fire immediately. A vapor cloud progressively formed from evaporation of the pool and reached about 8800 to 10,000 kg (estimated) when it found an ignition source that resulted in an unconfined vapor cloud explosion (UVCE) [11].

As can be seen, these event sequences cannot be predicted or modeled beforehand (a priori). However 'What if' scenarios with BN can provide some insight into possible accident paths. For example if we simulate the post release BN equivalent for ET, with the LOC =100%, Long duration of release greater than 20 mins, large pool =100, failure of operator action = 100% and failure of firefighting system=100%, it is seen that the probability of a Vapor Cloud Explosion (VCE) has gone from the normal average of 9.62 E-12 (From Figure 8.10) to 0.01, which is an indication that the risk of VCE is very high. This is shown in Figure 8.11.

Such type of analysis is very difficult in traditional QRA.

Several industrial QRAs available to the researcher as wells as from the internet has been examined, but none them have described the scenarios that are possible with a well modelled BN, as noted above.

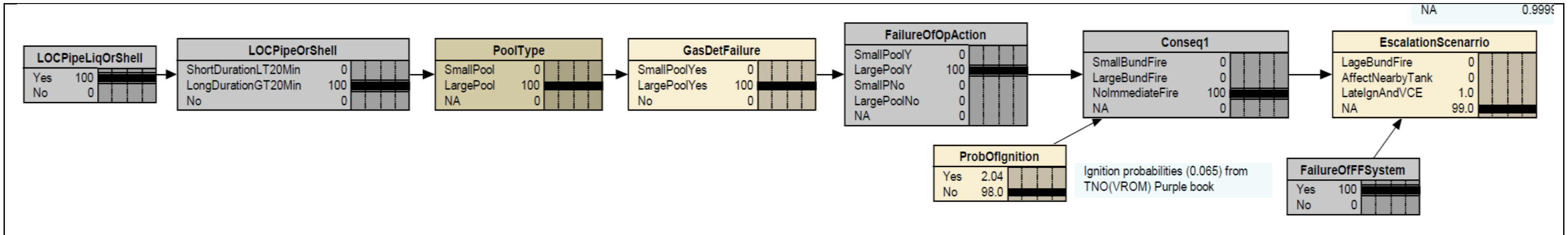


Figure 8.11. BN for Event tree for LOC and probbaility of VCE at IOC Jaipur tank farm

8.4 Limitations and gaps of QRA

As can be seen from the example, for QRA the failure frequencies are directly taken from published sources. There are also variations in data from different sources (See Part 1, c.3). Further, the available data does not clearly indicate presence of safety barriers and if at all, details of the same. This is a serious drawback of the data. Entire QRA is built up on these data and a revision of the same at later date during the operation of the plant will require considerable effort. In most cases, it is not done. In the course of time of the facility operations, the data itself will become outdated and thus the findings of QRA itself will be questionable.

Whereas, BN goes into a deeper analysis of factors affecting the failure frequencies, for example in the case of the storage tank model, a total of 9 main causal factors and 65 sub factors have been considered to arrive at the loss of containment failure frequencies. This includes historical data and expert opinions which can sometimes provide more insights. All of them can be revised as and when new data comes in.

When fire scenarios are considered, the BN for the equivalent event trees include the safety barriers and its failure frequencies that invariable change during the operating life of the facility. Influencing factors for such deterioration can be identified in a BN. QRAs basically do not attempt to explore the causal mechanisms for LOCs in detail and its relative importance in causing the LOCs.

8.4.1 Several authors have highlighted the limitations of QRA. They are summarized below:

- Uncertainties in identifying hazards, lack of precision of consequence models, uncertainties in data for frequencies, difficulties in identifying common cause failures- M. Tweeddale [80]
- Static, difficulties in capturing dependencies, variations and facility changes- Khakzad et al [32]
- Requires considerable specialist efforts, large variability in answers- H. Pasman et al [8]

- Software is costly, calculations are not quite transparent, limits in flexibility- H. Pasman et al [7]
- Data and methodology of QRA needs to be highly consistent with in a company to yield good results

8.4.2 Main gaps of the method are summarized below

- It starts with failure scenario. As can be seen from the example the failure frequency is based on past history. And historical frequencies can vary depending on the location. Causal mechanism are not explored
- If a scenario is missed the QRA process will not be able to analyze the same
- Failure frequencies are seldom available on site-specific basis for a new project and therefore generic published data is used. There is a high uncertainty associated with these data and so a variation of order of magnitude of 2 to 10 is expected in the final risk numbers as noted from the outcome of the ASSURANCE project [29].
- The method does not incorporate the safety barriers in place to prevent accident progression and potential for its failures. Effect of mitigation measures cannot be linked with risk reduction. See Figure 8.12 for typical layers of protection in a process pant
- Updating of a QRA study is time consuming. Additional information from the facility cannot be made use of.
- Assumptions are sometimes not transparent

