FACULTY OF SCIENCE AND TECHNOLOGY

MASTER'S THESIS

Study Programme/Specialization: **Risk Analysis and Governance**	Spring 2021 **Confidential**

Author: **Abdollah Kiani**

Programme Coordinator:

Faculty Supervisor: **Professor Riana Steen**

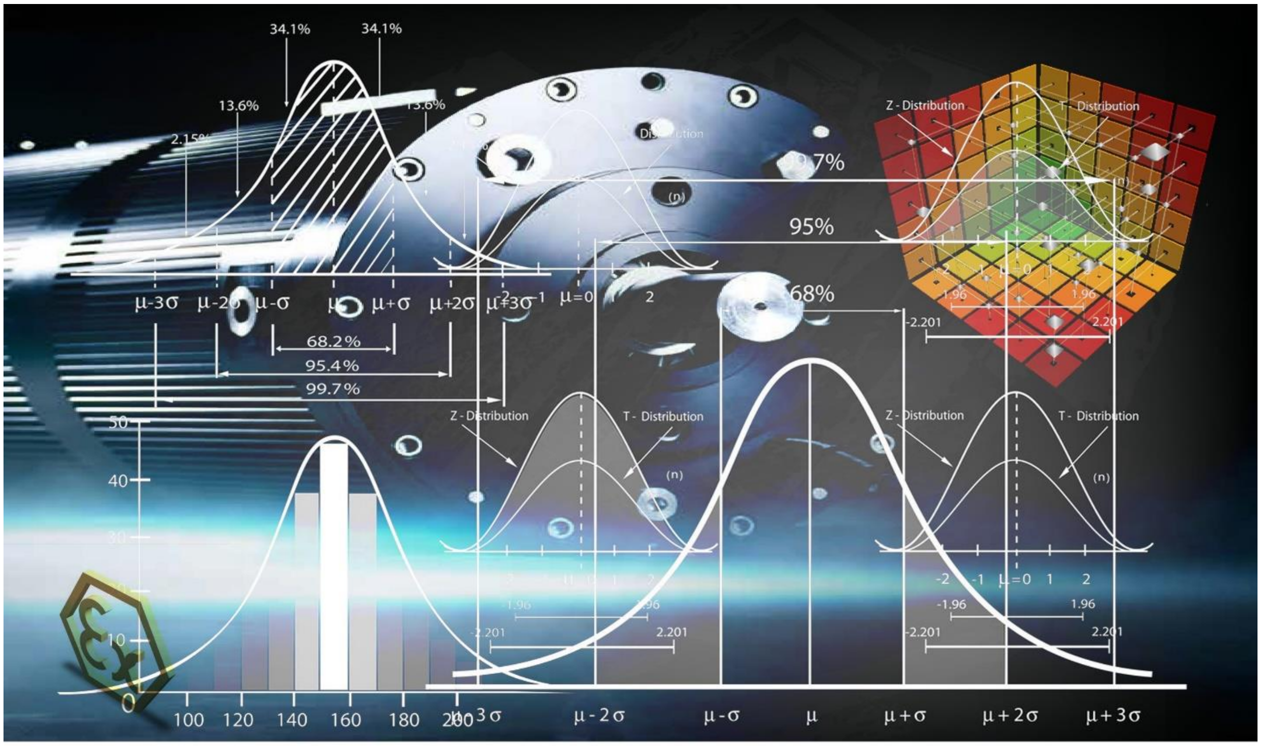
External Supervisor: **Carl-Johan Almestad**

Title of master's thesis:

Application of Bayesian Network in the EX-Risk-Based Inspection

Credits: **30**

Keywords: Bayesian Network, Risk based inspection, Fault tree Analysis, Event tree Analysis, Ex electrical equipment, Ignition risk, Risk Analysis, Risk Assessment	Number of pages:62 + Supplemental material: 17 Stavanger, July 2021



Application of Bayesian Network in the EX-Risk-Based Inspection

Writer: Abdollah Kiani

Study Program: Risk Analysis and Governance

Supervisors: Professor Riana Steen

Spring, 2021

Abstract:

In the oil and gas industry, many operating expenses assigns to the cost of inspection and maintenance. Therefore, an optimized inspection strategy can reduce the cost of inspection and maintenance when the system's integrity does not change. One of the inspection's main issues is providing the right balance between the benefits of inspection and the inspection cost. It has led to the emerging of a new concept of inspection called risk-based inspection (RBI). This is based on the logical view that most high-risk equipment is concentrated within a small portion of the plant. Therefore, this equipment has priority for inspection, and the extra cost could be decreased with reduced inspection for other equipment with lower risk. Different risk-based inspection approaches have been accepted and developed in the petroleum industry in the past few years. However, there is not any integrated approach for RBI. In this research, to minimize the inspection cost, a new risk-based methodology has been developed by employing the Bayesian Network. Therefore, this study started with the most common risk analysis techniques such as fault tree and event tree and then tried to present a Bayesian network that can deal better with uncertainty. The critical point is that the BN model has met the RBI principle, which required increasing inspection for high-risk equipment to ensure safety level. On the other hand, it makes balance in the cost by reducing the inspection for low-risk equipment.

Acknowledgment:

I would like to thank my supervisor Professor Riana Stain for supporting me to present my master thesis.

I would like to thank Mr. Carl-Johan Almestad and IKM Elektro AS for giving me an opportunity to work on an interesting topic for my master thesis.

I would like to thank my family and my dear son, Jubin, who always encourages me.

Finally, I acknowledge the University of Stavanger and the Department of Science and Technology for giving me good working conditions.

Stavanger, July 2021

Abdollah Kiani

Contents

Chapter 1. Introduction

Industrial accidents are not a new issue for humankind, and they are as old as the emerged of industry. Therefore, many standards and procedures have been developed to reduce the impacts of these hazards. Explosion and fire are two historical and well-known types of these mishaps. They can create major accidents or minor incidents base on their source and the environment. Fire is a rapid oxidation-reduction reaction that results in the production of heat and generally visible light. An explosion is an extreme and sudden expansion of gas combustion. An explosion can create a loud, sharp noise and a supersonic shock wave with a powerful and destructive force (Bottrill et al. 2005). A spark in a hazardous environment can create fire or explosion. This can happen in any place where flammable and radioactive materials are processed or stored because there is potential for leakage or the ability to create an explosive atmosphere in conjunction with oxygen from air or some oxidizing agent. Therefore, three main elements for the explosion are Fuel (any flammable material), Oxygen, and an ignition source (Bottrill et al. 2005).

Indubitably, nowadays, the wheel of the production process in any industry is electricity. Electricity creates a spark that generates energy, and this nature can lead to ignition or explosion where there is an explosive atmosphere. By the advent of the Industrial Revolution and subsequent industrial development in the twentieth century, the chemistry of electricity has been known as one of the critical ignition sources in different industries (Bottrill et al. 2005).

The first safeguard approach against fire and explosion in the production process has been used in discovering and extracting mines to reduce the risk of burning methane gas. Methane is lighter than air; therefore, it moves up and amasses near the roof in mines. In this initial method, some expert miners covered with wet sacking were entering the working area with lanterns in front of other miners. Changing the lanterns' fire color was a sign of the existence of methane (Bottrill et al. 2005).

Other risks were identified by emerging electricity and using it in the mining industry, and the need for control equipment appeared. Safety equipment introduced by the mining industry was developed in other sectors to control the risk of flaming or explosion. In the early 1900s, the first codes and standards for using electric equipment have introduced in the USA. Finally, the International Electrical Commission (IEC) was founded in Switzerland (Bottrill et al. 2005).

1.1 Research question

The international electrical Commission (IEC) is a worldwide organization for the standardization and coding of all electrical/electronic equipment and related technologies. IEC 60079 describes general requirements for Explosion-proof Electrical Equipment (Ex) on selection, installation, maintenance, and inspection in hazardous areas such as drilling rigs. Following this standard, IEC 60079-17 covers factors directly related to the inspection and maintenance of electrical installations within hazardous areas only, where flammable gases may cause the hazard, vapors, mists, dust, fibers, or flying (IEC Webstore, 2021).

Inspection is known as a critical tool to detect potential failures. So, Inspection of Ex electrical equipment is essential to ensure the continuing integrity of the types of protection that enable its use in potentially explosive atmospheres. Yet, such inspections are sometimes not carried out adequately regarding the frequency of inspection, grade of inspection, and completeness of the portfolio of Ex electrical equipment installed. Today, many inspections of Ex electrical equipment are carried out at the same level without adjustment for the different ignition risks that might apply. Still, Ex electrical equipment is typically located in various hazardous areas (where the probability of a flammable atmosphere being present differs). Also, different EX equipment presents different ignition risks based on the concept of EX protection type. In addition, the equipment may have different ages or be located where the environmental conditions differ (EI guideline, 2008).

One of the inspection's main issues is providing the right balance between the benefits of inspection and the inspection cost. It has led to the emerging of a new concept of inspection called risk-based inspection (RBI). This is based on the logical view that most high-risk equipment is concentrated within a small portion of the plant. Therefore, this equipment has priority for inspection, and the extra cost could be decreased with reduced inspection for other equipment with lower risk (Bhatia et al. 2019).

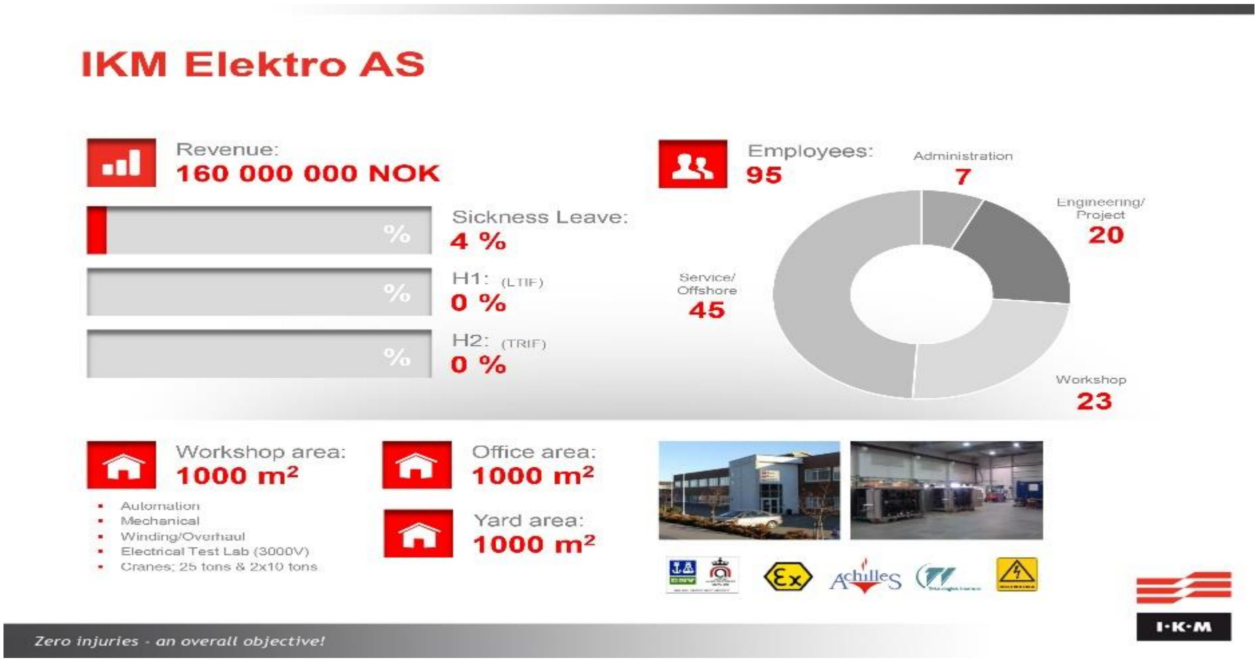
RBI has been defined as *"an integrated methodology that uses risk as a basis for prioritizing and managing an in-service equipment inspection program by combining both the likelihood of failure* *and the consequence of failure."* (EI guideline, 2008). As is apparent in the RBI definition, two critical factors in this approach are the probability of failure (PoF) and the consequence of failure (CoF). Therefore, the main objective of this thesis is to develop a risk-based inspection strategy for Ex electrical equipment ignition risk in support of standards and regulation by applying the Bayesian network. To this end, this study looks closer at two following research questions:

- RQ1: How to apply a Bayesian Network to estimate the PoF and CoF regarding the EX risk-based inspection (EXRBI)?
- RQ2: How the result of the Bayesian Network can apply to develop a risk-based inspection strategy of Ex electrical equipment in the Rowan Viking rig?

This research has been done in cooperation with the IKM Elektro As according to EX equipment installed in the Rowan Viking rig.

1.2. IKM Elektro AS

IKM group is one of the Norwegian international leading companies in the oil and gas industry, and IKM Elektro AS is a subsidiary company of the IKM group (ikm.com, 2021). Figure 1.1 shows the IKM Elektro information such as revenue, employees, office area, etc.



IKM Elektro AS

Revenue:
160 000 000 NOK

Sickness Leave:
4 %

H1: (LTIF)
0 %

H2: (TRIF)
0 %

Employees:
95

Workshop area:
1000 m²

- Automation
- Mechanical
- Winding/Overhaul
- Electrical Test Lab (3000V)
- Cranes: 25 tons & 2x10 tons

Office area:
1000 m²

Yard area:
1000 m²

Zero injuries - an overall objective!

Figure 1.1: General information for IKM Elektro AS
Source: IKM website

IKM Elektro AS provides services in different fields as follow (ikm.com, 2021):

- Ex-elektro service includes temporary installations, Ex inspection, Demolition and removal, operation service, and maintenance.
- Motor service includes condition check of motor, motor overhaul/repair, motor inspection, and sale of motors.
- High Voltage Services includes installation, maintenance, and operation of electrical high voltage installations.
- Offshore/Onshore Service Personnel. IKM Elektro uses skilled experts to handle and supervise planned resources, personnel, competence matrixes, and course certificates for baseline, skilled staff, commissioning, and decommissioning projects.

Figure 1.2 illustrates EX inspection process in IKM Elektro.

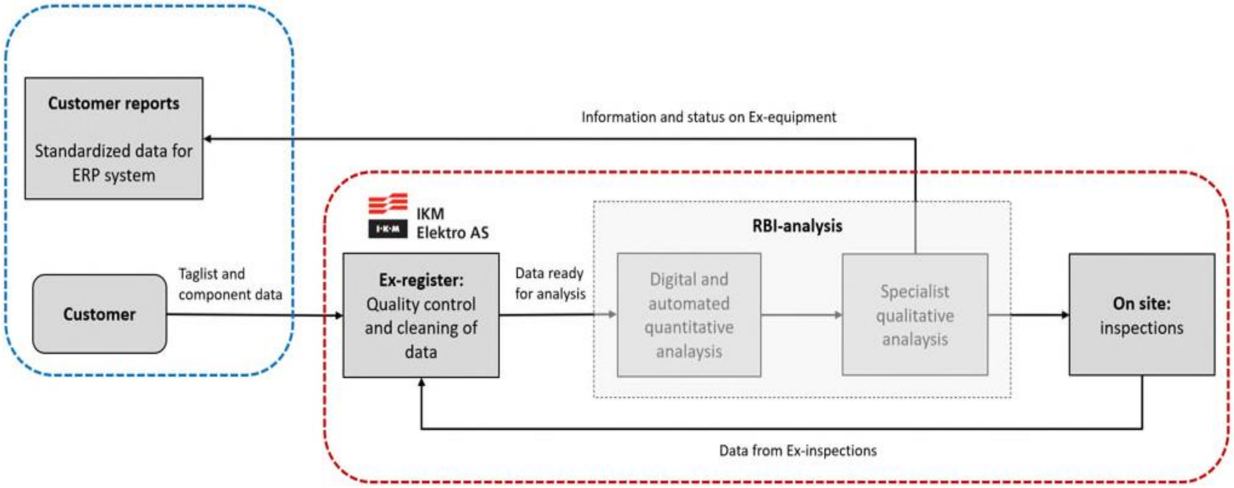


Figure 1.2: IKM Elektro's inspection process.
Source: Documents from IKM Elektro As.

For each customer, IKM Elektro registers data of equipment to find more information for PoF and CoF. After register data, the data will be "washed" and sorted to present the correct data; this information plays a central role in the assessment. Then, they do analysis and propound the checklists and intervals which will be used for inspection.

This company uses digital tools for inspection (i.e., "Inspectio" or equivalent software solution) to ensure high-quality reports in the RBI analysis. The software sends checklists to the inspection and receives data back after the inspection. IKM Elektro board of directors determined the Rowan Viking rig (figure 1.3) as the case study for this thesis and provided access to inspection data for this study.

Figure 1.3: The Rowan Viking rig
Source: https://www.ptil.no

The Rowan Viking is an 11-year-old jack-up rig for drilling offshore wells, which complies with Norwegian law. Today this rig is located at UKC - North Sea at position 58° 50' 29.652" N, 2° 14' 50.039" E (marinetraffic, 2021). Table 1.1 presents information for this rig.

Table 1.1: General information for The Rowan Viking rig

Name	ROWAN VIKING	CRANES	1 PTC 35
IMO	8769664	TRANSPORT	18 axle lines of SPMT
Vessel Type - Detailed	Platform	MARITIME EQUIPMENT	1sheerleg &1 barge
Status	Active	CREW	11 Mammoet professionals
MMSI	538004075	Dimension	80 x 10 m
Flag	Marshall Is [MH]	Year Built	2010

Source:https://www.marinetraffic.com

1.3. Structure of the thesis

1

Chapter 1 starts with the introduction, then 1.1 presents the research question,1.2 includes a brief presentation of the case study, and 1.3 contains the thesis structure.

2

Chapter 2 reviews relevant theoretical concepts. Section one of this chapter takes a look at basic concepts of risk analysis. 2.2 presents relevant theories according to RBI, and 2.3 introduces the Bayesian risk assessment.

3

Chapter 2 is assigned to methodology. 3.1 presents research strategy and design, 3.2 is about data collection, section 3.3 defines the methodology for converting from fault tree and event tree to the Bayesian network, 3.4 presents risk matrix, and 3.5 is assigned to reliability and validity.

4

Chapter 4 includes empirical data analysis. In 4.1, data has been analyzed to identify fault mechanisms for EX equipment; then, in 4.2, a primary Bayesian network has been developed.

5

The discussion about the result of the analysis has taken place in chapter 5, where 5.1 discusses how the primary model could be updated, 5.2 identifies acceptance criteria, 5.3 defines the concept of lots, and finally, 5.4 shows the application of The BN for inspection strategy bay an example from The Rowan Viking rig.

6

Chapter 6 presents the conclusion of the thesis, where some recommendations have been suggested.

Chapter 2. Related Literature and Theoretical Perspective

This chapter introduces some key concepts and theories related to risk-based inspection based on current industrial practice.

2.1 Concept of risk analysis

It is essential to make a difference between risk definition and describing the risk. Different researchers have present various definitions for risk. When we speak about the risk, something threatens the critical values (i.e., human life, environment). Usually, people use the word risk in a negative sense. But the point is that we do not know the consequences so, we do not classify the consequences as positive or negative. Therefore, the risk may consider an opportunity. This thesis generally defines risk as: *"the consequences (C) of the activity (A) and associated uncertainties (U)."* (Aven, 2020).

Risk= (A, C, U) or briefly (C, U)

The same as the risk definition, there are different methods to describe risk and measure its potential. For instance, consider initiating event A as gas leakage; As it is clear, some other concepts and elements are relevant to the risk of an event (A) like barriers, risk sources, safety, hazard, and vulnerability. Therefore, risk description needs to provide understanding about these concepts as well. Consequently, this thesis describes risk generally as: *"The triplet (C', Q, K), where C' is some specified consequences, Q a measure of uncertainty associated with C' (typically probability), and K the background knowledge that supports C' and Q (which includes a judgment of the strength of this knowledge)"* (Aven, 2020).

Risk description = (C', Q, K)

To describe risk as above provides the possibility of developing other concepts for risk assessment. For instance, we can extend the definition of risk with the concepts of vulnerability and threat as:

Risk = (A, U, C) = (A, U) + (C, U|A)

(A, U) present hazard and associated uncertainties, and (C, U|A) present vulnerability. That means vulnerability is consequences conditional on the occurrence of event A.

And Risk description = (C', Q, K) = (A', Q, K) + (C', Q, K|A').

Where risk is described as the combination of the uncertainty associated with the hazard and the vulnerability given the occurrence of the specific event A' (Aven, 2020).

Regardless of how risk is defined, the standard features of risk in all definitions are consequence C and uncertainty (possibility) U because of event A (Aven, 2020). Therefore, the risk analysis first needs to identify the relevant initiating events (A) and then develop the causal and consequence picture to determine where critical values are at stake. Risk analysis aims to provide an informative risk picture by describing risk. Figure 2.1 illustrates an example of a simple bowtie diagram, providing the main blocks of the risk picture (Aven, 2015).

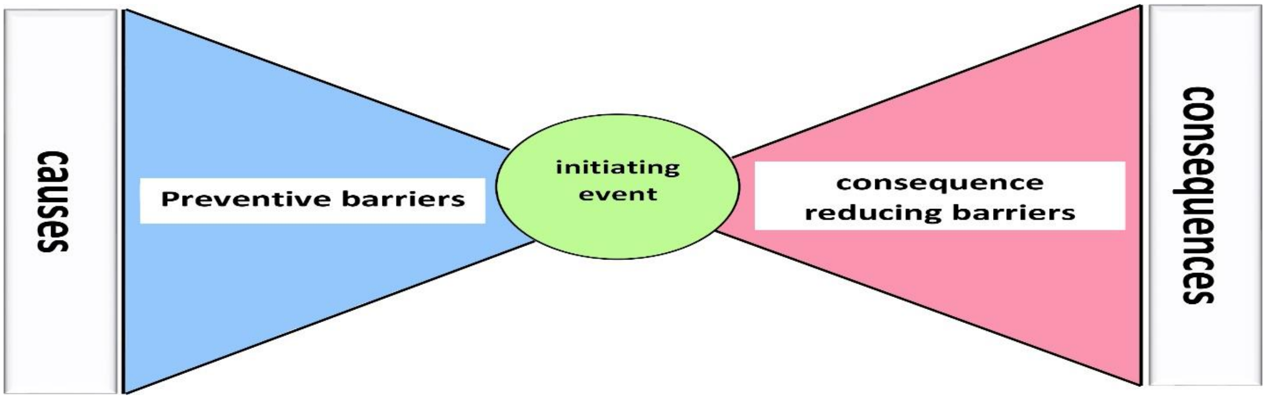


Figure 2.1: An example of bowtie diagram (based on Aven, 2008).