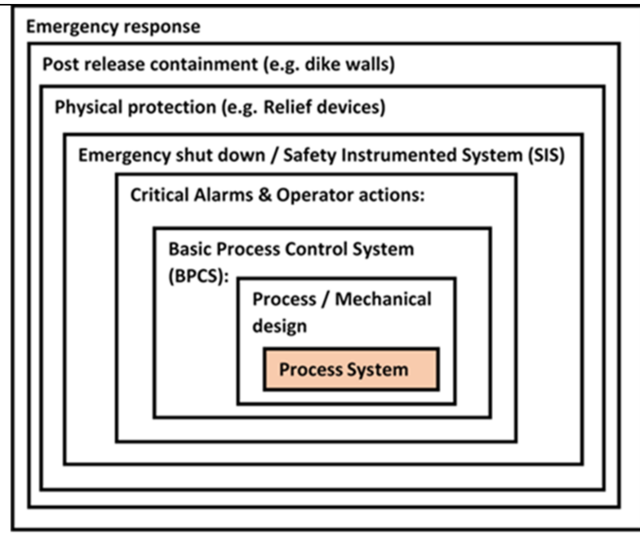


Figure 8.12 Typical layers of protection for a process system

8.5 Advantages of Bayesian Networks (BN)

Researchers' are applying BN techniques in diverse areas and have identified the main advantages of BN [1] [7] [8] [9] [30] [35] [37] [41] [42]. The growing interest in BN have also resulted in publication of a popular science book [81]. The main advantages of BN are summarized below:

- BN can represent causality of an event like LOC for a selected equipment in a visually easily understandable manner. Personnel in design, operations, maintenance and inspection can provide the necessary inputs to make BN comprehensive. Further, it can be updated as more information becomes available to reflect the current risk status. Failure frequencies assigned based on generic data can be updated during operational phase of the facility. This will in turn impact the effects and the risk profile. Thus BN allow risks to be monitored on a regular basis which is difficult in QRA.
- Bayesian approach not only provides quantifiable & auditable risk assessment, it also enables integration of multiple forms of data. It can perform powerful What if analysis to test sensitivity & conclusions.

- Bayesian Networks have proven to be an effective tool in diverse areas. It promises a reliable framework for system safety analysis and risk assessment.
- Bayesian Networks have great potential in scenario generation / description and analyzing risks taking in to account uncertainty and support decision making.

8.6 Chapter summary

The chapter first presents a table comparing QRA and BN considering 15 parameters. Then a full conventional QRA study for a Floating roof tank is described. The facility is similar to the tank at IOC Jaipur fuel terminal. Event frequencies are taken from available data. Distances from pool fire thermal radiation and effect of blast pressure from Vapor Cloud Explosion are calculated and the risk measure Individual risk per annum (IRPA) is computed.

The BN network for hazards of a Floating roof tank are taken from Chapter 7. The limits of probability of LOC are ascertained by simulating this BN with ‘Good’ and ‘Poor’ state values for the causal factor nodes. Then the node state values that best describes the existing situation at the facility are input to the BN to see the probability values for LOC. It is seen that the facility is operating near to high risk ‘Poor’ state.

BNs equivalent to Event Trees for post LOC scenarios are developed for 3 cases.

1. With probability values from published data
2. With confirmed LOC for small fire and failure of operator action
3. With confirmed LOC and large bund fires with failure of operator action.

The above illustrate the importance of detection mechanism and timely operator action to prevent a large scale disaster, which is not possible in QRA. Based on the above comparison, the limitations of QRA and the advantages of BN are highlighted.

9. Summary and conclusion

Though QRA is a well established method and limitations of the same are known and recognized by the practitioners, it is doubtful whether the decision makers in the industry are aware of the same. Therefore decisions are often made based on the outcome of QRAs. This could prove to be wrong. The ASSURANCE project [29] outcome is an example of how different consultant teams' assessment of risks for the same facility were widely different. Decisions have to be risk informed and not risk based. It is emphasized that there is nothing like absolute risk. Risks are only comparative and must be treated as such. In the course of search for better alternative methods, Bayesian methods have emerged as promising technique.

This research have the following main outcomes:

i. Comprehensive list of the causes and effects for loss of containment of critical equipments in oil and gas facility along with the relationships; depicted in an easily understandable form. The causes and relationships are based on the latest knowledge available about the failure modes of the equipment as well as opinion of experts in the area.
ii. Bayesian models for the loss of containment of the selected equipments: As noted in i. above, the models are based on latest knowledge and on sound mathematical basis. All assumptions are transparent. The models can be run in predictive or diagnostic mode to see the various scenarios.
iii. Diagnostic mode is a valuable tool for root cause analysis as well as for verifying the most probable cause for any effect in a BN, that can be simulated.
iv. An appreciation of the power and flexibility of the Bayesian models: As shown in the simulation with generic as well as case studies, the models are modifiable to suit site specific conditions. Data requirement is moderate. The models enable risk profile of the facility to be updated and maintained on a continuous basis.

v. Recognition of situations when mitigation action is required: the sensitivity analyzes feature of Bayesian models enables immediate recognition of the factors that are major contributors to the loss of containment. The case studies have shown that the prevailing conditions before the accidents at IOC Jaipur and GAIL pipeline at Andhra Pradesh were not normal situations. In both cases, the probability of accidents were predicted as high.

vi. A comprehensive comparison of QRA and BN is presented for the decision makers to appreciate the scope and deliverables of both techniques.

vii. Operating personnel can quickly understand and fine tune the BN to suit the site specific conditions, since the cause effect relationships presented are visually appealing.

10. Main contribution from the research

10.1 Main contributions from the research work is noted below:

i. Detailed causal mechanisms have been developed for LOC of oil and gas separator, hydrocarbon pipeline, hydrocarbon storage tanks Floating roof and Cone roof, and compressor after extensive review of industry HAZOP, LOPA & SIL analysis reports as well as available publications and accident investigation reports. Corresponding Bayesian Networks have been developed and parametrized with generic published data. Predictive and diagnostic modes of BN simulation have been described to illustrate the flexibility of the BN. Sensitivity to finding feature is depicted which can give support for prioritizing mitigation actions.

ii. The causal models include influence of safety barriers and expert opinion, which is not available in QRAs.

iii. The BN models developed are easily customizable for site specific situations and can provide valuable insight into the nature of risk of the facility.

iv. Application of the BN will make it possible, for maintaining the facility risk profile up to date in a visually understandable manner and action be taken on the factors that prominently contribute to the failure mechanism. Prioritizing of mitigation actions can have a sound basis.

v. The model will be flexible and will allow faster and easier visualization of 'What if' scenarios in complex systems

vi. Two case studies with site specific data existing before the accident are given. They demonstrate that careful review of the status of the causal factors would have prevented the large scale disasters. BN could have provided the information on the high risk they were operating.

vii. Bayesian Network simulation will be a valuable tool for training design and operations personnel

The main conclusion is that Bayesian networks are ideally suited for learning from the past and predicting the future. The method should be popularized and should be adopted by the oil and gas industry.

10.2 Publications from the research

10.2.1 Papers published

i. G. Unnikrishnan, Shrihari and N. Siddiqui, "Application of Bayesian methods to event trees with case studies," *Reliability Theory & Applications, Gdenko Forum*, RT &A #3, (34) Vol 9, September 2014. (http://gnedenko- forum.org/Journal/2014/032014 /RTA_3_2014-06.pdf)

ii. G. Unnikrishnan, Shrihari, and N. Siddiqui, "Analysis of independent protection layers and safety instrumented system for oil gas separator using Bayesian methods," *Reliability Theory & Applications, Gdenko Forum*, RT &A #1 (36) Vol 10, March 2015. (http://gnedenko-forum.org/Journal/2015/012015/RTA_1_2015-05. pdf)

iii. G. Unnikrishnan, Shrihari, and N. Siddiqui, "Application of Bayesian methods for risk assessment of oil & gas separator," *International Journal of Applied Engineering Research*. Vol. 10, No. 9, pp 22959-22968, 2015.

iv. G. Unnikrishnan, Shrihari, and N. Siddiqui, "Understanding Oil & Gas Pipeline Failures and Mitigation Measures Using Bayesian Approach," *International Journal of Applied Engineering Research*. Vol 10, No.11, pp. 29595-29608, 2015.

v G. Unnikrishnan, Shrihari, and N. Siddiqui, "Monitoring Probability of Failure on Demand of Safety Instrumented Systems by Bayesian Updating," *International Journal of Applied Engineering Research*. Vol 10, No.15, pp. 35774-35777, 2015

vi. Paper under review:

G. Unnikrishnan, Shrihari, and N. Siddiqui, "Practical Aspects of Cause and Effect Modeling in Process Industries using Bayesian Methods," *International Journal of Performability Engineering*

10.2.2 Papers presented in international conferences

i. G. Unnikrishnan and B. Muruganantham. "Bayesian approach to Risk assessments," presented at American Society of Safety Engineers, 7th International HSSE & Loss Prevention Professional Development Conference and Exhibition, Kuwait, 26-28 Nov13.

ii. G. Unnikrishnan, F. A Zalzalah, Shrihari and N. Siddiqui. "Risk Management in the Process Industry-New Directions With Bayesian Approach," in *Proc. SPE International Conference on Health, Safety and Environment, USA.* 17-19 Mar14. http://dx.doi.org/10.2118/168436-MS

10.3 Future work

Work in the following areas will encourage and strengthen application of BN in oil and gas industry.

i. Development of BN modules for LOC for various equipment, to be kept as library of models that can be customized to individual company needs. As of now there is no published work on how to build BN for LOC for typical equipment in a systematic manner.

ii. Incorporation of Experts opinion

iii. Methodology for incorporation of Human & Organizational factors

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Bio-data of author

The author of the thesis G. Unnikrishnan is a chemical engineer with BSc Degree in Chemical Engineering (Calicut University, I Class-Honors) and M. Tech Degree with specialization in Project Engineering (Cochin University of Science and Technology-CUSAT, I Class-Distinction).