The left side of the bowtie describes the causal picture that may cause event A and introduces barriers to prevent event A. It is common to use the Fault Tree Analysis (FTA) for this part. The right side illustrates the possible consequences of A and mitigation measures, where The Event Tree Analysis (ETA) is the most common method (Aven, 2015).

It is crucial to make a difference between the term "risk analysis process" and risk assessment. The risk picture, which is established by risk analysis, provides a basis for comparing different alternatives and solutions. Risk analysis supports decision-making to provide input for risk evaluation. Then combination of risk analysis and risk evaluation navigates the basis for risk assessment (Aven, 2015). The risk analysis process includes three main phases: planning, risk assessment, and risk treatment. The risk analysis process covers principles and fundamental concepts for risk assessment, risk perception, risk communication, and risk management to solve risk issues (Aven, 2020).

Nowadays, managing risk against health, safety, and environment (HSE) is one of the essential subjects in the oil and gas industry. The main object of HSE is to provide a safe workplace where there is minimum life cycle cost. Therefore, risk analysis has become growingly recognized as an effective tool for this matter (Bai & Jin, 2015).

Risk management includes all measures and activities to manage risk. Risk management tries to balance development and protection. Various risk management strategies (i.e., risk-informed, cautionary, resilience, etc.) are used for this matter. One of the most common strategies in the petroleum industry is the risk-based strategy based on codes and standards (Aven, 2020).

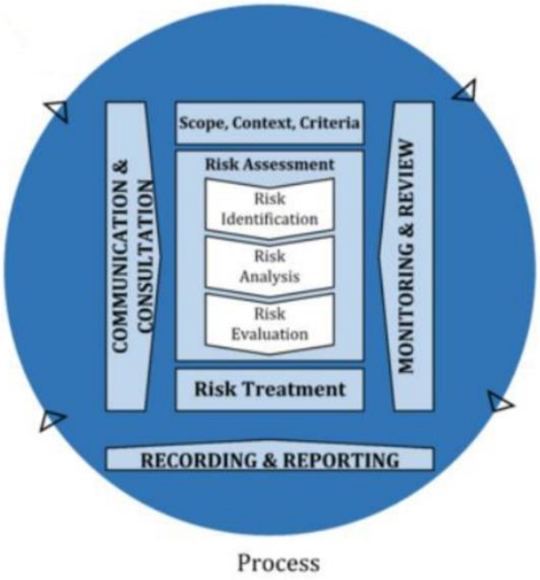


Figure 2.2: ISO 31000 risk management process
Source: Iso 3100

In most cases, the risk management process divided into several steps. Figure 2.2 illustrates ISO 31000 risk management process.

2.2. Risk-based inspection

In the oil and gas industry, many operating expenses assigns to the cost of inspection and maintenance. Therefore, an optimized inspection strategy can reduce the cost of inspection and maintenance when the system's integrity does not change.

Risk-based inspection is a precious tool to design and optimize an inspection strategy, which uses risk assessment to determine priorities of inspection activities based on the historical data, analytical methods, and experts' judgment (Bai et al., 2014).

RBI considers the consequences and probability of failure from specific degradation mechanisms then develop an inspection strategy that will effectively reduce the associated risk of loss. However, RBI is still a developing approach. Various RBI methodologies are available, and each of them has its advantages and disadvantages (Bai et al., 2014).

As illustrated in figure 2.3, a risk-based inspection process follows four steps: system definition, quantitative risk assessment, risk analysis application, and development of inspection strategy (Bai & Jin, 2015).

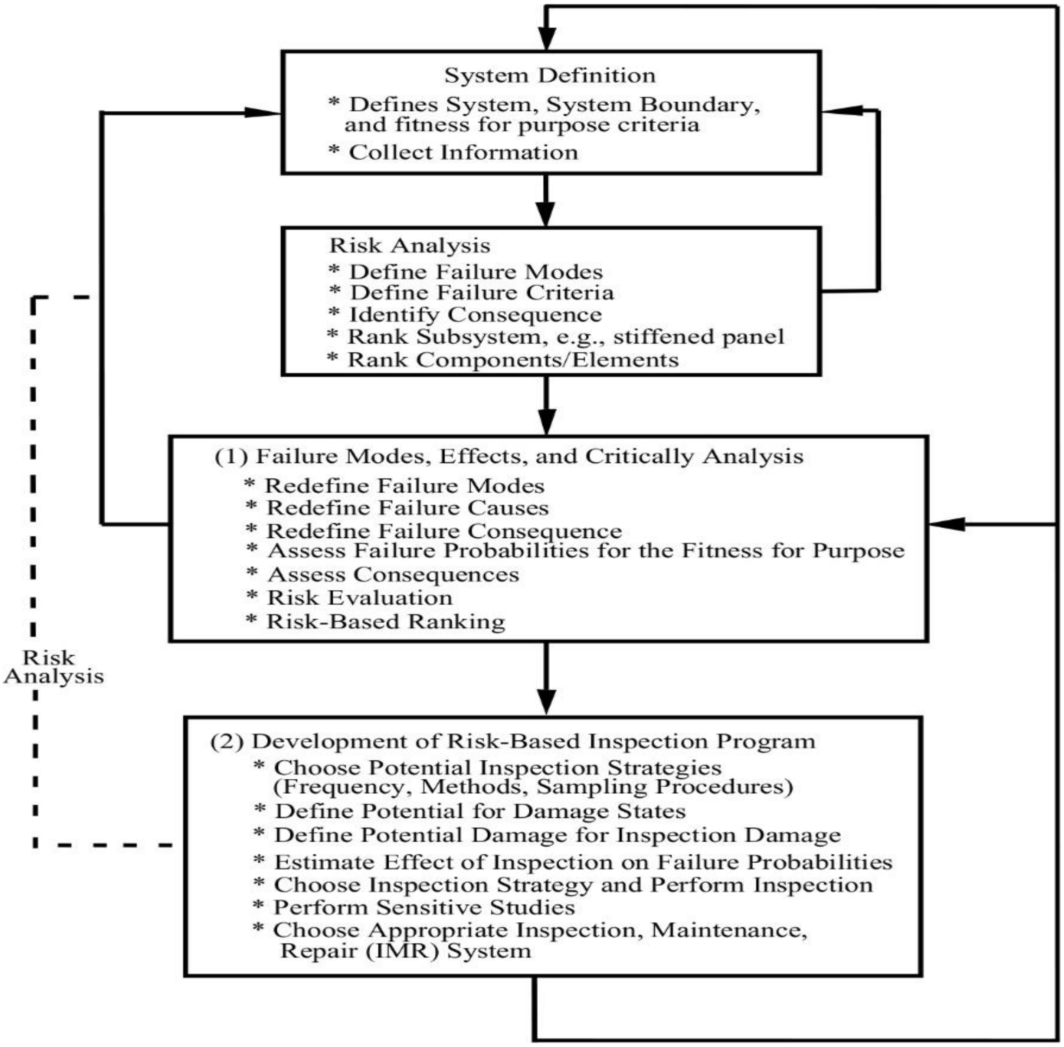


Figure 2.3. Risk-based inspection process (based on Bai & Jin, 2015).

The RBI's process starts with definition of the system, define a risk, and identify acceptance criteria (Bai & Jin, 2015). The system's detailed study includes a general description of the system's structure and operation, the functional relationship between the elements of the system, and any other system constraints. Therefore first, the relevant failure modes should be recognized. By identification of the failure modes, the risk of failure could be assessed by estimating the probability and consequence of the failure modes based on the acceptable level. Then the inspection and measures could be used to ensure the level of risk would not dominate the level of acceptance criteria. In the RBI process, risk acceptance criteria should be established first to compare in risk analysis (Bai et al., 2014).

RBI defines risk as to the product of the probability of failure (PoF) and the consequence of failure (CoF): Risk= PoF x CoF. Risk matrices could calculate the result for the components and provide the risk picture (Bai et al., 2014).

As a result, risk assessment is a vital part of the RBI process (Bai & Jin, 2015). According to Aven (2020), risk assessment is the systematic process to identify risk sources, threats, hazards, and opportunities; understanding how these can occur, what their consequences can be; representing and expressing uncertainties and risk and determine the significance of the risk using relevant criteria. The assessments help us identify what might go wrong, why and how it might go wrong, the consequences, and how bad they are. Risk assessment is in many ways a conventional approach, with suitable methods and models for responding to such questions and issues, founded to a large extent on probabilistic and statistical thinking and tools. Probability theory and other frameworks represent, model, and treat variation and uncertainties; statistics and Bayesian analysis provide essential risk assessment tools.

Analysis of the initiating events and identify the possible causes for them provide the best basis to recognizing measures that may prevent undesirable consequences. POF and COF can be estimated both qualitatively and quantitatively. The most common methods are (Bai & Jin, 2015):

- Historical data
- Fault tree analysis

- Event tree analysis
- FMEA
- Human reliability analysis

However, one of the popular methods to analyze the failure causes of engineering systems and safety-critical systems is fault tree analysis and could be used both qualitative and quantitative. Figure 2.4 shows an example for the FT.

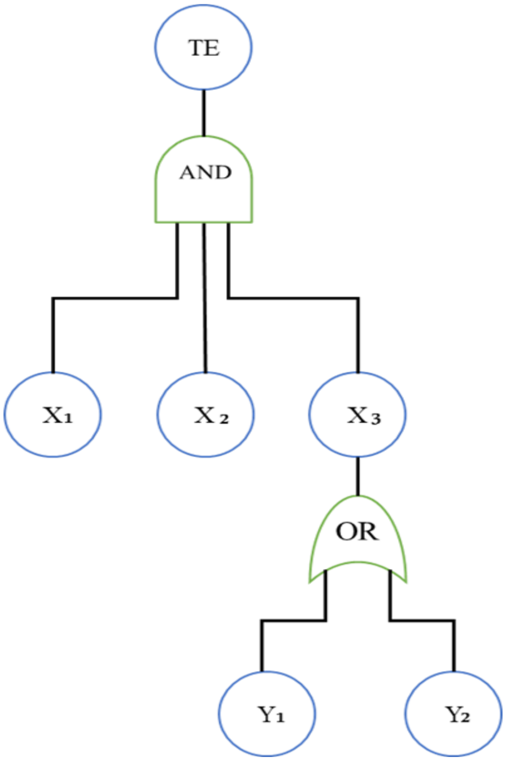


Figure 2.4: FT graphical model example. Provided by this study.

FTA is a top/down approach and first identifies the expected undesired event of the system as a top event; then, the tree diagram is refined layer by layer from leading events to causes until the primary cause of the system failure is reached. Events in an FTA diagram are statistically independent, and PoF for each event is based on the distribution of the random variable for the event, X1= {U1, U2, U3 … Un} (Bobbio et al, 2001).

Relationships between events and causes represent through logical gates, and these logical gates could be shown by different symbols, as is shown in figure 2.5 (Casal, 2017).

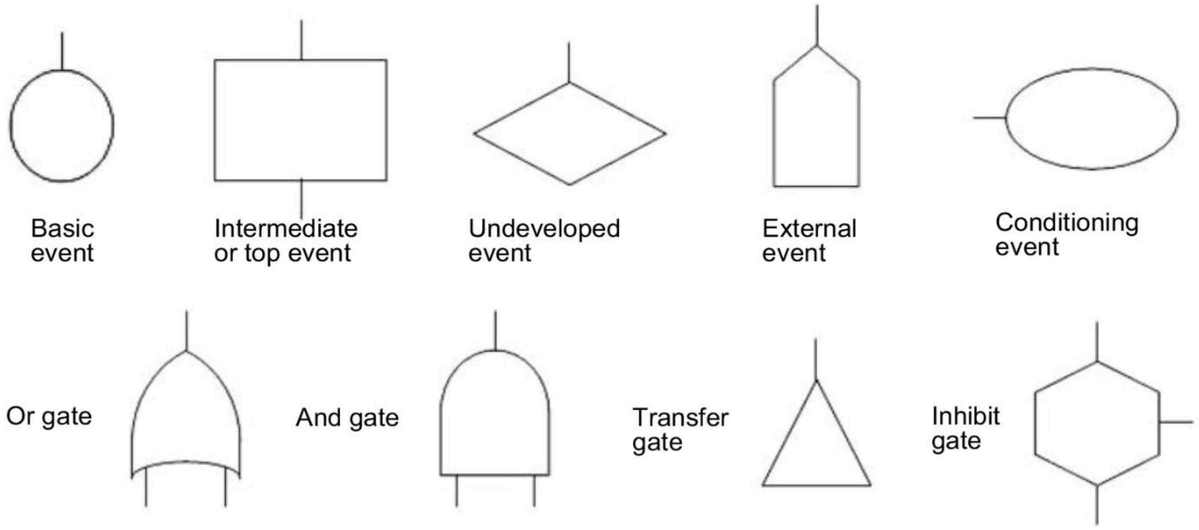


Figure 2.5: Most common symbols used in fault trees (Casal, 2017).

Event trees (ET) is the most common method to analyze the consequences of each accident scenario and estimate their likelihood. Figure 2.6 illustrates an example for ET (Casal, 2017).

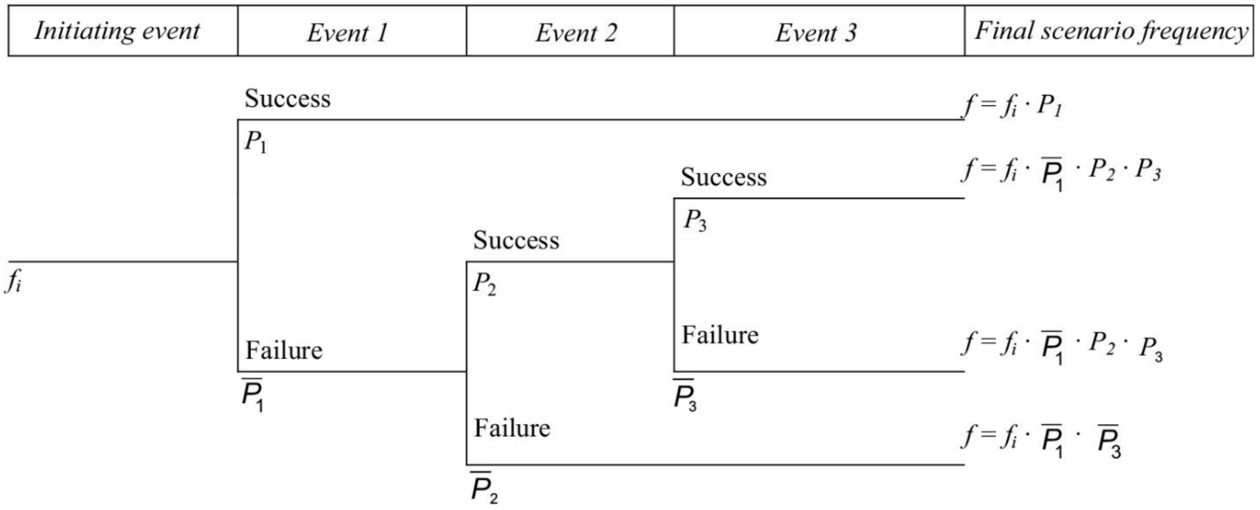


Figure 2.6: The structure of the event tree (Casal, 2017).

The consequence sequence is concerning the occurrence or nonoccurrence of the intermediate events. Therefore, an ET starts with the initiating event and then, the sequence's progress according to a binary (success/failure) mode (Casal, 2017). In RBI usually, consequences are divided into three segmentation of safety, economic, and environmental (Bai & Jin, 2015).

As mentioned earlier, the risk is defined as R= f (C, U). In RBI, it is common to use probabilistic risk analysis (PRA) to calculate PoF and CoF. Bayesian models are often applied to reliability updating for probability-based inspection planning. Therefore, according to the RBI perspective, R=f (Pf, C), where Pf is the failure probability; C is the consequence of the failure. A more general expression of the risk for practical calculation is given by R=∑ (Pfi. Ci). The risk-based inspection can be planned by minimizing the risk: min{R} (Bai & Jin, 2015).

The risk picture could be provided by a matrix of CoF and PoF categories. Usually, a 5 x 5 risk matrix are used as shown in figure 2.7 (Bai et al, 2014).

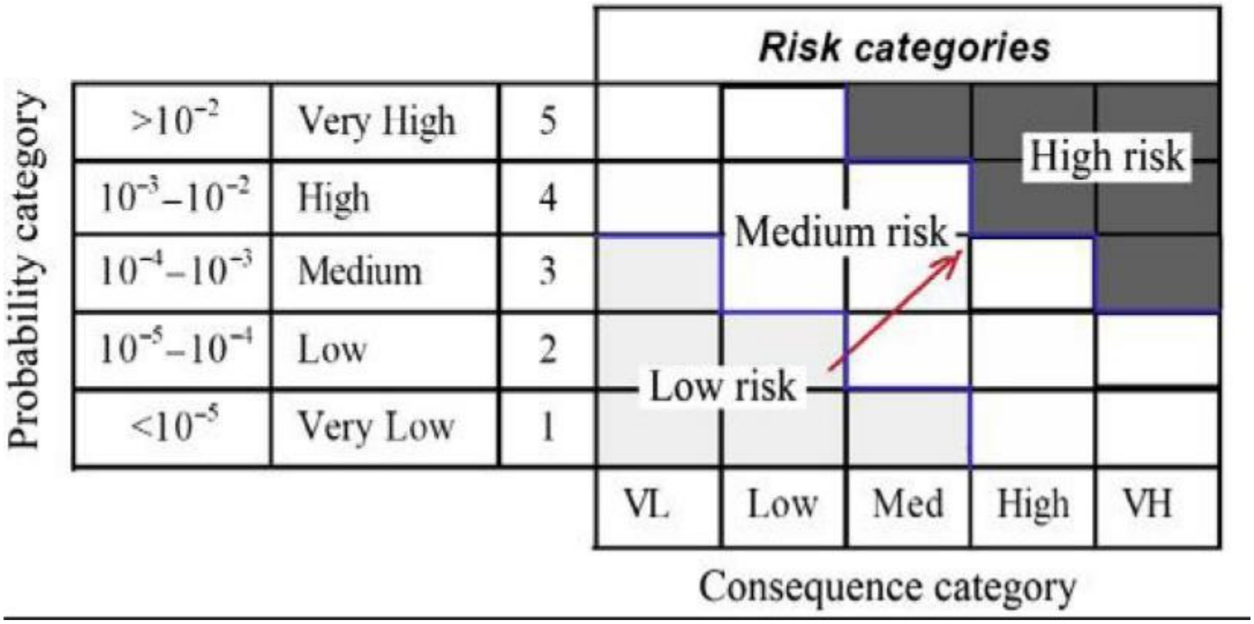


Figure 2.7: Example of RBI risk matrix (Bai et al, 2014).

The vertical axis presents PoF, and CoF is indicated on the horizontal axis. In the matrix table, the risk has three levels: low risk (usually is shown with green color), medium risk (usually is yellow), and high risk (red color), and the risk increases from the low level at the left-bottom corner to the high level at the right-top corner. Usually, low and medium risks could be acceptable based on the acceptance criteria. High risk is unacceptable, and action must be taken to reduce the probability, consequence, or both to ensure that risk lies within the acceptable region (Bai et al, 2014).

Therefore, the risk acceptance criterion defines the overall risk level. The criteria are a reference for evaluating the need for risk-reducing measures, and therefore need to be defined before initiating the risk analysis. Additionally, the risk acceptance criteria must reflect the safety objectives and the distinctive characteristics of the activity. There are different methods for identifying acceptance criteria (Bai et al., 2014):

- High-level criteria for quantitative studies
- Risk matrices and the ALARP principle
- Risk comparison criteria

The ALARP ("as low as reasonably practicable") principle is sometimes used in the oil and gas industry (figure 2.8). The use of the ALARP principle may be interpreted as satisfying a requirement to keep the risk level "as low as possible" provided that the ALARP evaluations are extensively documented (Aven, 2020).

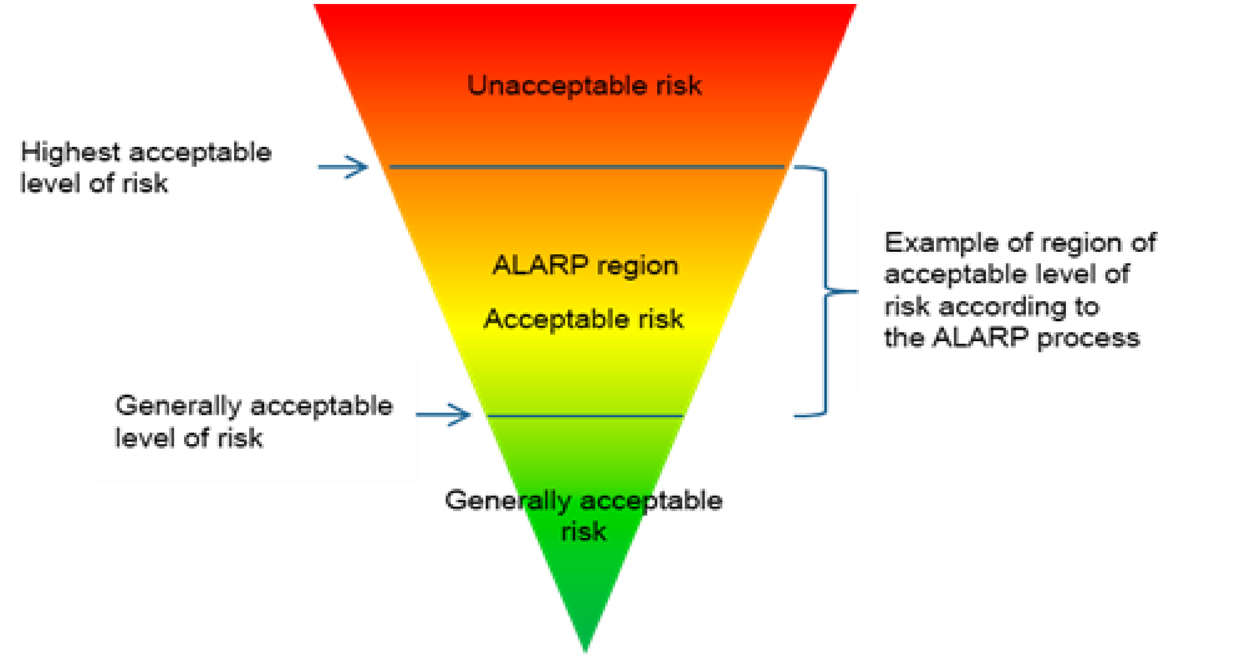


Figure 2.8: The AlARP triangle (Bai & Jin, 2015)

Between "lower tolerable limit" and "tolerable upper limit," the risk is tolerable when risk reduction is impracticable, or the cost for reducing the risk is grossly disproportionate to the improvement gained (Bai & Jin, 2015).

2.3 Bayesian risk assessment

Today, the Bayesian risk assessment method is employed in various domains for many different stochastic modeling situations. The basis of many traditional risk analyses, especially in the engineering field, has been based on probabilistic risk analysis (PRA). As mentioned earlier, engineering systems usually use deterministic models such as ETA and FT and logically relate low-level events to the higher-level event. The occurrence of initiating events and system failures in the fault trees and event trees is modeled probabilistically. The associated probabilistic models contain one or more parameters whose values are known only with uncertainty (Kelly & Smith, 2011). Figure 2.9 shows the structure of risk assessment according to a classic risk analysis approach.

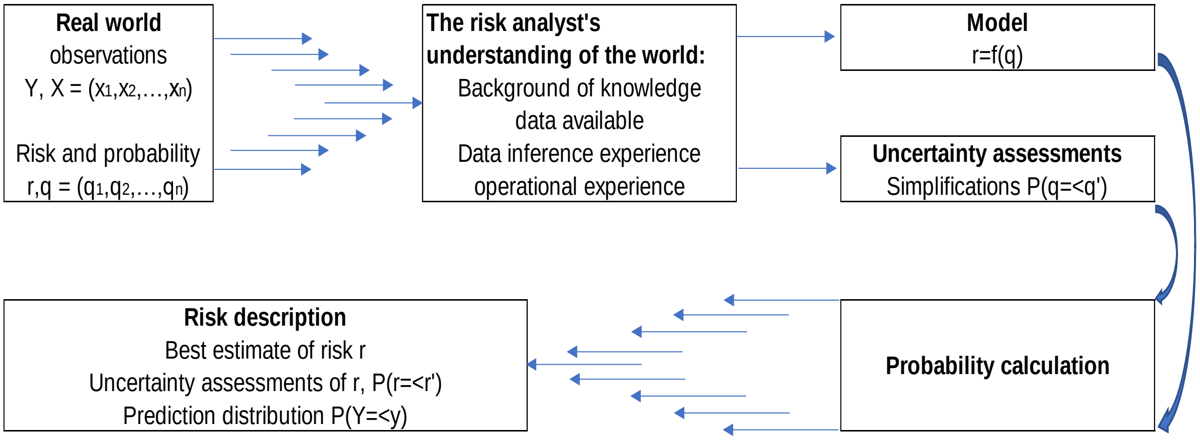


Figure 2.9: Structure of risk assessment according to a classic risk analysis approach (provided by this study based on Kelly & smith, 2011).

The classical risk analysis approach with uncertainty assessment allows uncertainty in the parameters to be expressed as subjective probability distributions to quantify uncertainty.

Probability is perceived as a measure of our belief in the outcome of the experiment. It measures an uncertainty about future events and effects seen by an analysis group or an analyst. The Bayesian approach has given background information and knowledge, with probability as a subjective measure of uncertainty for predicting the future. Bayesian methods to estimate parameters with associated uncertainty use all available information, leading to informed decisions based upon the applicable information at hand (Kelly & Smith, 2011).

Figure 2.10 shows the structure of risk assessment according to a Bayesian risk analysis approach.

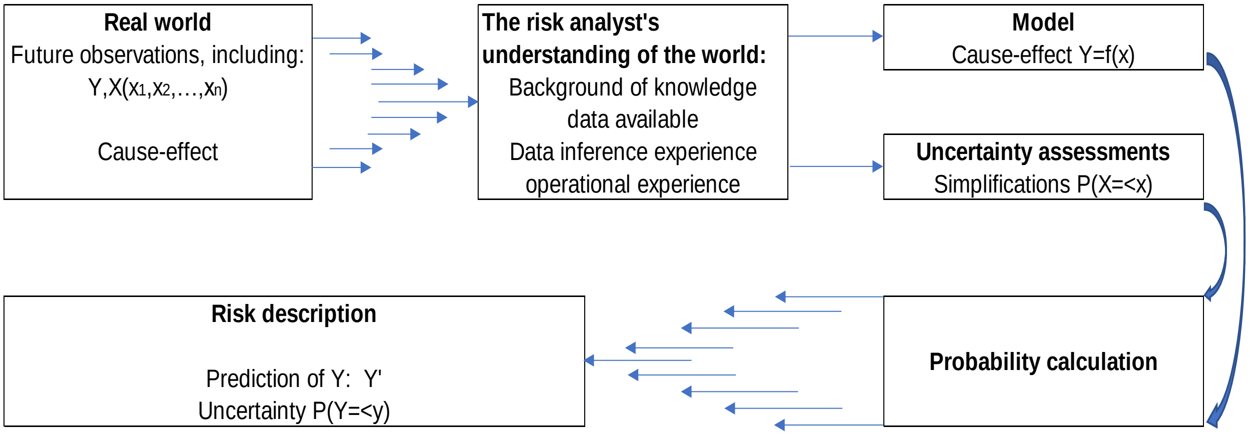


Figure 2.10: Structure of risk assessment according to a Bayesian risk analysis approach (provided by this study based on Kelly & smith, 2011).

The Bayesian risk analysis approach focuses on the system's future performance and certain variables that reflect system Y's performance. Based on the analyst's understanding of the world, one or more models are developed related to Y to X's general performance goal. The analyst then assesses X. Using a probability calculation, the uncertainty assessment of X, together with model f, will give the result of the analysis. This will be the probability distribution of Y, which can be deduced from a prediction of y. The critical difference and critical point of the Bayesian method are about uncertainty. Uncertainty is now a significant risk analysis component. But traditional risk analysis does not care about this vital factor. The Bayesian method could be used to estimate risk distribution, and it could be used as a tool to select or parameterize input distributions for a risk model (Kelly & Smith, 2011).

According to Kelly & Smith (2011), some advantages of The Bayesian methods could be as follow:

- By redefining probability as a subjective quantity rather than a measure of limiting frequencies, Bayesians can compute “credibility intervals” to characterize the uncertainty about parameter estimates.

- It is excellent for visualization of problem domains/risk pictures (causal interactions, risk drivers, and barriers)

- It supports constructive discussions on risk.
- It is a systematic approach for combining knowledge from different sources (Historical data and expert input, Knowledge from different experts)
- It easily updates with new knowledge.
- It is excellent for modeling dependencies.
- It allows peeking at the data.
- It is possible to guarantee that decisions are sensible in that they meet the axioms of coherent decision theory by expressing all uncertainties with probabilities and employing the Bayesian approach.

Bayes' Theorem provides the mathematical means of combining information and data to update a prior state of knowledge in the context of a probabilistic model. This theorem modifies a prior probability, yielding a posterior probability, via the expression (Kelly & Smith, 2011):

$$P(H|D) = P(H)\ \frac{P(D|H)}{P(D)}$$

- *P(H|D) Posterior distribution, which is conditional upon the data D that is known related to the hypothesis H.*
- *P(H) Prior distribution, from knowledge of the hypothesis H that is independent of data D.*
- *P(D|H) Likelihood, or aleatory model, representing the process or mechanism that provides data D.*
- *P(D) Marginal distribution, which serves as a normalization constant.*

One of the Bayesian risk assessment approaches that have received more attention in the past few years is The Bayesian Network (BN). Bayesian networks (figure 2.11) are acyclic directed graphs in which nodes represent random variables and arcs demonstrate the causal relationship between two variables (Abbasi, 2016).

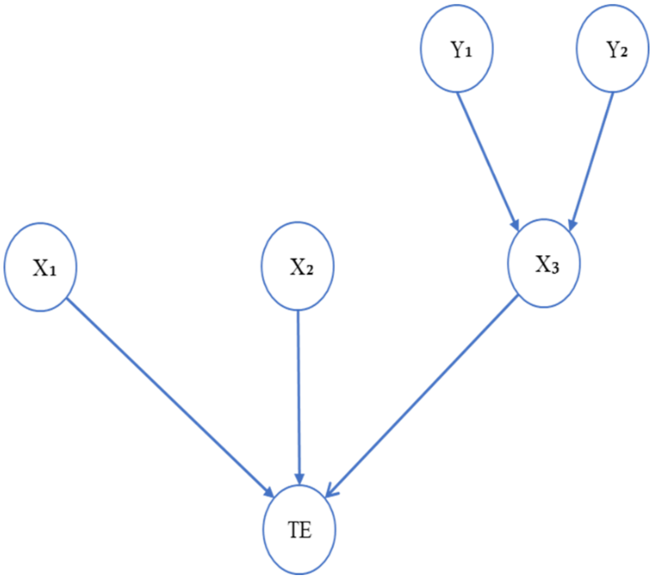


Figure 2.11: The graphical example of the Bayesian network (the figure is provided by this study).

Every node could come from some parent nodes and present some children nodes. In BN nodes are conditional dependent on each other. This feature is of the important advantages of BN because provides the possibility for cause-effect analysis. Nodes without any parents can be considered root nodes, and marginal prior probabilities are assigned to root nodes (Bian, 2021).

Usually, random variables for each node in a BN, Z= {X1, X2 ... Xn}, are discrete; however, it is possible to formalize some form of continuous random variables as well. The arrows between the two nodes indicate causal probabilistic between them. So, each node has a Conditional Probability Table (CPT) that contain all conditional probabilities of all combination of values of the node and parent nodes. The number of combinations for n variables could be 2n. As a result, a BN represents the joint distribution of variables Z= {X1, X2 ... Xn} and P(Z) by the following formula (Bobbio, 2001):

$$P(Z) = \prod_{i=1}^{n} P[Xi \mid parent(Xi)]$$

By achieved new knowledge such as new data, new information, or expert judgment in the operational life cycle of a process, which is called evidence (M), the probability P(Z) could be update based on Bayes theorem (Bobbio, 2001):

$$P(Z) = \frac{P(Z,M)}{P(M)} = \frac{P(Z,M)}{\sum_{Z} P(Z,M)}$$

Chapter 3. Methodology

This chapter aims to introduce the research methodology for this semi-qualitative study regarding developing and managing an inspection program for Ex electrical equipment ignition risk in support of IEC 60079-17 and a risk-based inspection strategy.

3.1. Research strategy and design

This study used a mix- method approach, based on both quantitative and qualitative approach data gathering. Quantitative vs. qualitative, descriptive vs. analytical, and conceptual vs. empirical are only examples of different research methods, which can be used in risk analysis. Therefore, choosing the proper methodology is very important for the success of RBI. Qualitative, quantitative, and semiquantitative methods are three different approaches that are commonly used in the RBI process (Bai et al. 2014).

A qualitative method usually uses an engineering judgment-based approach for risk assessment. In this approach, the failure probability is based on qualitative rankings of PoF and CoF. Therefore, the results present a rough estimation because of the consideration of few essential data. In a qualitative method, analysts do not calculate a numerical value, using descriptive ranking such as low, medium, or high. Quickly assessment process with a low initial cost, no many requirements for detailed information, and accessible presentation and understanding results can be named as advantages for RBI qualitative method (Bai et al. 2014).

Since the 1970s, Quantitative Risk Assessment (QRA) has been started in the nuclear industry as the basis for supporting risk-related decisions. Quantitative methods are model-based approaches. QRA calculated the risk by probability tools and expresses metrics for PoF and Cof based on computing probabilities for the events, scenarios, and related outcomes (Bai et al. 2014). Quantitative risk assessment required more data, so a much more comprehensive database presents more reliability where the PoF value can be evaluated by structural reliability and well-published numerical consequence modeling support CoF value. For instance, PLL (Potential Loss of Lives) expresses the expected number of fatalities in terms of indices for an individual risk, and the expected number of accidents can be presented by FAR (Fatal Accident Rate) and f-n curves (Aven, 2020).

As mentioned in section 2.1, this study describes risk as specified consequences with associated uncertainty (typically probability) and the background knowledge that supports consequences and uncertainty. It is essential to consider that QRA is based on some knowledge, which could be more or less strong and also wrong. Knowledge is not objective; it is inter-subjective among experts. The main aim of using different research methodologies is to provide knowledge by the most justified representation. How can be represented uncertainties is the crucial point and most important issue in risk analysis. Experiments, case studies, questionnaires, interviews, simulation, various statistical methods, etc., can be used as a tool for this matter, and any tool has limitations and should be adopted. In risk analysis, the metrics' knowledge also needs to be considered and explain what probability's results mean; therefore, risk cannot be characterized only by numbers (Aven, 2020).

As a result, choosing a purely quantitative or qualitative approach brings challenges to representing and treating all types of risks and uncertainties. Semiquantitative methods use more information and calculations to solve this problem, and results can be more accurate (Bai et al. 2014). Therefore, this thesis used the semiquantitative approaches, which are widely used in RBI. Figure 3.1 illustrates the main steps of this thesis.

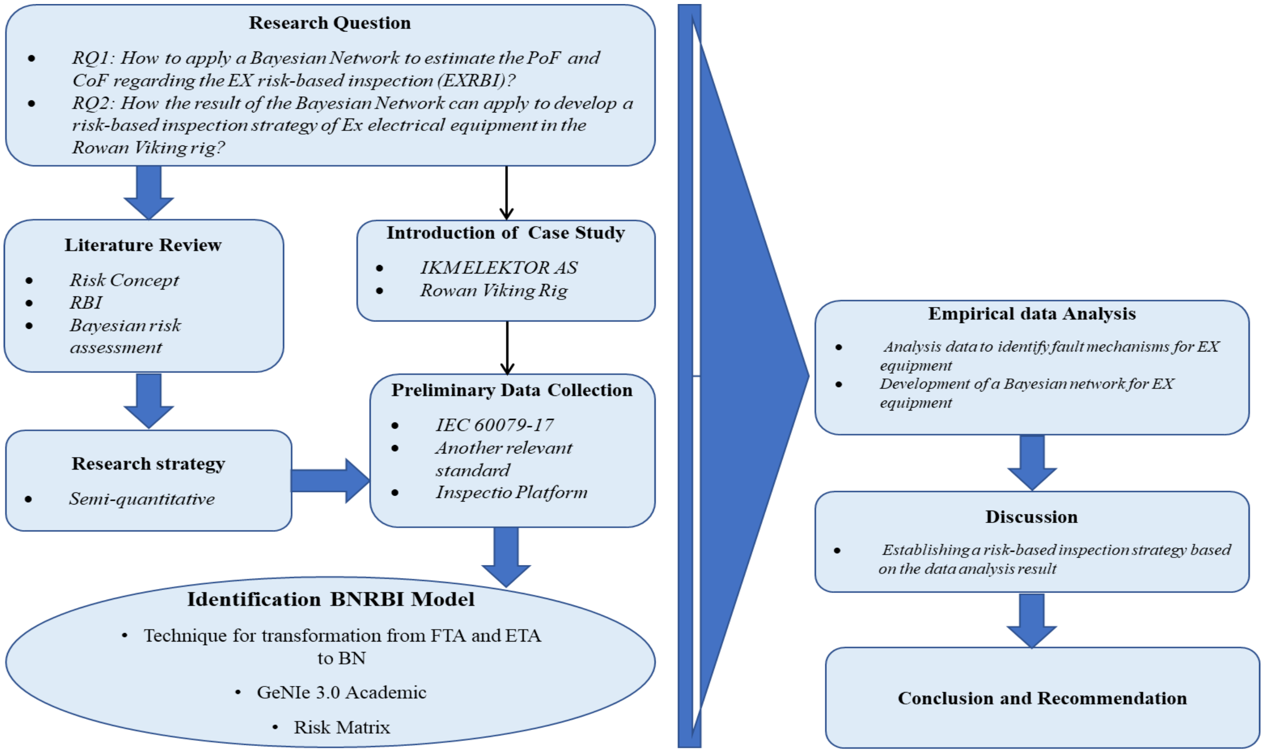


Figure 3.1. The research structure (provided by this study).

After the field of research is identified and research questions have been developed, relevant theories defined which type of research could be more appropriate. Then, all available and relevant data have been collected based on the research design. Data have been sorted and classified. The technique for transforming available data to the BN identified and appropriate software has been chosen. Data have been analyzed and transfer to a primary BN. Then primary BN has been updated based on expert knowledge and historical data. RBI strategies have been selected, then inspection strategy applied by BN and conclusion have been made.

3.2 Preliminary data collection

In addition to relevant scientific literature and articles, this study used several documents, which are present in the table 3.1.

Tabel 3.1: Relevant documents

Data	Topic	Edition
IEC 60079-17	Explosive atmospheres- part 17: Electrical installation inspection and maintenance	IEC 60079 - 17: 2013
ATEX Directive guideline	The directive for equipment for potentially explosive atmospheres defines the essential health and safety requirement and conformity assessment procedures to be applied before products are placed on the EU market.	ATEX Directive 2014/34/EU
NORSOK Z-013	Risk and emergency preparedness analysis	NORSOK Z-013: 2010
ISO 31010	Risk management - Risk assessment techniques	IEC 31010: 2019
ISO 2859-1	Sampling procedures for inspection by attributes- part 1: sampling schemes indexed by acceptance quality limit (AQL) for lot-by-lot inspection	ISO 2859-1: 1999
IP Research Report	Ignition Probability Review, Model Development and Look-up Correlations	January 1, 2006
EI Guideline	Guidelines for managing inspection of Ex electrical equipment ignition risk in support of IEC 60079-17.	First edition, October 2008
GeNIe	Software for modeling a Bayesian Network.	Version 3.0.R2, Built on 11/5/2020
Inspectio	The platform for registration the inspection data	

IEC 60079-17

The IEC 60079 series of international standards specifies the general requirements for designing Ex electrical equipment, and part 17 of this document includes information on its maintenance and inspection.

According to IEC 60079-17:2013, Ex equipment should be maintained based on its functional requirements, and inspection ensures that equipment continues to comply with its original Ex certification requirements. This document divided inspection into four different types: initial inspection, periodic inspection, sample inspection, continuous supervision, and visual, close, and detailed can be different grads of inspection.

ATEX Directive

ATEX stands for ATmosphere EXplosive; this directive defines the workplace's essential health and safety requirements and equipment used in an explosive atmosphere. ATEX directive 2014/34/EU, used in this thesis, replaced the previous ATEX Directive 94/9/EC, which was applicable between 1 July 2013 and 19 April 2016. The Guidelines are used in this thesis in conjunction with the directive itself (European, 2021).

Two relevant ATEX documents for this thesis are ATEX 100a and ATEX 137. ATEX 100a includes *"approximation of the Laws of Member States concerning Equipment and Protective Systems Intended for Use in Potentially Explosive Atmospheres,"* which is known as The ATEX 'Equipment Directive'; And ATEX 137 presents *"Directive on the Minimum Requirements for Improving the Health and Safety of Workers Potentially at Risk from Explosive Atmospheres" and is known as The ATEX 'Workplace Directive'.*

NORSOK Z-013

NORSOK standards are developed by Standards Norway and supported by OLF (The Norwegian Oil Industry Association) in the line of adequate safety, value adding and cost effectiveness for petroleum industry developments and operations. NORSOK Z-013 has covers the emergency preparedness planning in the Norwegian offshore oil & gas industry.

The aim of this standard is to describe how to plan for emergency response and establish requirements for consequence-reducing. NORSOK Z-013 presents requirements for effective planning and executive of risk and (or) emergency preparedness assessment in contribution with other international standards and industry guidelines to meet the NORSOK goals.

ISO 31010

Another relevant standard of The International Electrotechnical Commission (IEC) used in this study is IEC 31010:2019.

International Standard IEC 31010 has been prepared by The International Organization for Standardization and The International Electrotechnical Commission (IEC). It presents guidance on selecting and applying techniques for assessing risk to help improve the way uncertainty.

This document uses ISO 31000 risk assessment steps to identify, analyze, and evaluate risk, and it focuses on understanding uncertainty and its effects. The first edition was published in 2009. However, this study used the second edition, which cancels and replaces the first edition.

ISO 2859-1

ISO 2859-1 specifies sampling procedures for inspection by attributes where sampling is indexed by the acceptance quality limit (AQL). Although this standard has been developed for manufacturing applications, IEC 60079-17 guideline is provided suitable adaptations of it to the inspection of Ex electrical equipment.