His started his career in a public sector engineering consultancy company, where the responsibilities included design and engineering of process plants. He was mainly involved in process design of Sulphuric acid, Nitric acid, Ammonia plants and oil terminals. Subsequently he moved to oil and gas industry and is currently with Kuwait Oil Company (KOC) in Kuwait as Technical Specialist. After working several years in design of upstream oil and gas facilities, he became interested upstream process safety and focused on this area.

In process safety domain, he has conducted several HAZOP study sessions as HAZOP Leader. He holds the TUV Functional Safety Engineer Certificate that enables him to conduct Safety Integrity Level (SIL) studies for process plants. He has conducted and supervised a number of SIL as well as Layer of Protection Analysis (LOPA) and Quantitative Risk Assessment (QRA) studies for oil and gas and pipeline projects. He was involved in several committees in KOC that was instrumental in initiating and implementing the Health, Safety and Environmental Management Systems in the company. He continues to be a member in KOC's Process Safety Management implementation committee. He is also a member of the company's Standards Technical Committee and has been the Task Force leader for the company standards related to process safety. He has a total of over 30 years of experience in design, engineering management and process safety in oil and gas industry.

Apart from his official duties and responsibilities, he has been a researcher on process design and safety. His publications and paper presentations apart from the papers listed under 10.2 are noted below:

A. Papers published:

1. G. Unnikrishnan, “What HAZOP Studies cannot do”, *Hydrocarbon Processing*, October 2005.
2. G. Unnikrishnan, “Visualize Pump & Control valve interaction easily”, *Hydrocarbon Processing*, August 2007.

The paper under 2 above has been included in the following two design books

i. K. A. Coker, *Ludwig’s Applied Process Design for Chemical & Petrochemical Plants, Volume 1.*
ii. E. W. McAllister, *Pipeline Rules Of Thumb Handbook*, 7^{th} Edition, Gulf Publishing Company, June 2009
iii.

B. Conferences presentations:

1. G. Unnikrishnan. “Management Of Change –Systems Approach”, presented at Society of Petroleum Engineers International Conference on Health, Safety and Environment, Abu Dhabi, April 2006.
2. G. Unnikrishnan. “Oily Water Separation-Challenges”, presented at Society of Petroleum Engineers Advanced Technology Workshop-Impact of IOR/EOR on facilities, Marrakesh, February 2007
3. G. Unnikrishnan. “International Trends in Process Safety”, presented at National Conference of Hydrocarbon Safety-Petrosafe 2007, Kochi, April 2007. (Best Paper Award)
4. G. Unnikrishnan and Ameena Rajab. “Integrating Systems Approach in Accident & Incident Investigations”, Society Of Petroleum Engineers International Conference on Health, Safety and Environment, Nice, France, April 2008.
5. G. Unnikrishnan. “Impact Of Texas City Refinery Incident –Baker Panel Report”, presented at Middle East Health, Safety, Security & Environment Conference, Society of Petroleum Engineers, Doha, Qatar, October 2008 (Invited Presentation)

6. G. Unnikrishnan. "Understanding the Other Side of Process Safety", Global Congress on Process Safety, 25th Center for Chemical Process Safety International Conference, American Institute of Chemical Engineers, San Antonio, Texas, March 2010 (Poster Session)
7. G. Unnikrishnan. "Emerging Trends in Process Safety", presented at Middle East Health, Safety, Security and Environment Conference, Society of Petroleum Engineers, Manama, Bahrain, October 2010

8. G. Unnikrishnan. "Managing Process Safety During Project Implementation", presented at 6th International Health, Safety, Security, Environment & Loss Prevention Professional Development Conference & Exhibition". American Society Of Safety Engineers, Kuwait, 01 Dec 2011

9. G. Unnikrishnan "Process safety during facilities design", 6th International Petroleum Technology Conference", Beijing, China, 26-28 March 2013 (Poster Session)

His professional achievements and awards include the following:

a. Kuwait Oil Company Chairman & Managing Director's Health Safety & Environment Award-2007
b. Kuwait Oil Company Chairman & Managing Director's Health Safety & Environment Award 2008
c. Kuwait Oil Company Significant Achievement Award, 2010-2011