IP Research Report

IP research report provides a guideline for the probability of ignition of flammable releases from onshore and offshore installations for quantitative risk analysis. This document reviewed current data in the petroleum industry (such as Cox et al., HSE OSD research, E&P forum, Ws Atkins, OIR12, etc.) and developed an ignition probability model for assigning ignition probabilities in quantitative risk analysis. In addition, it formed a superficial basis and guidance to assist practitioners in assigning ignition probabilities to generic scenarios. Energy Institute publishes this document.

EI Guideline

Guidelines for managing inspection of Ex electrical equipment ignition risk in support of IEC 60079-17 are another document from the Energy Institute used in this study. This document presents the methodology for EX inspection based on the sampling plan.

GeNIe academic version 3.0

This software was developed by BayesFusion LLC in 2015 and acquired a license from the University of Pittsburgh. This company has three software as GeNIe and SMILE Engine for quantitative BN and QGeNIe for qualitative BN. One can download the free academic version of GeNIe 3.0 from the company website through the link https://www.bayesfusion.com.

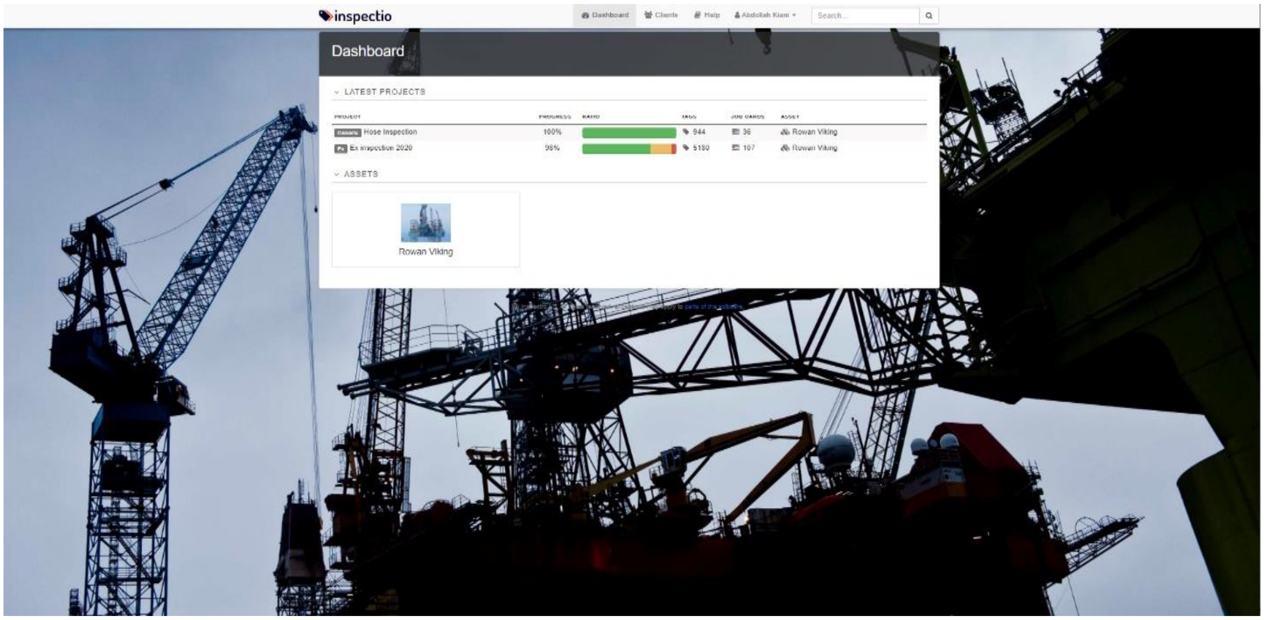
GeNIe has been written for the Windows operating systems, and the complete installation of the software requires less than 30 MB of disk space. Still, it is possible to use it on a Mac with Boot Camp. A helpful user manual for software is available on the company website. By GeNIe 3.0 academic version could create Clemen Models, Discrete Bayesian Networks, Dynamic Bayesian Networks, Hybrid Bayesian Networks, and Influence Diagrams.

This software consists of different useful tools that allow the user to expand a BN quickly and avoid calculate complex functions manually. It could be possible to reduce the number of variables that are not dependent on the BN by several tools like Noisy Max, Noisy Add, etc. Therefore, the result of the analysis could be based on the correct value for parameters. It could be possible to reduce the number of variables that are not dependent on the network by several tools like Noisy Max, Noisy Add, etc.

For more information about the software and its functionality, please peruse the user manual.

Inspectio Platform

Modeling an effective EX RBI program requires specific data such as hazardous area classification, protection type, environmental conditions, equipment age, etc. Therefore, the recorded data are essential for EX maintenance and RBI strategy. These initial data, including historical information on installed Ex electrical equipment on the Rowan Viking rig, are provided by the Inspectio platform. IKM Elektor As has provided access to Inspectio platform for this study. Inspectio is a platform that is comfortable with web and mobile technologies as well. Figure 3.2 shows the Inspectio platform dashboard.



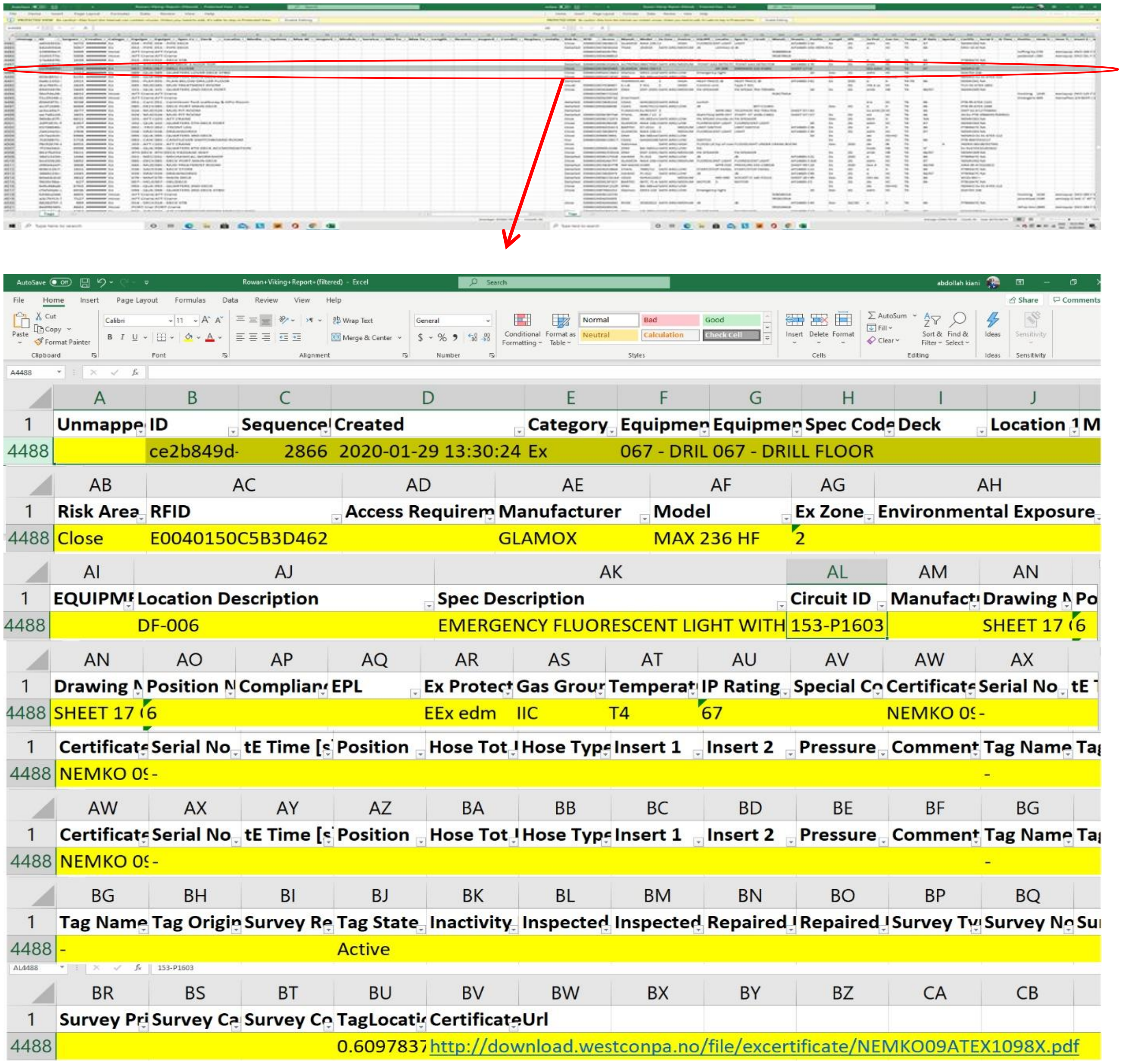
PROJECT	PROGRESS	RATIO	TAGS	JOB CARDS	ASSET
Hose Inspection	100%	🟩	944	36	Rowan Viking
Ex inspection 2020	98%	🟩🟨🟥	5180	107	Rowan Viking

Figure 3.2: Inspectio platform dashboard (Provided by Inspectio software)

In this platform, companies can record their database for digital inspection in the hazardous area and offshore industry (inspection.no). EX equipment can be registered in Inspection based on their tag number and recorded all relevant documents and historical inspection reports. One can provide information about all equipment for the project in an excel sheet and individual reports for concerned equipment based on its tag number on a PDF file.

Because of the enormous size of the excel sheet report, figure 3.3 shows only a part of the excel report. For instance, consider row 4488 the "EMERGENCY FLUORESCENT LIGHT." Column B shows ID and column C sequence of tag number. The date of creation can be found in column D and the Ex-zone in column AG. As figure 3.3 shows, one can summarize all relevant information by following columns of the excel sheet.

When requires more consideration and detailed information of a particular piece of equipment, one can use tag numbers in the search bar and obtain recorded data. Annex A illustrates a sample of these types of reports.



	A	B	C	D	E	F	G	H	I	J
1	Unmappe	ID	Sequence	Created	Category	Equipmen	Equipmen	Spec Code	Deck	Location 1 M
4488		ce2b849d-	2866	2020-01-29 13:30:24	Ex	067 - DRIL	067 - DRILL FLOOR			

	AB	AC	AD	AE	AF	AG	AH
1	Risk Area	RFID	Access Requirem	Manufacturer	Model	Ex Zone	Environmental Exposure
4488	Close	E0040150C5B3D462		GLAMOX	MAX 236 HF	2	

	AI	AJ	AK	AL	AM	AN
1	EQUIPMI	Location Description	Spec Description	Circuit ID	Manufact	Drawing N Po
4488		DF-006	EMERGENCY FLUORESCENT LIGHT WITH	153-P1603		SHEET 17 (6

	AN	AO	AP	AQ	AR	AS	AT	AU	AV	AW	AX
1	Drawing N	Position N	Complian	EPL	Ex Protect	Gas Group	Temperat	IP Rating	Special Co	Certificate	Serial No tE T
4488	SHEET 17 (	6			EEx edm	IIC	T4	67		NEMKO 0	-

1	Certificate	Serial No	tE Time [s	Position	Hose Tot	Hose Type	Insert 1	Insert 2	Pressure	Comment	Tag Name Ta
4488	NEMKO 0	-									-

	AW	AX	AY	AZ	BA	BB	BC	BD	BE	BF	BG
1	Certificate	Serial No	tE Time [s	Position	Hose Tot	Hose Type	Insert 1	Insert 2	Pressure	Comment	Tag Name Ta
4488	NEMKO 0	-									-

	BG	BH	BI	BJ	BK	BL	BM	BN	BO	BP	BQ
1	Tag Name	Tag Origin	Survey Re	Tag State	Inactivity	Inspected	Inspected	Repaired	Repaired	Survey Ty	Survey No Su
4488	-			Active							

AL4488 153-P1603

	BR	BS	BT	BU	BV	BW	BX	BY	BZ	CA	CB
1	Survey Pri	Survey Ca	Survey Co	TagLocatio	CertificateUrl						
4488				0.6097837	http://download.westconpa.no/file/excertificate/NEMKO09ATEX1098X.pdf						

Figure 3.3: Emergency fluorescent light report (provided by Inspectio platform)

3.3 The Bayesian Network Methodology for risk-based inspection

Nowadays, inspection and maintenance have become a strategic concern in many industries to protect the public, financial investment, and the environment against the consequences of failures. Due to the increase in the variety of physical assets, more complex design, and changes in organizations' responsibilities, inspection and maintenance have considerably changed over the last few decades than other management disciplines. Because of the limitation on the maintenance resources, the available sources and funds should be spent more efficiently to reduce potential risks Abbasi et al. 2016).

Inspection plays an essential role in detecting potential risks by detecting potential failures. These have led to the emergence of a new view to inspection and maintenance approach, known as risk-based inspection (RBI). The main objective of RBI is to find an appropriate balance between the benefits of inspection and the cost of maintenance and inspection. Therefore, RBI strategies classify the level of risk of equipment or systems and then reduce the extra expense by reducing maintenance for equipment with lower risk (Abbassi et al. 2016).

According to current inspection strategies, should inspect a nominal percentage of all EX-equipment per annum. In some cases, it can be more than 50000 items, and in practice, it is not possible. Therefore, the cost of inspection increases, but the weight of the risk of ignition for critical equipment consider the same as others. However, such approaches do not best target inspection resources because different types of EX equipment present various risks based on their characteristics (EI, 2008).

Mapping from Fault Tree Analysis (FTA) to Bayesian Network.

In 1988, Pearl propounded the Bayesian network, and it has received increasing attention in different fields in the past few years because of its strong uncertainty reasoning ability. A BN combines probability theory and graph theory and represents a graph with a set of probability tables (Bian, 2021). Babio et al. (2001) discussed how can transcend the limitations of FTA by relying on the Bayesian network. This section of the thesis used a simple example of failure probability to clarify the algorithm for transmission from FTA to BN.

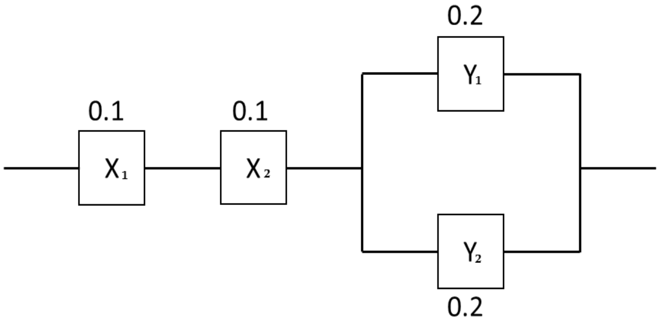


Figure 3.4: The example figure (Created by this study).

Consider an electrical system consists of four components X_1, X_2, Y_1, and Y_2, such as figure 3.4. The system works when components X_1 and X_2 and either of the components Y_1 or Y_2 works. The aim is to calculate the probability of failure for the system. Figure 3.5 shows FT for the example.

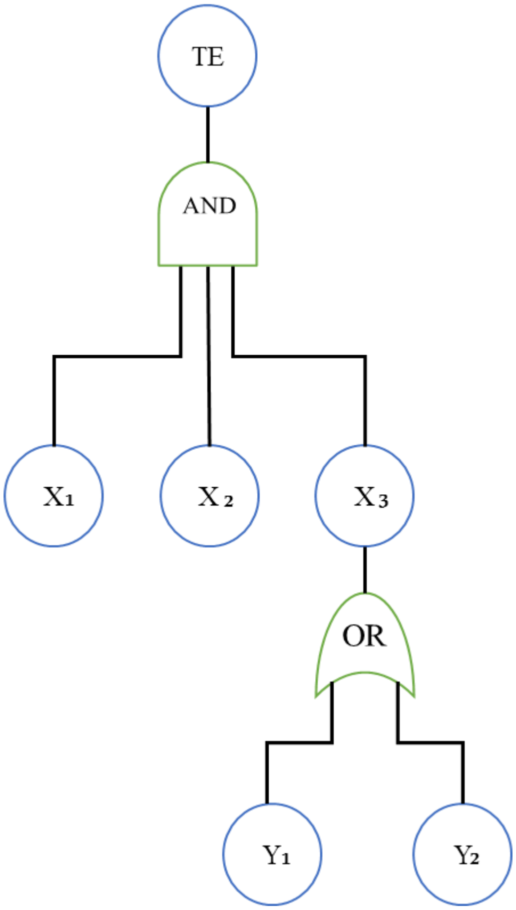


Figure 3.5: FT for example (created by this study)

In the example, FTA defines the probability of failure for the system by:

$P[A \cap B \cap (C \cup D)] = (0.1)(0.1)[1-(0.2)(0.2)]=0.0036$

Converting from FTA to BN consist of two tasks, probability transformation and graphic transformation. Figure 3.6 illustrated the mapping algorithm for converting.

The primary event, intermediate event, and top event of FT convert to the root node, intermediate node, and child node for BN. Consider X_1 in figure 3.5 X_1 represents the status of a binary component. Therefore, it could be assigned values $X1 = 0$ if the component is working and $X_1 = 1$ if there is a failure. On the other hand, X_1 will be inspected at time t, and the probability distribution of $X_1 = 1$ = faulty could be considered the prior probability for each basic node.

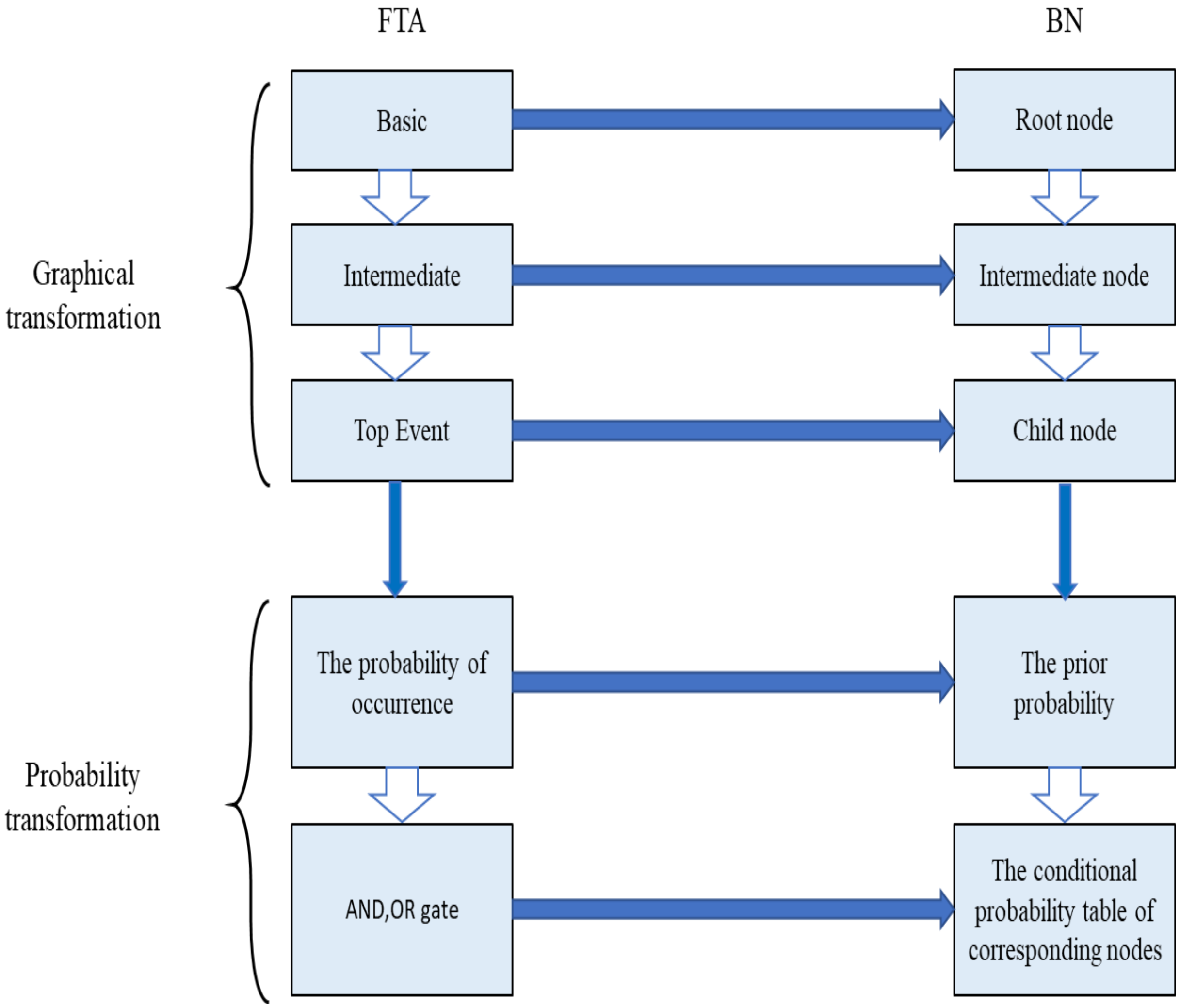


Figure 3.6 algorithm for converting from FT to BN (Bobbio, 2001).

Transforming logic gates (OR and AND) from FT by CPT into BN could be the main challenge of modeling. Consider Figures 3.5, basic events Y_1 and Y_2 are parents' nodes for BN, and output events X_3 is the child node (the same logical relationships are between X_1, X_2 and X_3 with TE).

The purpose is to use the logic relation between parents' nodes and assign conditional probability tables for children's nodes. The logic gates represent deterministic causal relationships, where Fault=1 and working=0; consequently, all the entries of the corresponding CPT are either 0s or 1s.

Table 3.2 shows entries CPT assigned to nodes X3 and TE.

Table 3.2: Conditional Probability Table (CPT) for the example	
$X_3 = Y_1$ OR Y_2	TE = X_1 AND X_2 AND X_3
$P(X_3=1 \mid Y_1=0, Y_2=0) = 0$	$P(TE=1 \mid X_1=0, X_2=0, X_3=0) = 0$
$P(X_3=1 \mid Y_1=1, Y_2=0) = 1$	$P(TE=1 \mid X_1=0, X_2=0, X_3=1) = 0$
$P(X_3=1 \mid Y_1=0, Y_2=1) = 1$	$P(TE=1 \mid X_1=0, X_2=1, X_3=1) = 0$
$P(X_3=1 \mid Y_1=1, Y_2=1) = 1$	$P(TE=1 \mid X_1=0, X_2=1, X_3=0) = 0$
	$P(TE=1 \mid X_1=1, X_2=0, X_3=0) = 0$
	$P(TE=1 \mid X_1=1, X_2=1, X_3=0) = 0$
	$P(TE=1 \mid X_1=1, X_2=0, X_3=1) = 0$
	$P(TE=1 \mid X_1=1, X_2=1, X_3=1) = 1$

0 = The System Work 1 = The System Failure

In many cases, FTA presents implicit gates like figure 3.7.

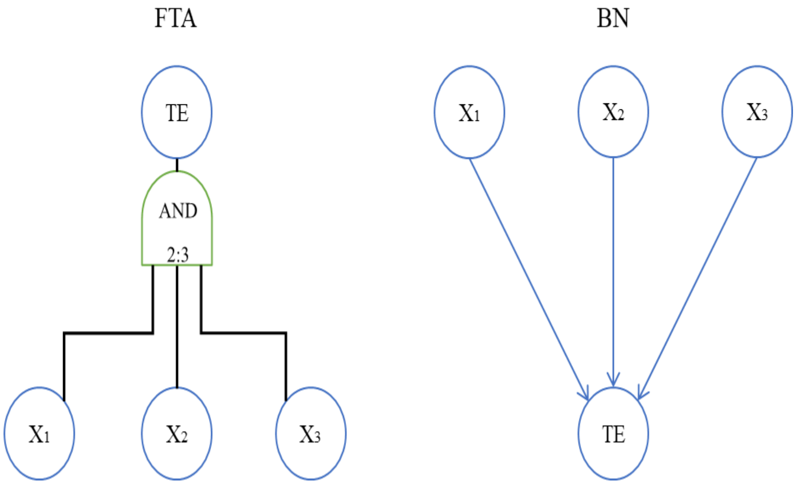


Figure 3.7: Implicit AND gate (Bobbio, 2001).

Practically an FTA solver uses Boolean functions to tackle the problem. Therefore, BN should modify the corresponding CPT based on Boolean functions as follow (Bobbio, 2001):

$P(TE=1 \mid X_1 = 0, X_2 = 0, X_3 = 0) = 0$

$P(TE=1 \mid X_1 = 1, X_2 = 0, X_3 = 0) = 0$

$P(TE=1 \mid X_1 = 0, X_2 = 1, X_3 = 0) = 0$

$P(TE=1 \mid X_1 = 0, X_2 = 0, X_3 = 1) = 0$

$P(TE=1 \mid X_1 = 1, X_2 = 1, X_3 = 0) = 1$

$P(TE=1 \mid X_1 = 0, X_2 = 1, X_3 = 1) = 1$

$P(TE=1 \mid X_1 = 1, X_2 = 0, X_3 = 1) = 1$

$P(TE=1 \mid X_1 = 1, X_2 = 1, X_3 = 1) = 1$

In a BN, n variables can present 2^n combinations. As is shown in table 3.2, node X3 with two-parent nodes has $2^2=4$ parameters, and node TE with three parents has $2^3=8$ parameters. Since the number of parameters is exponential in the number of parents, and the number of parameters could grow exponentially. Please consider a node with 15 parents; then, the number of parameters could be 32768 and increase to 1048576 parameters by adding only five new parents.

On the other hand, a BN represents probability distributions of each variable conditional on other variables. Every joint probability distribution over n random variables can be factorized in n! ways. Consider a simple BN with four-node A, B, D, and C then the joint probability distribution over these four variables can be factorized in 4! =24 ways as follow:

$P(A, B, C, D) = P(A \mid B, C, D)\, P(B \mid C, D)\, P(C \mid D)\, P(D)$

$P(A, B, C, D) = P(A \mid B, C, D)\, P(B \mid C, D)\, P(D \mid C)\, P(C)$

$P(A, B, C, D) = P(A \mid B, C, D)\, P(C \mid B, D)\, P(B \mid D)\, P(D)$

$P(A, B, C, D) = P(A \mid B, C, D)\, P(C \mid B, D)\, P(D \mid B)\, P(B)$

....

$$P(A, B, C, D) = P(D \mid A, B, C)\, P(A \mid B, C)\, P(B \mid C)\, P(C)$$

As a result, an expanded BN by belief updating is computationally complex. The other source that the complexity of probabilistic models could stem from is the connectivity of the directed graphs modeling the problem structure (Cooper, 1990). Anyway, several efficient software (MSBN, GeNIe, HUGIN, etc.) make the expansion of a BN easier and reduce the risk of a mistake on computationally complex. As mentioned, this study uses GeNIe 3.0 academic version.

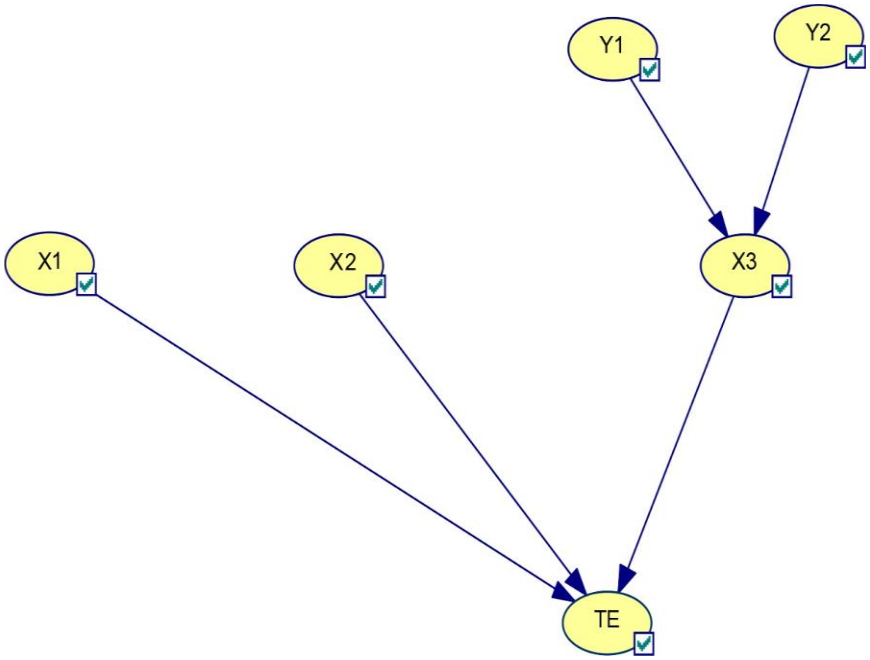


Figure 3.8: The GeNIe graph view window (Created by GeNIe academic version 3.0).

Figure 3.8 shows the model for example graphically. By double-clicking on the node Y_1, the node properties window could be opened; then, it is possible to assign the prior distribution values for each state in the definition part as follow:

State 0 = Working = 0.8

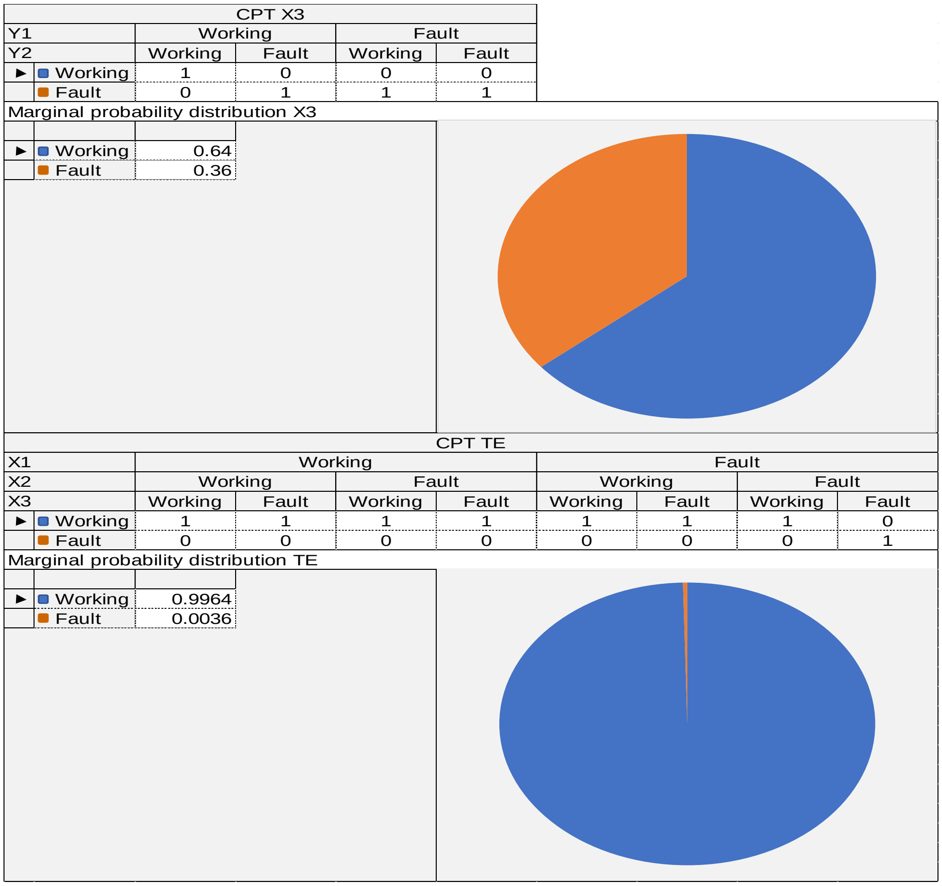
State 1 = Fault = 0.2

The same task is required for nodes X_1, X_2, X_3, and Y_2. The CPT table for node X_3 should be written as follow:

Table 3.3: The CPT table for X_3

States for parent nodes		States for Child Node	
		Node X3	
Y_1	Y_2	Working	Fault
Working	Working	1	0
Working	Fault	0	1
Fault	Working	0	1
Fault	Fault	0	1

By assigning the CPT to the child nodes X3 and TE, the result of BN and the values for critical parameters are shown in figure 3.9. The result is equal to FTA, and the probability of failure for the system is 0.0036.



CPT X3

Y1	Working		Fault	
Y2	Working	Fault	Working	Fault
► 🟦 Working	1	0	0	0
🟧 Fault	0	1	1	1

Marginal probability distribution X3

► 🟦 Working	0.64
🟧 Fault	0.36

CPT TE

X1	Working				Fault			
X2	Working		Fault		Working		Fault	
X3	Working	Fault	Working	Fault	Working	Fault	Working	Fault
► 🟦 Working	1	1	1	1	1	1	1	0
🟧 Fault	0	0	0	0	0	0	0	1

Marginal probability distribution TE

► 🟦 Working	0.9964
🟧 Fault	0.0036

Figure 3.9: The result of BN (created by GeNIe academic version 3.0)

Mapping from Event Tree Analysis (ETA) to Bayesian Network.

Figure 3.10 shows the algorithm for transmission from ETA to BN (Bearfield & Marsh, 2005).

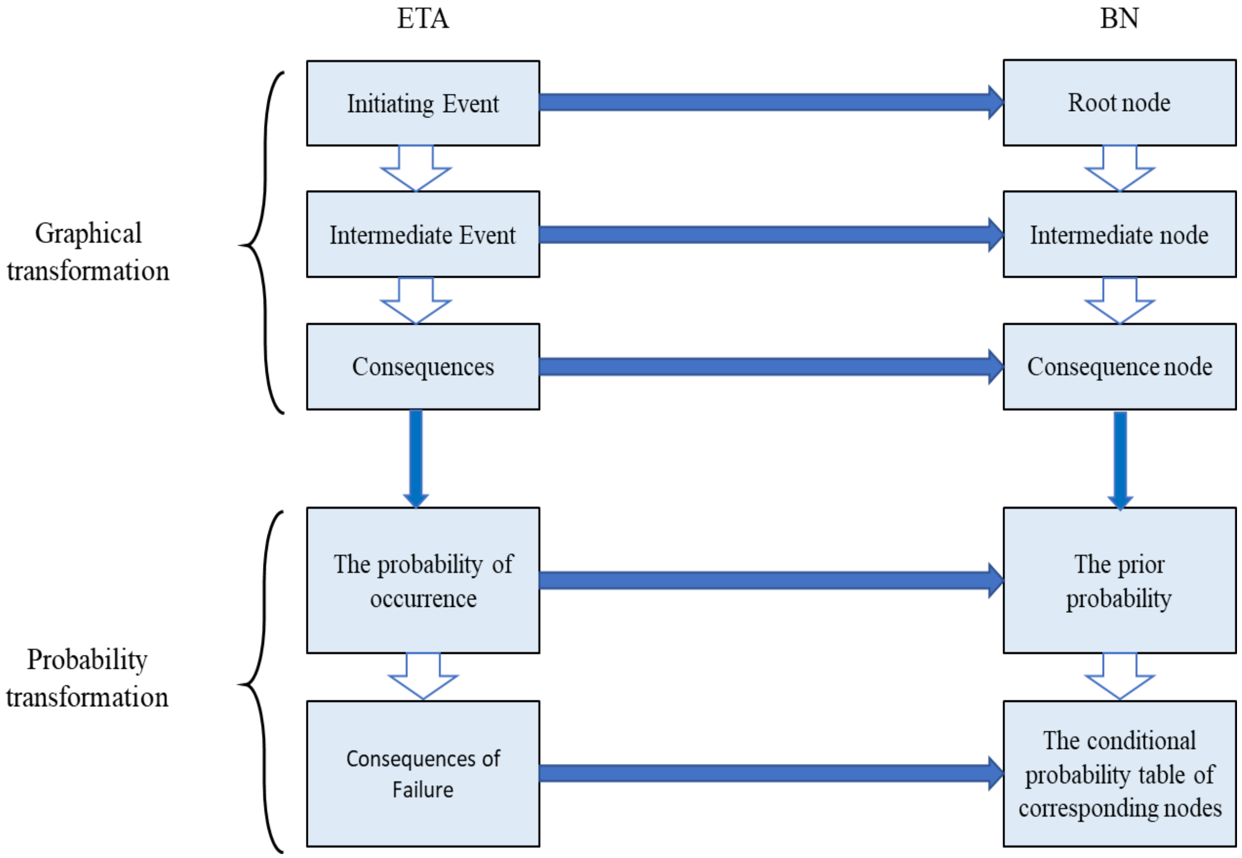


Figure 3.10: Algorithm from ETA to BN (Bearfield & Marsh, 2005).

Consider the previous example; the analysis aims to quantify the consequences of failure where there is a potential for ignition. The top event on PoF analysis could be considered as the initial event on CoF analysis. The initial event may create undesirable events, such as immediate ignition and delayed ignition, respectively. The final consequences could be fire, explosion, and no consequences, where CoF=C_1+C_2. Figure 3.11 illustrates the ET.

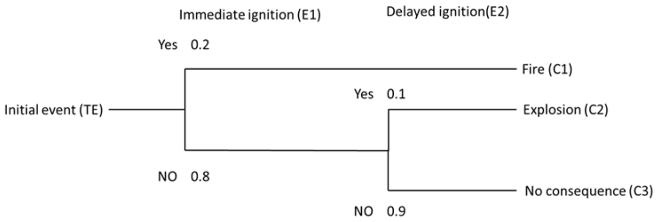


Figure 3.11: Example for ET (Created by this study).

Figure 3.12 shows the graphic view window on GeNIe after updating new information. This software provides two possibilities for a graphic view window. The result can be shown in icon shape like figure 3.8 or by bar chart like figure 3.12.

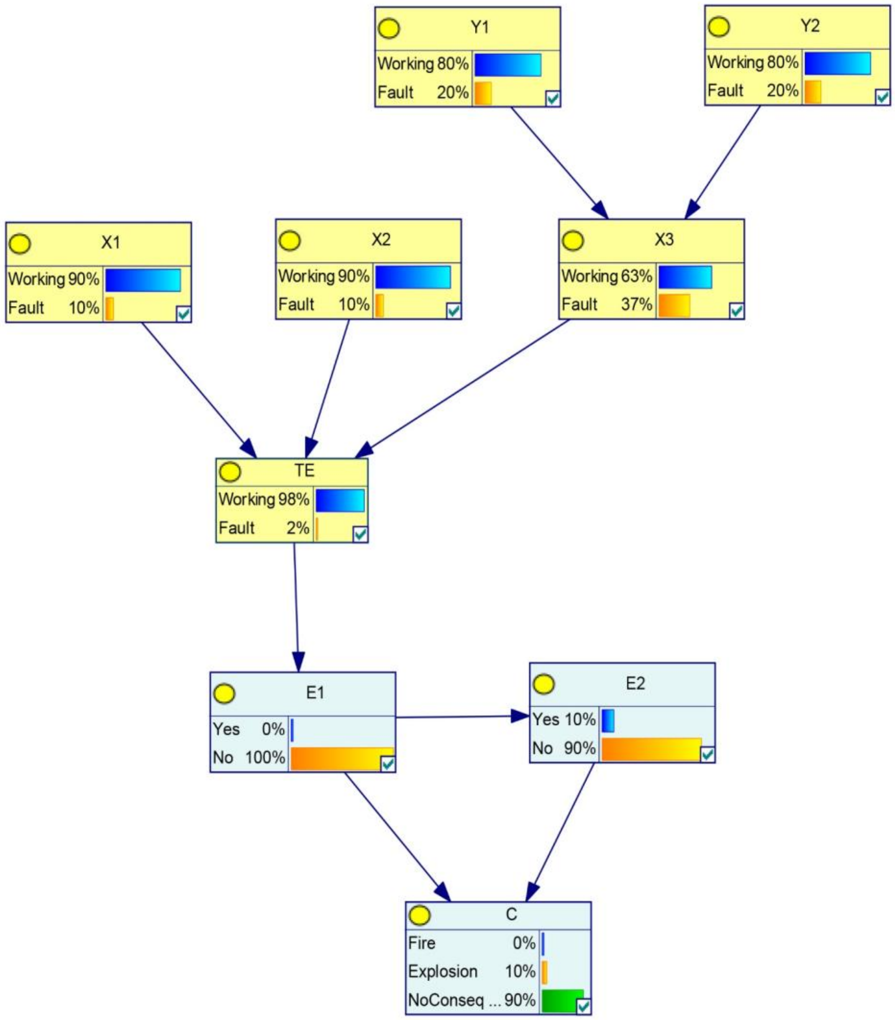


Figure 3.12: The GeNIe graph view window for resultof example (Created by GeNIe academic version 3.0).

The concept of the consequence node is the same as the concept of the logic gates on FTA and express a deterministic causal relationship.

As mentioned earlier, generally, in risk-based approaches, the risk is a product of the probability of failure and consequence of failure. Therefore, these two parameters are the main blocks of risk-based analysis. Still, the relationship between these two is unclear in most calculations (Bai et al. 2015). Consider node C in the example as the target node; by selecting sensitivity analysis from the network toolbar, the algorithm calculates a complete set of derivatives of the posterior probability distributions over the target nodes over each of the numerical parameters of the Bayesian network efficiently. When the product is significant for a parameter p, then a slight change in p may lead to a considerable shift in the posteriors of the targets. Highly sensitive parameters affect the reasoning results more significantly.

On the one hand, this feature provides an opportunity for analyzers to identify critical parameters and deal with them, and on the other hand, identifies critical events of models. Figure 3.13 illustrates the sensitivity analysis of the model and informs nodes E_1 and TE are vital to the model. In the word, PoF and E1 have more effect on CoF than others.

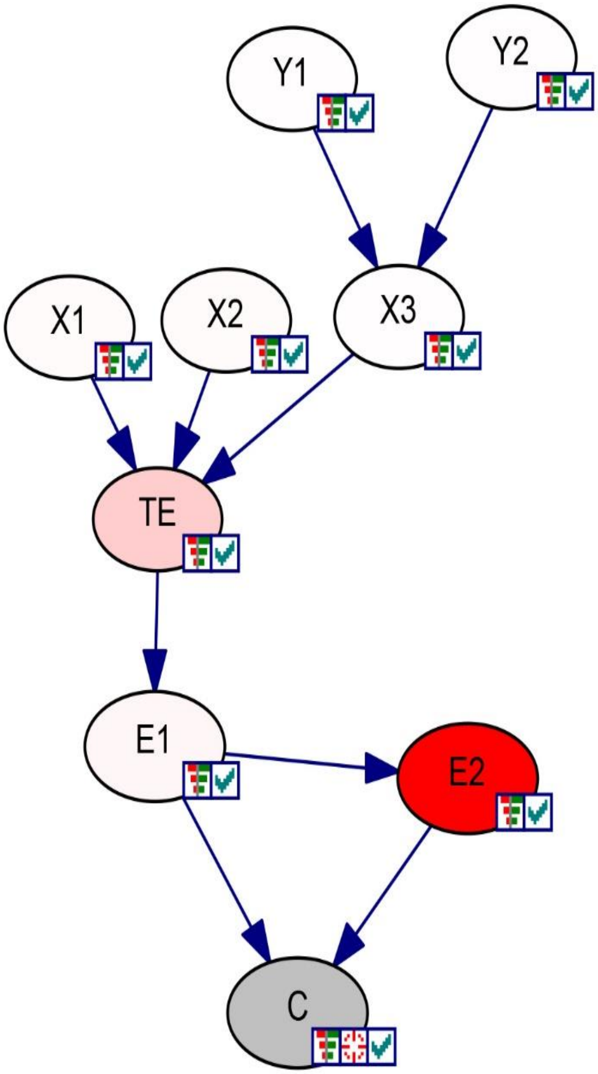
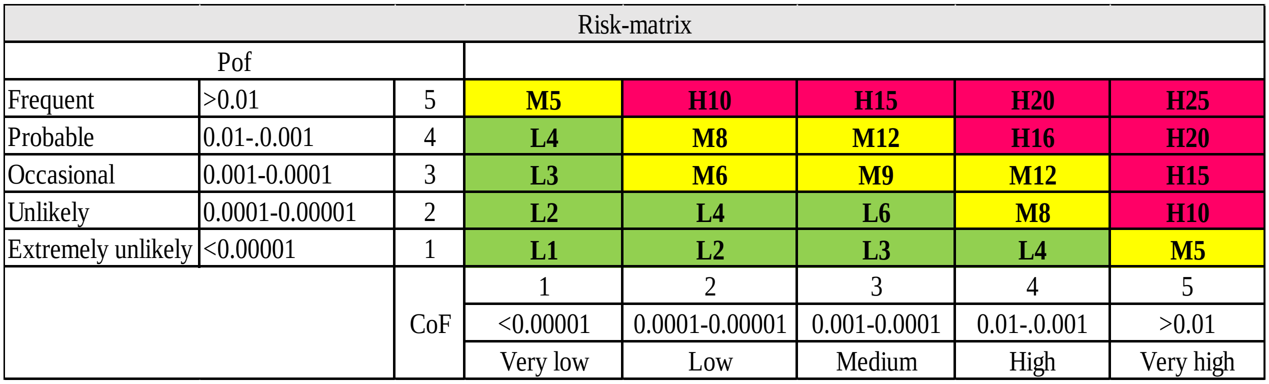


Figure 3.13: Sensitivity analysis (Created by GeNIe academic version 3.0).

4.4. Risk Matrix

POF and CoF results will be introduced in five-level, and then a 5x5 risk matrix will develop based on API-580 guideline recommendation. Figure 3.14 illustrates the risk matrix.



Risk-matrix								
Pof								
Frequent	>0.01	5	**M5**	**H10**	**H15**	**H20**	**H25**
Probable	0.01-.0.001	4	**L4**	**M8**	**M12**	**H16**	**H20**
Occasional	0.001-0.0001	3	**L3**	**M6**	**M9**	**M12**	**H15**
Unlikely	0.0001-0.00001	2	**L2**	**L4**	**L6**	**M8**	**H10**
Extremely unlikely	<0.00001	1	**L1**	**L2**	**L3**	**L4**	**M5**
		CoF	1	2	3	4	5
			<0.00001	0.0001-0.00001	0.001-0.0001	0.01-.0.001	>0.01
			Very low	Low	Medium	High	Very high

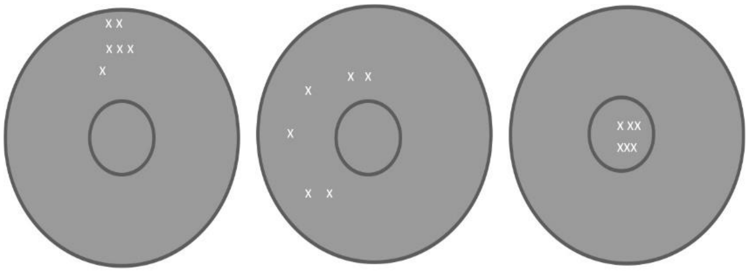
Figure 3.14: Risk matrix (Created by this study)

This study uses the qualitative risk matrix. BN analysis could be transferred to the risk matrix and present the risk of ignition in three-level low, medium, and high.

The vertical axis assigned to the value of POF and could be frequent, probable, occasional, unlikely, and extremely unlikely based on the result of the analysis. The horizontal axis identifies the level of COF. It could be very low, low, medium, high, and very high.

4.5 Reliability and Validity

According to Aven (2020), "*the concept of reliability is concerned with the consistency of the 'measuring instrument' (analysts, methods, procedures), whereas validity is concerned with the success at 'measuring' what one set out to 'measure' in the analysis*." Figure 3.15 shows traditional illustrations of the concepts of reliability and validity.



Reliable but not valid   Not reliable, not valid   Reliable, valid

Figure 3.15: Traditional illustrations of the concepts of reliability and validity (Aven, 2020).

The circle center presents the actual value and will be achieved when the analysis has repeated quantity measurements. The result of research could be achieved reliability when the measurements are close to each other and could achieve validity when measurements are close to the center.

Consider P as the frequentist probability that a chosen component in a considerable population of ex equipment has a specific failure. By repeated sampling, reliability and validity could be obtained. The reputation of the same failure in many observations shows consistency (reliability) and accuracy (validity) relative to the actual P.

This perspective on reliability and validity is based on the traditional statistic theory. Still, it is so difficult to obtain these two concepts based on the conventional view in the real world. Consider the situation where two different teamwork in the same area to evaluate the risk of equipment. As mentioned in the theoretical chapter, the probability of failure these two groups provide is conditional based on their knowledge background. Consequently, they could present different P, and when their background of knowledge is so far from each other, this value of P could significantly differ.

In reality, when an analysis model provides more place for dealing with uncertainty, it has more chance to obtain validity and reliability. One of the advantages of the Bayesian network is this characteristic, where it is possible to repeat sampling and provide the traditional concept of validity and reliability. On the other hand, it could be updated based on the expert's judgment and provide good dealing with uncertainty.

Chapter 4. Empirical Data Analysis

This chapter presents and analyzes data from The Rowan Viking Rig according to standards, regulations, and theoretical understanding to provide appropriate answers for research question 1: *" How to apply a Bayesian Network to estimate the PoF and CoF regarding the EX risk-based inspection (EXRBI)?"*

The start point for data analysis is based on the ISO-31000 risk assessment principle. So, this chapter contains five steps as follow:

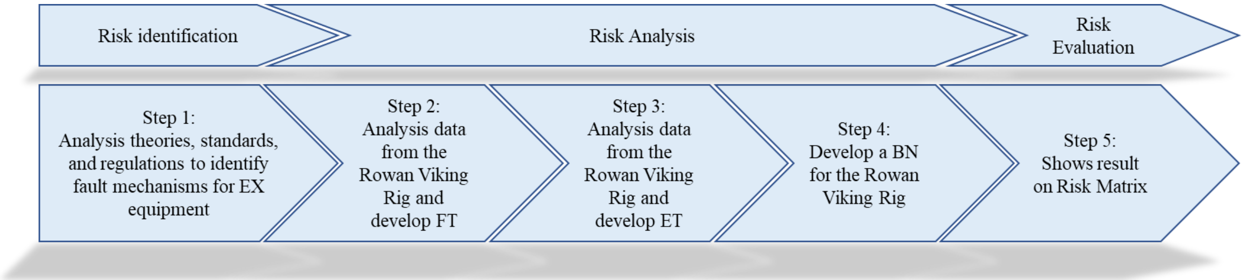


Figure 4.1: Steps for data analysis (Provided by this study)

4.1. Analysis data to identify fault mechanisms for EX equipment.

Working with electrical equipment is generally risky and, when they are used in hazardous areas, requires a fully alert about designing, installing, and maintaining these systems (Bottrill et al. 2005). IEC 60079 series provides general requirements Ex equipment (construction, testing, inspection, and marking) for explosive atmospheres. The main concern of IEC standards is about the risk of ignition, which can be created by EX equipment. IEC 60079-17 defines ignition risk for EX equipment as:

(Probability of flammable atmosphere being present) **X** (Probability of source of the ignition being present)

Therefore, first needs to identify where there is the possibility of a conducive atmosphere for ignition. The area classification could be considered a tool to ensure overall platform safety and minimize the risk of loss to life and assets (Bottrill et al. 2005). The concept of hazardous areas in this thesis refers to areas with a risk of explosion because possible flammable atmospheres exist, such as drilling rigs (offshore or onshore), petrochemical plants, or refineries. Therefore, it is necessary to ensure the electrical equipment installed in a hazardous area could not form a spark or hot surface and igniting the flammable atmosphere. According to IEC 79, flammable material is "a gas, vapor, liquid, or solid that can react continuously with atmospheric oxygen and may therefore sustain fire or explosion when such reaction is initiated by a suitable spark, flame, or hot surface." Since the case study of the thesis is an offshore rig, the hazardous materials of concern for this study are gas and oil.

Forasmuch as each installation will differ in some respects, finding a consistent method or standard for area classification will not be easy. Therefore, different industries use their accepted industry standard ways. Area classification in the offshore industry is based on three situations for hazardous areas (EI, 2008):

- Zone 2 (low risk): secondary grade release, where an explosive atmosphere rarely occurs in normal operation or only for a short period. e.g., > 1 000 hours per annum
- Zone 1 (medium risk): primary grade release, where an explosive atmosphere frequently occurs. e.g., 10-1 000 hours per annum.
- Zone 0 (high risk): continuous grade release, where an explosive atmosphere is continuously present or present for long periods (continuous). e.g., 1-10 hours per annum

According to IEC 60079-17 non-hazardous area is an *“Area in which an explosive atmosphere is not expected to be present in quantities such as to require special precautions for the construction, installation, and use of equipment.”* As it is evident, identification source of release and the grade of release are two essential elements to establishing the hazardous zone types are the identification of the.

The second factor of ignition risk is the source of ignition. The source of ignition in this study is electrical equipment installed in an offshore flammable atmosphere. When electrical equipment installing in hazardous areas, the designers should have adequate knowledge of the sources of heat generation. Electrical energy could be converted to heat energy by resistance heating, dielectric heating, induction heating, leakage current heating, heat from arcing, static electricity heating, and heat generated by lighting. Therefore, the ignition sources could ignite electrical equipment in hazardous areas through hot surfaces, electrical arcs and sparks, and electrical discharge (Bottrill et al. 2005).

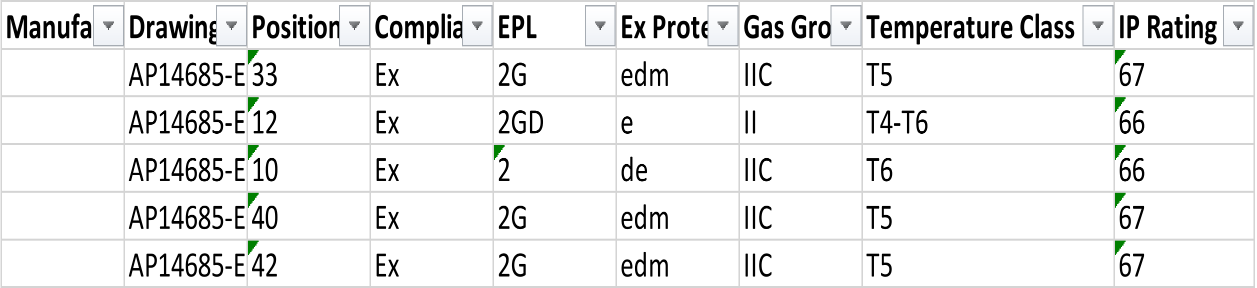
Generally, electrical equipment for an explosive atmosphere is divided into two categories. The group I includes electrical equipment for underground industries, and they are not the subject of this study. Group II contains electrical equipment for surface industries divided into three subgroups. Two important factors in this subdivision are MESG value and MIC ratio. MESG stands for maximum experiment safe gap, and MIC ratio refers to minimum igniting current ratio. Based on these two elements, different subgroups are as follow (Bottrill et al. 2005):

- IIA: MESG > 0.90 mm, and MIC > 0.80
- IIB: 0.90 mm ≥ MESG > 0.50 mm, and 0.80 ≥ MIC > 0.45
- IIC: 0.50 mm ≥ MESG, and 0.45 ≥ MIC.

Today, there are different approaches to make the equipment safe for use in hazardous areas. They are known as EX protection and are introduced by a code which depicting the type of protection. Some of these different types of protection based on IEC60079-17 are:

- flameproof ('d');
- increased safety ('e') and
- non incendive ('n');
- intrinsic safety (i,'ia', 'ib');
- pressurized apparatus ('p'), and
- other type of protection (oil-filled ('o'), powder-filled ('q'), encapsulated("m")

Data from the Inspectio platform present The Rowan Viking Rig electrical equipment according to different factors, as shown in figure 4.2. Some of these factors are already have been introduced. All equipment has been coded base on the IP rating. The Ingress Protection (IP) Codes define by two numbers, such as IP 66. The first number indicates the degree of protection against solids and could be between 0= no protection and increase until 6 = complete protection against contact and ingress of dust. The second numeral specified the degree of protection against harmful effects due to the ingress of liquid or water. It could be between 0 = no protection until 8 = Protection against indefinite immersion in water (Bottrill et al. 2005).



Manufa	Drawing	Position	Complia	EPL	Ex Prote	Gas Gro	Temperature Class	IP Rating
	AP14685-E	33	Ex	2G	edm	IIC	T5	67
	AP14685-E	12	Ex	2GD	e	II	T4-T6	66
	AP14685-E	10	Ex	2	de	IIC	T6	66
	AP14685-E	40	Ex	2G	edm	IIC	T5	67
	AP14685-E	42	Ex	2G	edm	IIC	T5	67

Figure 4.2: Columns AN, AO, AP, AQ, AR, AS, AT, and AU of report excel sheet from Inspectio platform (provided by Inspectio software).

Moreover, equipment is classified based on the maximum surface temperature. The temperature class for equipment must be lower than the ignition temperature, which could be present by the release source. These codes could vary in different standards, so table 4.1 illustrates this difference worldwide (Bottrill et al. 2005).

Table 4.1: different temperature classification codes

IEC/CENELEC Australia		Japan (RIIS-TR-79-1)		USA (NEC 1984)	
Class	Maximum Surface Temp. (° C)	Class	Maximum Surface Temp. (° C)	Class	Maximum Surface Temp. (° C)
T1	450	G1	360	T1	450
T2	300	G2	240	T2	300
				T2A	280
				T2B	260
				T2C	230
				T2D	215
T3	200	G3	160	T3	200
				T3A	180
				T3B	165
				T3C	160
T4	135	G4	110	T4	135
				T4A	120
T5	100	G5	80	T5	100
T6	85	G6	70	T6	85

Source: Bottrill et al. 2005

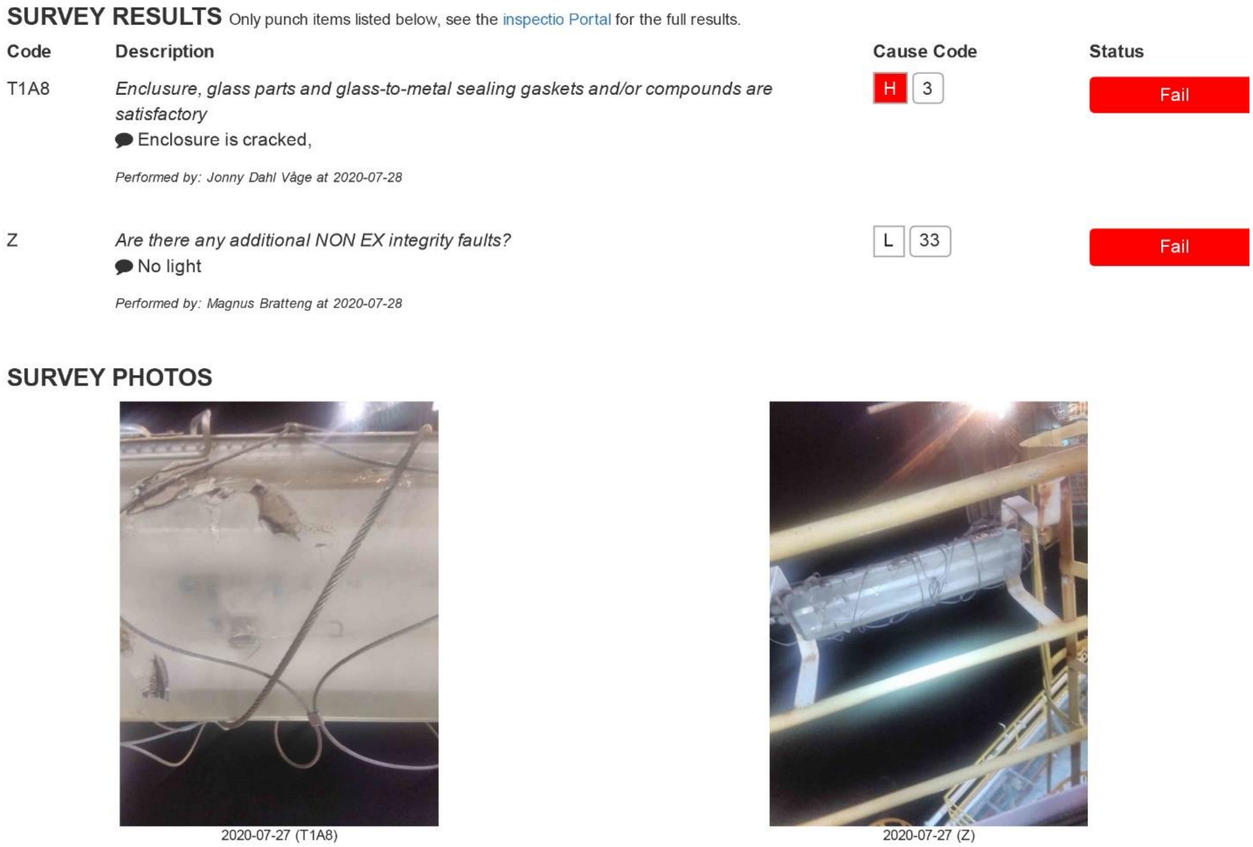
Based on historical information from the Inspectio platform, In the Rowan Viking rig, there is 5181 active EX equipment. Table 4.2 shows information about EX equipment according to this rig.

Table 4.2: information about EX equipment on The Rowan Viking Rig.

	Fault equipment	Working equipment	Total
Zone Safe	629	2540	3169
Zone 2	481	1043	1524
Zone 1	173	308	481
Zone 0	4	3	7
Total	1287	3894	5181

Source: Inspectio software.

As shown in table 4.2, there is 1287 fault equipment in this rig. There is a difference between fault equipment and failure code. For example, consider the fluorescent light with tag number 8266.15-E14, which is installed in the safe area. Figure 4.3 illustrates the inspection data for this tag.



SURVEY RESULTS Only punch items listed below, see the inspectio Portal for the full results.

Code	Description	Cause Code	Status
T1A8	*Enclusure, glass parts and glass-to-metal sealing gaskets and/or compounds are satisfactory* Enclosure is cracked, *Performed by: Jonny Dahl Våge at 2020-07-28*	H 3	Fail
Z	*Are there any additional NON EX integrity faults?* No light *Performed by: Magnus Bratteng at 2020-07-28*	L 33	Fail

SURVEY PHOTOS

2020-07-27 (T1A8)

2020-07-27 (Z)

Figure 4.3: PDF report for tag number 8266.15-E14 (presented by Inspectio platform)

There are two faults for this tag; code Z is about EX integrity, and code T1A8 is about safety and increases the risk according to this tag. This study divided the failure codes into three categories:

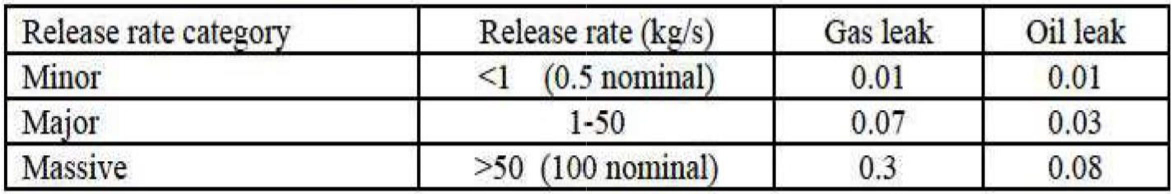
- Priority 1 includes faults that require quick action, and corrective action should be taken during a week; these faults are more influence the safety and increasing the risk of equipment (For example, loose terminations or damage on cable).
- Priority 2 includes faults where corrective action could take in the medium term. They are more related to EX integrity (For example equipment group is not correct).
- Priority 3 includes some faults that are non-compliance with standards, and corrective action could take longer because they do not affect risk (for example, unreadable labels).

4.2 Development of a Bayesian network for EX equipment

As mentioned in the previous section, the main risk according to EX equipment is their potential for ignition, which is influenced by two factors, flammable atmosphere, and source of ignition.

IEC-60079, ATEX directive, or other relevant standards and guidelines use qualitative approaches to identify the explosive atmosphere based on the different zones mentioned in section 4.1. The Rowan Viking Rig data are based on these qualitative approaches where equipment is placed in four zones: safe zone, zone 2, zone 1, and zone0. These qualitative approaches are not appropriate for a BN because it requires assigning a value for this parameter, indicating the probability of a flammable atmosphere. Still, data and practical models are not available to give suitable values for this parameter in QRA. One of the most reliable references in this regard is the IP research report. Therefore, this study assigned value for the release source based on the IP research report, as shown in Table 4.3.

4.3:Ignition probability for source of release



Release rate category	Release rate (kg/s)	Gas leak	Oil leak
Minor	<1 (0.5 nominal)	0.01	0.01
Major	1-50	0.07	0.03
Massive	>50 (100 nominal)	0.3	0.08

Source: (IP research report, 2006).

In modern offshore platforms, zone classification is based on other factors such as proper process equipment, special ventilation arrangements, etc. Still, in abnormal operations, an explosive atmosphere may be present in designated non-hazardous areas; For instance, offshore accommodations have emergency lighting that would be expected to operate in abnormal operations. The term *'abnormal'* is not intended to mean *'unperfect.'* It does mean *'unactual'* or *'unreal'* applied to the conditions, as they exist in any given offshore platform (Geoffrey Bottrill,2005). The EI guideline (2008) suggests considering non-hazardous areas as Zone 2 areas to inspect Ex electrical equipment in offshore installations. Therefore, this study considers zone safe as zone2 where the release rate category follows minor (<1kg/s) in abnormal operation, Zone2 as zone1 where the release rate category follows major (1-50 kg/s) in abnormal operation, and zone0 & zone 1 as zone0 where the release rate category follows massive (>50 kg/s) in abnormal operation.

The sources of ignition for this study are EX equipment installed on the Rowan Viking Rig. Figures 4.4 and 4.5 shows the failure scenarios of this thesis.

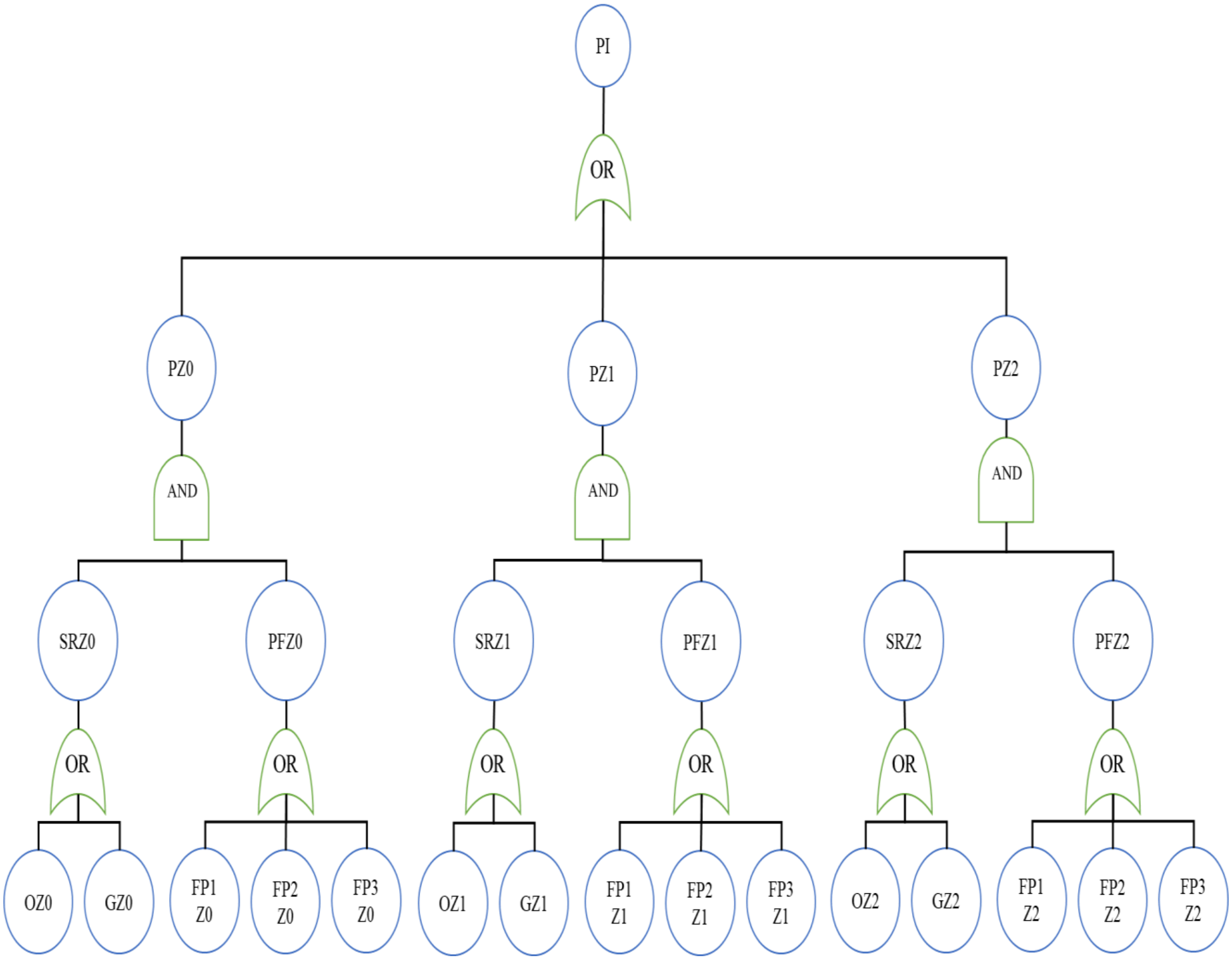


Figure 4.4: Fault tree model for the Rowan Viking rig concerning the probability of ignition (created by this study).

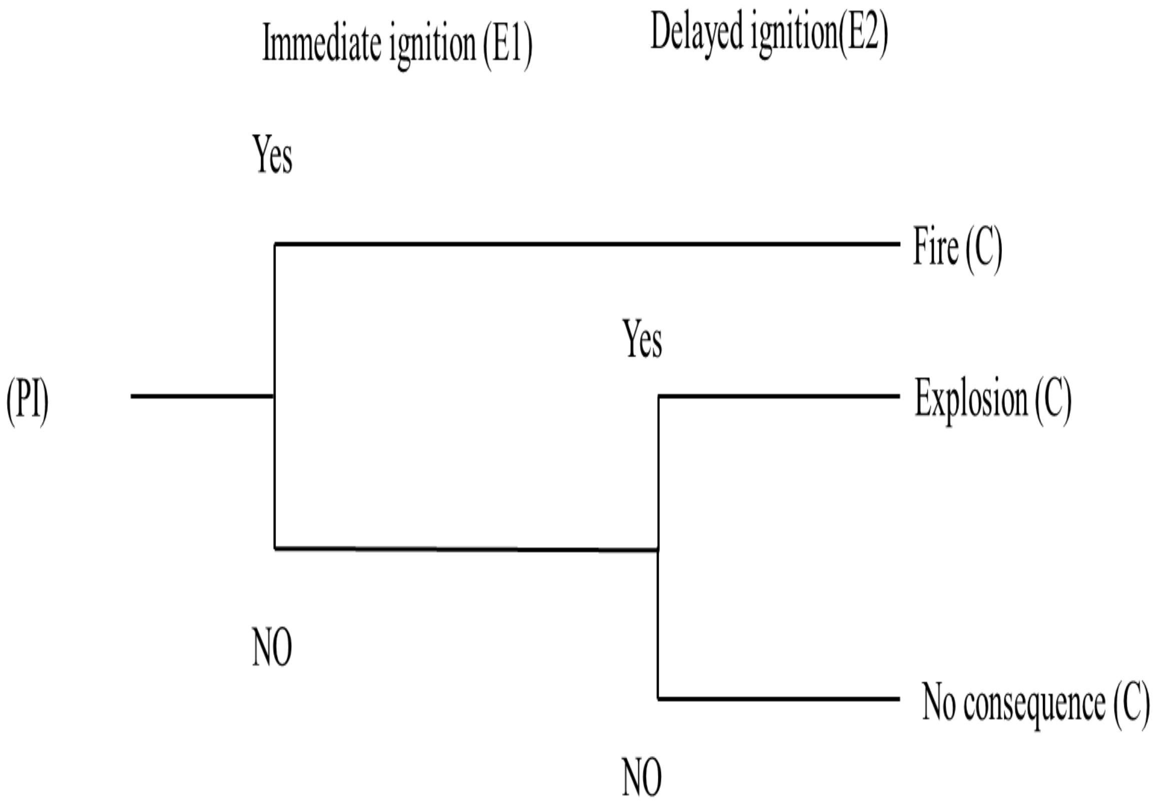


Figure 4.5: Event tree model for the Rowan Viking rig concerning the probability of ignition (created by this study).

The EX-equipment has been divided into three categories according to their operational atmosphere. The possible failure for each zona is based on data analysis from The Rowan Viking Rig (Table 4.2 and 4.4). This study considers consequences according to two intermediate events, immediate ignition and delayed ignition, and the final consequences could be fire, explosion, or no consequences.

Table 4.4: Data based on failure priority.

	Zone 2	Zone 1	Zone0	Total
P1	147	59	35	241
P2	26	7	2	35
P3	456	415	140	1011
Total	629	481	177	1287

Source: Inspectio report

Table 4.5 introduces root nodes and components of BN and their probabilities.

Table 4.5: components for BN.

Symbol	Probability	Description
OZ0	0.08	Probability of oil release in Zone 0
GZ0	0.3	Probability of gas release in Zone 0
P1Z0	0.0272	Probability of failure equipment with priority 1 in Zone 0
P2Z0	0.001554	Probability of failure equipment with priority 2 in Zone 0
P3Z0	0.1088	Probability of failure equipment with priority 3 in Zone 1
OZ1	0.03	Probability of oil release in Zone 1
GZ1	0.07	Probability of gas release in Zone 1
P1Z1	0.04584	Probability of failure equipment with priority 1 in Zone 1
P2Z1	0.005439	Probability of failure equipment with priority 2 in Zone 1
P3Z1	0.3225	Probability of failure equipment with priority 3 in Zone 2
OZ2	0.01	Probability of oil release in Zone 2
GZ2	0.01	Probability of gas release in Zone 2
P1Z2	0.1142	Probability of failure equipment with priority 1 in Zone 2
P2Z2	0.0202	Probability of failure equipment with priority 2 in Zone 2
P3Z2	0.3543	Probability of failure equipment with priority 3 in Zone 3
PFZ0	Logic OR gate	Probability of failure equipment in Zone 0
SRZ0	Logic OR gate	Probability of source of release Zone 0
PFZ1	Logic OR gate	Probability of failure equipment in Zone 1
SRZ1	Logic OR gate	Probability of source of release Zone 1
PFZ2	Logic OR gate	Probability of failure equipment in Zone 2
SRZ2	Logic OR gate	Probability of source of release Zone 2
PZ0	Logic AND gate	Probability of ignition Zone 0
PZ1	Logic AND gate	Probability of ignition Zone 1
PZ2	Logic AND gate	Probability of ignition Zone 2
PE	Logic OR gate	Probability of ignition
E1	0.4	Immediate ignition
E2	0.5	Delayed ignition
C	Logic gate	Consequence node

By converting fault tree and event tree on GeNIe software and assigning values for parameters, the primary model for this thesis is shown in figure 4.6.

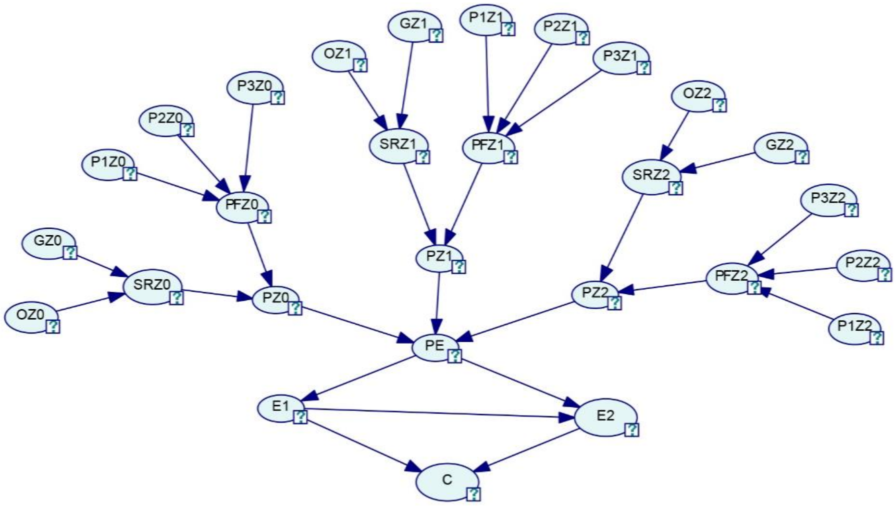


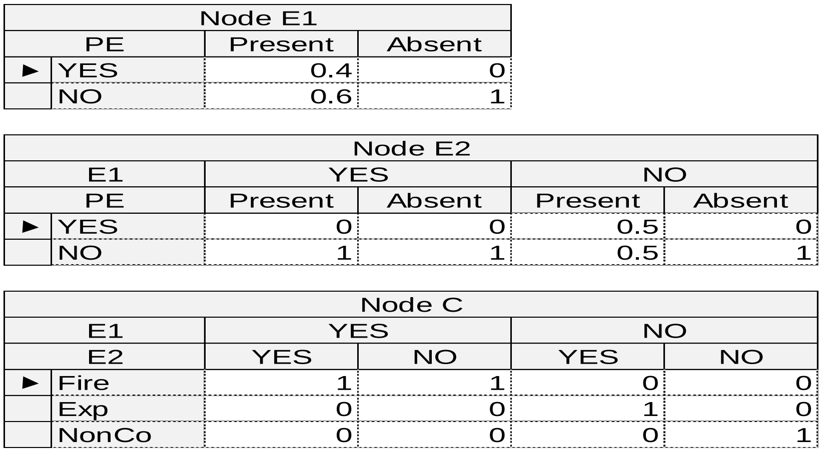
Figure 4.6: Primary model for this thesis

Two states are identified for basic nodes: the Present, which indicates the probability value, and the Absence indicates 1-P. CPT for logic gates are as follow:

Table 4.5: CPT for parents nodes

Nodes for gates AND & OR		
SRZ0 = OZ0 OR GZ0	PFZ0= P1Z0 OR P2Z0 OR P3Z0	PZ0 = SRZ0 OR PFZ0
P(SRZ0=1 | OZ0=0, GZ0=0) = 0	P(FZ0=1 | X1=0, X2=0, X3=0) = 0	P(PZ0=1 | SRZ0=0, PFZ0=0) = 0
P(SRZ0=1 | OZ0=1, GZ0=0) = 1	P(FZ0=1 | X1=0, X2=0, X3=1) = 1	P(PZ0=1 | SRZ0=0, PFZ0=1) = 0
P(SRZ0=1 | OZ0=0, GZ0=1) = 1	P(FZ0=1 | X1=0, X2=1, X3=1) = 1	P(PZ0=1 | SRZ0=1, PFZ0=0) = 0
P(SRZ0=1 | OZ0=1, GZ0=1) = 1	P(FZ0=1 | X1=0, X2=1, X3=0) = 1	P(PZ0=1 | SRZ0=1, PFZ0=1) = 1
	P(FZ0=1 | X1=1, X2=0, X3=0) = 1	
	P(FZ0=1 | X1=1, X2=1, X3=0) = 1	
	P(FZ0=1 | X1=1, X2=0, X3=1) = 1	
	P(FZ0=1 | X1=1, X2=1, X3=1) = 1	

Figure 4.7 shows the definition for event nodes.



Node E1

PE	Present	Absent
► YES	0.4	0
NO	0.6	1

Node E2

E1	YES		NO	
PE	Present	Absent	Present	Absent
► YES	0	0	0.5	0
NO	1	1	0.5	1

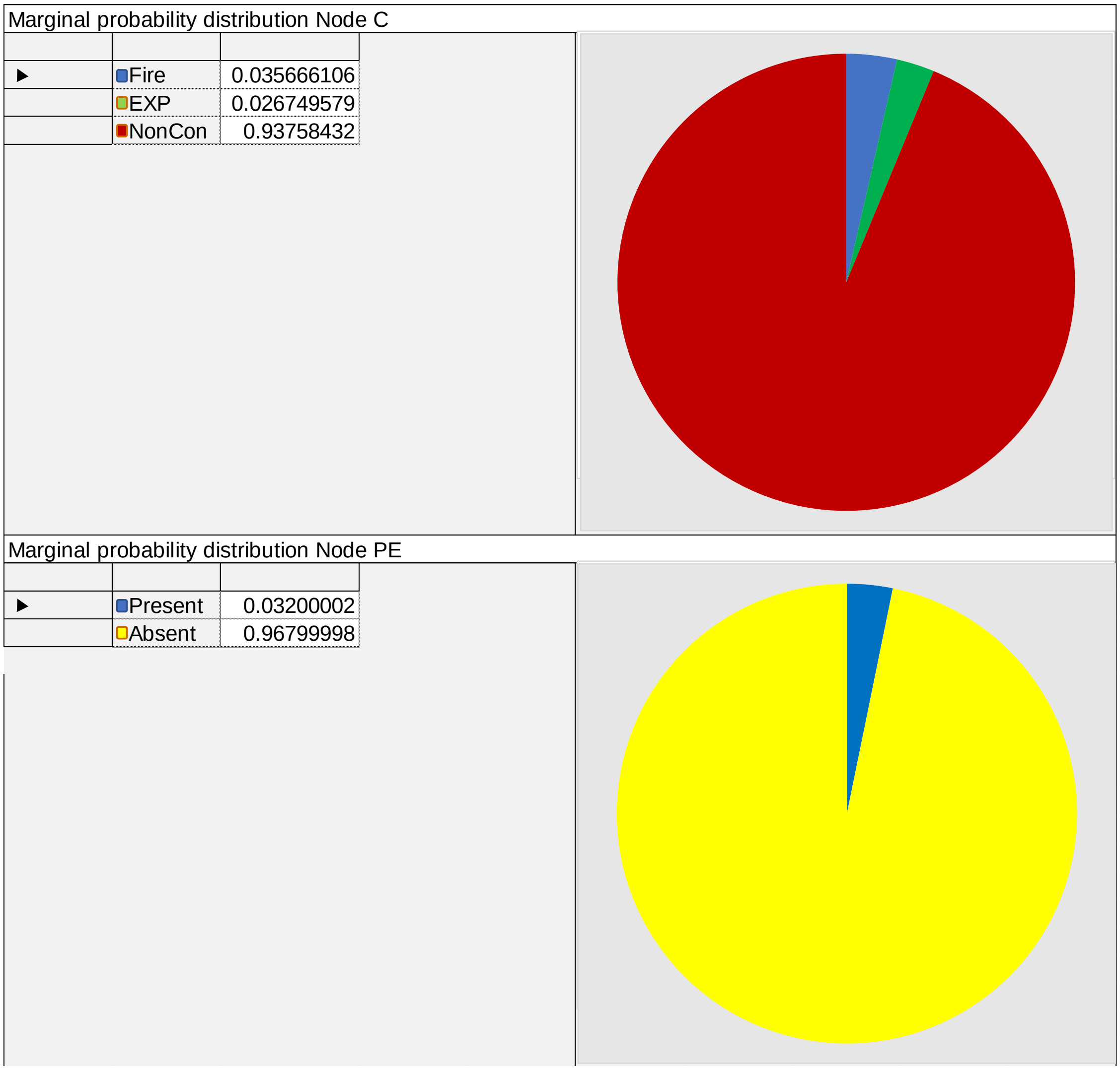
Node C

E1	YES		NO	
E2	YES	NO	YES	NO
► Fire	1	1	0	0
Exp	0	0	1	0
NonCo	0	0	0	1

Figure 4.7: CPT for consequences nodes

Data on the timing of ignition and consequences are not available on the data set of the Rowan Viking Rig because there were no such events for this rig. Therefore, in this study is used the IP research report for ignition timing and fire explosion probabilities.

The result of the primary model shows in figure 4.7.



Marginal probability distribution Node C

▶	🟦Fire	0.035666106
	🟩EXP	0.026749579
	🟥NonCon	0.93758432

Marginal probability distribution Node PE

▶	🟦Present	0.03200002
	🟨Absent	0.96799998

Figure 4.7: The result of primary model analysis. (GeINe academic version 3.0)

The primary model results provide general knowledge about all EX equipment installed in The Rowan Viking Rig. Still, they are not sufficient for presentation on the risk matrix. Therefore, they need to be updated based on historical information and experts' judgment to provide appropriate values for the risk matrix. The next chapter will discuss how this model could be updated and apply in the risk-based inspection.

Chapter 5. Discussion

The previous chapter presents a Bayesian network for Ex electrical equipment, which indicates the probability of ignition because of failure and consequences. This chapter aims to update the primary model and present a risk-based strategy based on the BN result. Figure 5.1 illustrates the strategy that is suggested by this thesis.

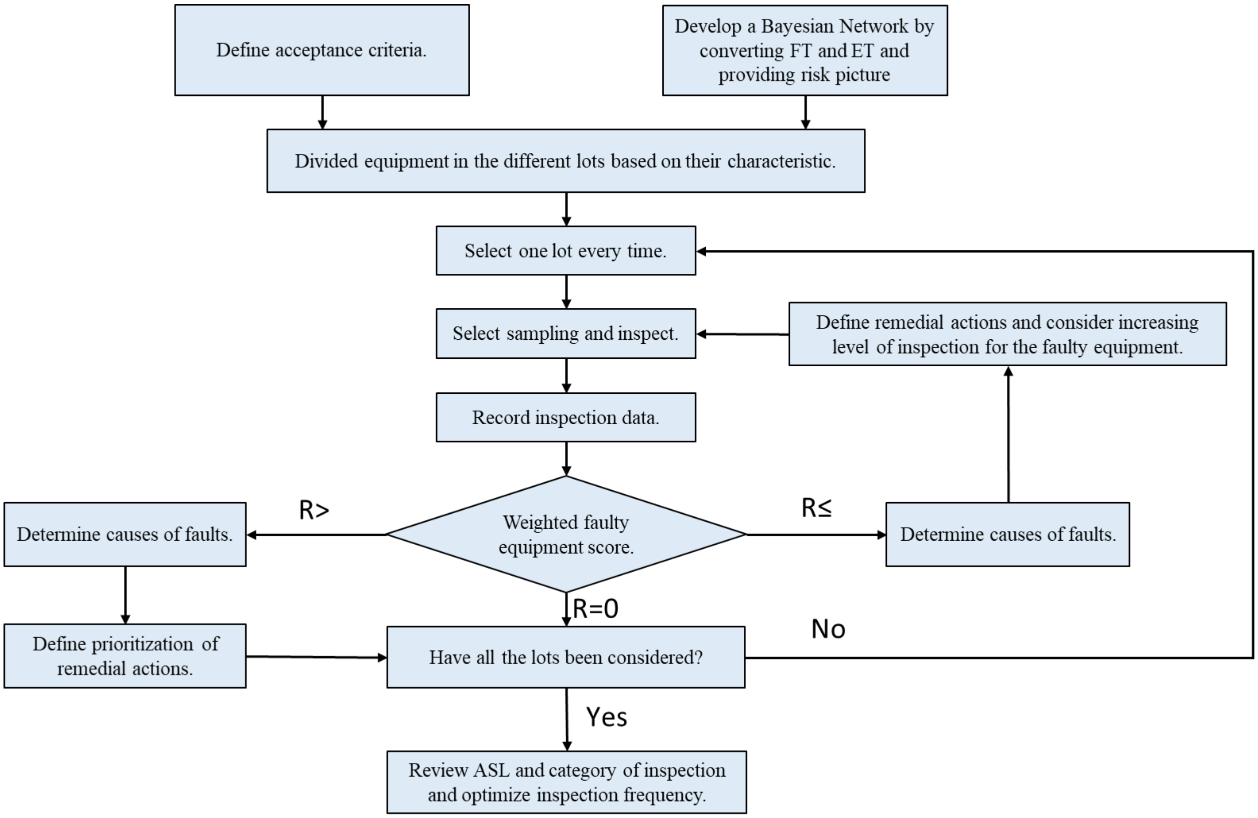
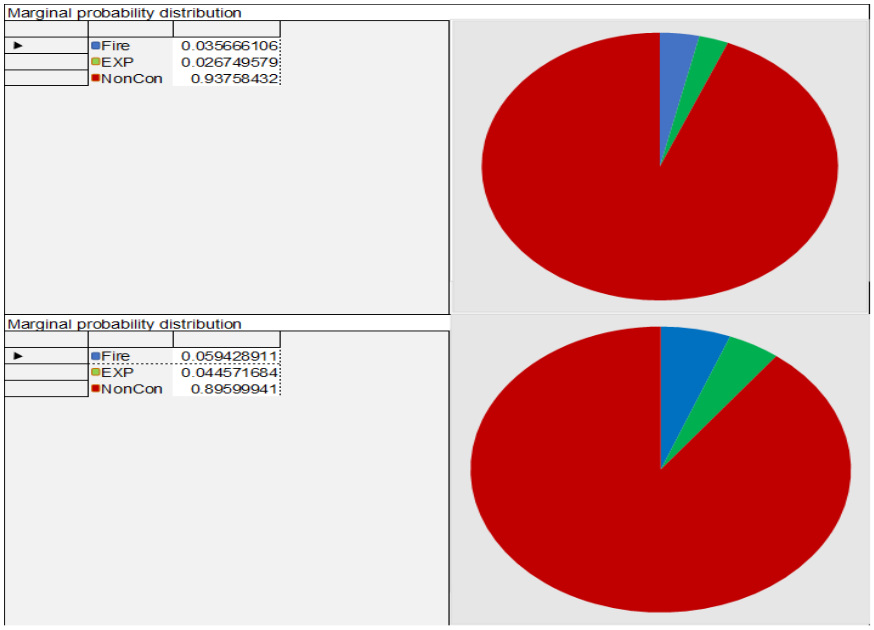


Figure 5.1: Risk-based inspection Strategy for EX electrical equipment (presented by this study).

5.1 Updating the BN

One of the advantages of BN is the possibility of updating the model based on evidence and providing a cause-effect analysis. Figure 5.2 illustrates two different results for the consequences node. The first figure shows consequences in general situations where the aim is to provide knowledge about all EX equipment installed in The Rowan Viking Rig. Consider the case where inspection identifies a failure in Zone 1; the objective is to understand the effect of this failure on the consequences and its associated risk. Therefore, the probability distributions on the BN need to update in light of the empirical evidence. Data will be updated based on this new information by selecting state present as evidence on node PFZ1. The second figure shows the posterior probability distribution after updating the network.



Marginal probability distribution

►	🟦Fire	0.035666106
	🟩EXP	0.026749579
	🟥NonCon	0.93758432

Marginal probability distribution

►	🟦Fire	0.059428911
	🟩EXP	0.044571684
	🟥NonCon	0.89599941

Figure 5.2: Result based on primary model and updating (GeINe academic version 3.0)

In the first case, the probability of ignition is 0.034%, and the likelihood of undesirable consequences is a total of 0.064%. By updating BN based on failure on Z1, the probability of ignition and CoF have increased respectively to 0.1485% and 0.104%. The sensitivity analysis shows (figure 5.3) the probability node and consequence node are influenced by the parent's nodes. That means changes in these nodes have more effect on the result of the model.

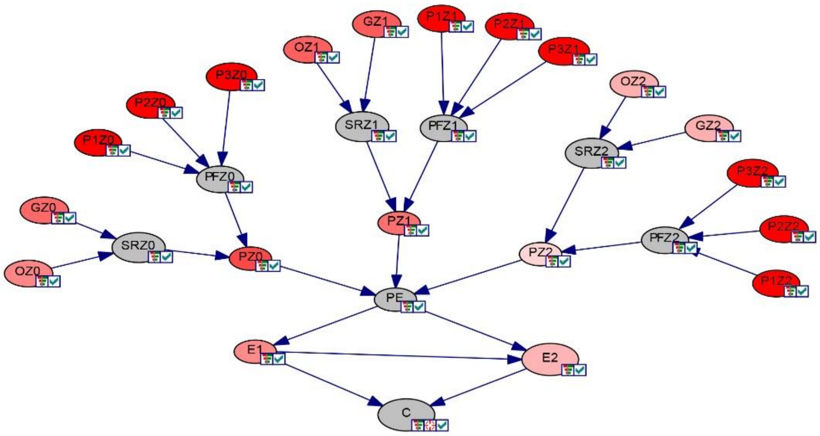
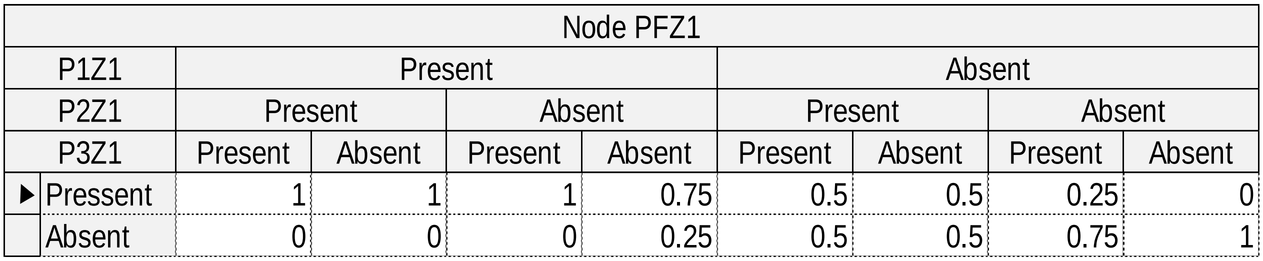


Figure 5.3: The sensitivity analysis result (GeNIe academic version 3.0)

The quantitative analysis of a Bayesian Network has two aspects, predictive and diagnostic. On the one hand, the probability of occurrence of any node could be calculated based on the prior probabilities of the root nodes and the conditional dependence of each node, which provide a predictive view for analysis. On the other hand, modeling of some of the variables to one of their permissible values by the evidence provides the computation of the posterior probability of any given set of variables, which gives molding a diagnostic view. These two features allow the analyst to consider uncertainty on analysis and update the model with new data. For instance, the risk scenario in this thesis is divided faults equipment into three categories based on their priority; the primary assumption on the model for the logic gates was based on Boolean functions from FT. These functions have deterministic relations with values 0 or 1. Therefore, nodes PFZ1,2 and 3 explain that the failure will occur when P1, P2, and P3 exist. This status expresses with certainty, and the model presents the same weight to all of them. But in reality, when P3 exists, the equipment works without functionality fault. The BN allows analyses to modify the uncertain relations of the logic gates based on expert judgment or historical analysis data.

This study updated the primary model in two areas. First, nodes PZ0,1, and 2 could be updated based on information about the probability of ignition from the IP research report. The second could be provided weighting for P1, P2, and P3 based on recommendations from IEC 60079-17 guidelines. Figure 5.4 illustrates the definition of modifying nodes PFZ1, PFZ2, and PFZ3.



Node PFZ1								
P1Z1	Present				Absent			
P2Z1	Present		Absent		Present		Absent	
P3Z1	Present	Absent	Present	Absent	Present	Absent	Present	Absent
▶ Pressent	1	1	1	0.75	0.5	0.5	0.25	0
Absent	0	0	0	0.25	0.5	0.5	0.75	1

Figure 5.4: Definition of modifying nodes PFZ1, PFZ2, and PFZ3 (GeNIe academic version 3.0).

Updating the model based on the information could evaluate the risk of failure according to ex electrical equipment in the inspection. But before definition about how could use it in practice, it is required to identify the inspection strategy and acceptance criteria. An appropriate EX equipment risk-based inspection strategy needs to ensure the integrity of Ex equipment throughout its life cycle phases, where the inspection approach should cover the objectives of the organization with the criteria and principles as well as legislation, regulations and standards at the same time. Therefore, a risk-based inspection strategy requires to identify appropriate acceptance criteria to support management system to ensure the safe operation, maintenance, and work on Ex electrical equipment (EI, 2008). However, IEC 60079-17 provide flexibility for the size of equipment and grade of inspection, where the frequency of inspection can reduce by good performance. Therefore, this study uses sampling strategy and adjust IEC 60079-17 guideline to introduce suitable risk-based inspection methodology and provide balance between the cost of inspection and confidence in the Ex-integrity of the equipment by ALARP principle. The main goal of using ALARP principle as acceptance criteria and sampling strategy is reducing the cost of inspection by reduction on inspected equipment where the objectives of risk-based inspection should be meet. The next section defines the concept of acceptance criteria.

5.2 Acceptance Criteria

The sampling plan basically follows the ISO-2859-1 acceptance sampling system and then adopts the IEC 60079-17 and ALARP principles. Therefore, several parameters play an essential role for acceptance criteria as ALARP acceptance safety level (ALARP-ASL), rejection number (R), 10 %probability of acceptance Pa(10%), and 5% probability of rejection Pr(5%).

Generally, the hypergeometric distribution and the binomial distribution are used for the acceptance sampling. When the sample size (n) is small compared to the lot (N), changes in the N items are not significant, but the calculation of N! will be so complicated. Therefore, it is helpful to use the binomial distribution when n/N<0.15 (EI, 2008):

When $n/N \geq 0.15$ **When $n/N < 0.15$**

$$P(X=x) = \frac{\binom{K}{x}\binom{N-K}{n-x}}{\binom{N}{n}} \qquad P(X=x) = \binom{n}{x} p^{x}(1-p)^{n-x}$$

x= faulty equipment in sampling

K = faulty equipment in the lot

N= the lot size

n= the sample size

P=K/N

As mentioned earlier, R is the rejection number; therefore, a sample with R-1 faulty equipment will be acceptable. For example, if R=10, then the sample could be accepted until nine faulty equipment. So, the probability of acceptance sampling with R-1 faulty equipment can be cumulative distribution when x=R-1 (EI, 2008):

$$P(X=R-1)=\sum_{j=0}^{R-1} p(x=j)$$

According to ISO-2859-1, AQL is the acceptable quality level. This study uses the concept of ASL, which is defined as an acceptable safety level by the IEC 60079-17 guideline. Same as AQL, the concept of ASL indicate the worst tolerable process average and an unacceptable number of faulty equipment in the sampling. The IEC guideline has already calculated some standard value for ASL as 0,25%; 0,4%; 0,65%; 1%, 1,5%; 2,5%; 4% and 6,5%. Still, it is possible to calculate other values by using the formulas which are mentioned above (EI, 2008).

EX risk-based inspection requires a reasonable balance between the cost of inspection and the quality of the lot. IEC 60079-17 guideline uses two parameters pa(10%) and pr(5%) as discrimination ratio (pa/pr) to adjust ASL with ALARP principle in EX equipment risk-based inspection. Using the sampling for inspection, sometimes the safety level of the lot would not be acceptable when the safety level of the sample is acceptable. Pa(10%) indicates 10 percent confidence of sampling plan according to the lot and calculates as P(X=R)=0.1. It means the probability to accept a lot of N equipment containing R faulty equipment is one in 10 times with the sampling plan of n equipment. In other words, it means one in ten times the safety level of the sample is acceptable when the safety level of the lot is not acceptable. This value considers the quality of the sampling plan (EI, 2008).

On the other hand, an inspection plan should consider the cost of inspection as well. The parameter pr(5%) indicates the criteria for inspection cost. In the inverse with the previous situation, there is a possibility for the rejection of the safety level for the sampling plan when the safety level of the lot size is acceptable. This situation will charge the cost of new sampling and inspection. Pr(5%) defines the safety level of the lot as not acceptable with a 5% probability and calculates it as P(X=R-

1)=0.05. That means one in twenty times is possible to reject sampling when the quality of safety level is acceptable (EI, 2008).

Selecting lower ASL than the ALARP ASL disproportionately increases the inspection cost; On the other hand, selection of a higher ASL than the ALARP ASL reduces inspection quality. Annex B identifies cliff-edge effects based on pa(10%)/pr(5%) versus ASL for different lot sizes to determine ALARP ASL (EI, 2008).

Annex B contains sampling tables for various ASLs and the determination of ALARP-ASLs for different lot sizes which are provided by EI guideline, and this study use them as acceptance criteria. These tables included seven columns as

- Lot size
- Global failure rate level
- Normal inspection
- Reduced inspection
- Increased inspection
- Pa(10%) for normal inspection (%)
- Pr(5%) for normal inspection (%)

The concept of global failure level refers to the observed failure rate based on the type of protection. According to the EI guideline: *"The commonly assumed failure rate of a lot is the mean failure rate of a similar lot in a similar location. In the absence of any specific information, a default value of level II should be assumed."*

Also, these tables are based on three categories of inspection reduce, normal and increased. The first sampling plan should be based on the normal category. These categories should not be confused with the inspection grade visual, close, and detailed (EI, 2008).

5.3 Define lots.

Ex electrical equipment can be different based on protection type, hazardous area, age, and environmental conditions. Therefore, lots of equipment should be divided them into the similar group based on these factors (EI, 2008).

There are different ways to assigning equipment to specific lots. It will be more practical if a lot comprises mixed equipment like motors, junction boxes, etc. It can give the advantage to introduce a large number of EX equipment in different lots to taking sampling based on acceptance criteria. When the lot size is too small, it is likely only one faulty equipment reject sampling because of the small value of the rejection criteria. The rejection criterion is determined by R in the acceptance criteria. The sample is accepted when the number of faulty equipment is less than R. Another advantage can be in the inspection process; when a lot includes different types of equipment, an inspection can cover various types of equipment in shutdown time (EI, 2008).

Deterioration processes and faults such as corrosion, vibration, and inadequate equipment selection will always be present to some degree. They may reduce the system's performance beyond what is acceptable. Therefore, an EXRBI methodology should identify the failure mechanism for EX equipment to improve the continuing management of ignition risk by assuring the continuing integrity of Ex electrical equipment. A risk-based inspection gives more weight to high-risk equipment applied in the BN model to identify equipment criticality. So, the inspection priority is to start inspecting high-risk equipment located in a high-risk area (EI, 2008).

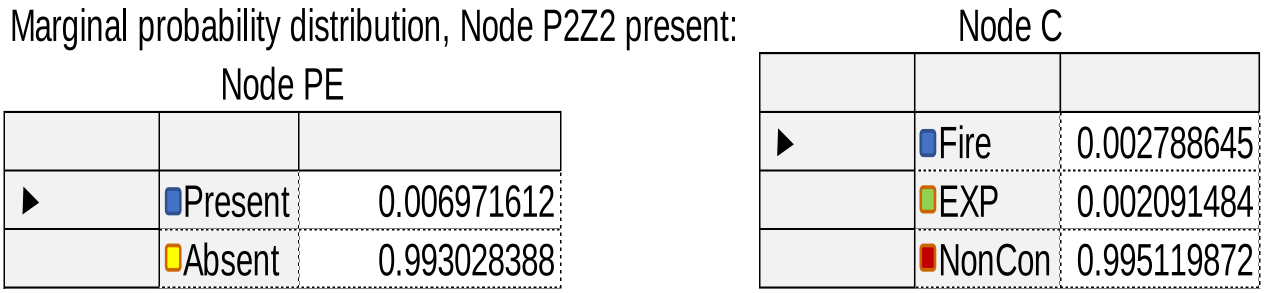
5.4 Applying the BN model in the inspection

This section presents how to apply the BN for inspection using two examplesss from the Rowan Viking Rig. As mentioned before, the equipment in a lot should be homogeneous in one or more characteristics.

The first Lot includes 839 pieces of equipment from gas group II installed in a safe zone based on historical data from the Inspectio platform. According to table C.12 in annex B, the ALARP/ASL=1% and sample size will be 80 with three rejection numbers (table C.7 annex B). There are two types of sampling progressive and random. This study used random sampling.

The result shows five faulty equipment in this sampling. The inspection reports are available in annex A.

To evaluate the risk of ignition for this faulty equipment, the nodes P1Z2, P2Z2, and P3Z3 have to update. This task would be done separately for each piece of defective equipment based on the presented failure. Then the result from nodes PE and C could be transferred in the risk matrix to show the level of the risk. Figure 5.5 illustrates the outputs from the BN model when node P2Z2 is on present.



Marginal probability distribution, Node P2Z2 present:

Node PE

▶	🟦Present	0.006971612
	🟨Absent	0.993028388

Node C

▶	🟦Fire	0.002788645
	🟩EXP	0.002091484
	🟥NonCon	0.995119872

Figure 5.5: Outputs from the BN model for node P2Z2 the state present as evidence (GeNIe academic version 3.9)

It needs to pay attention When a piece of equipment has more than one failure, so each failure priority needs to find its present state on the node simultaneously. For example, in the case of the heater trace, both nodes P1Z2 and P3Z2 should be in the present state.

The result of the analysis has been presented on the next page by table 5.1.

At the start point, the analysis should identify the ignition risk for each failure. Therefore, findings from BN are transferred to the risk matrix, which is presented on section 4.4 figure 3.14. The risk matrix shows cell H16 for the heater trace, cell M9 for junction box tag number 8253-C11-5, and cell L4 for the rest. In the next step, the result of the risk matrix provides weight for every failure code. This weighting is based on EI (2008) recommendation:

High risk=1

Medium risk=0.5

Low risk= 0.25

Despite the faulty equipment number being five and the reject number was three, the sample is acceptable because of the low ignition risk.

Table5.1: Results of inspection for Lot number 1

Lot Information	Equipment	Fault code (Note)	Failure priority	Ignition risk	Number of faulty equipment	Tag number
Zone 2, Gas group II	SOLENOID	S02T1	P3	🟩 Low	1	NO TAG NORGREN FOAM
		S03T1	P3			
		-	-			
	HEAT TRACE	T1A17	P1	🟥 High	1	8284-JB2401
		T1A9	P1			
		T1B11	P1			
		T1B6a	P3			
	Junction Box	T1A11b	P2	🟨 Medium	1	8253-C11-5
		Z	P1			
	SOLENOID	S02T1	P3	🟩 Low	1	NO TAG
	Junction Box	So2T1	P3	🟩 Low	1	NO TAG JB2 WINDSOCK
Result:						
🟩 Low				0.25	3	0.75
🟨 Medium				0.5	1	0.5
🟥 High				1	1	1
				Total Faulty equipment		2.25
				2.25<3 sample is acceptable		

Note: Definition of fault
S02T1: Equipment Tag is missing (Regular equipment tag either on equipment or cable)
S03T1: Ex label is missing (Manufacturer label with Ex information)
T1A9: Lead cable into the HT box is not connected, loose in the box
T1A11b: Loose nipple, not get tightened against nut due to corrosion
T1A17: Electrical not connected
T1B6a: Bonding is missing, not connected to the structure
T1B11: Cables not in use are not correctly terminated
Z: There are additional NON-EX integrity faults

To make the concept more precise, it could assume the same process for Zone 1. The same lot size with the same faulty codes. The result of the analysis could be as follow. The new evidence indicates cell H20 for the heater trace, cell H16 for junction box tag number 8253-C11-5, and cell M12 for the rest. The result is shown in table 5.2.

5.2: Results of inspection for Lot number 2

Lot Information	Equipment	Fault code (Note)	Failure priority	Ignition risk	Number of faulty equipment	Tag number
Zone 0, Gas group II	SOLENOID	S02T1	P3	🟨 Medium	1	NO TAG NORGREN FOAM
		S03T1	P3			
		-	-			
	HEAT TRACE	T1A17	P1	🟥 High	1	8284-JB2401
		T1A9	P1			
		T1B11	P1			
		T1B6a	P3			
	Junction Box	T1A11b	P2	🟥 High	1	8253-C11-5
		Z	P1			
	SOLENOID	S02T1	P3	🟨 Medium	1	NO TAG
	Junction Box	So2T1	P3	🟨 Medium	1	NO TAG JB2 WINDSOCK
Result :						
🟩 Low				0.25	0	0
🟨 Medium				0.5	3	1.5
🟥 High				1	2	2
				Total Faulty equipment		3.5
				3.5>3 sample is not acceptable		
Note: Definition of fault S02T1: Equipment Tag is missing (Regular equipment tag either on equipment or cable) S03T1: Ex label is missing (Manufacturer label with Ex information) T1A9: Lead cable into the HT box is not connected, loose in the box T1A11b: Loose nipple, not get tightened against nut due to corrosion T1A17: Electrical not connected T1B6a: Bonding is missing, not connected to the structure T1B11: Cables not in use are not correctly terminated Z: There are additional NON EX integrity faults						

As the result shows, based on the new evidence, the sample is not acceptable. This new sample needs remedial action. The critical point is that the BN model has met the RBI principle, which required increasing inspection for high-risk equipment to ensure safety level. On the other hand, it makes balance in the cost by reducing the inspection for low-risk equipment.

Chapter 6. Conclusion and recommendation

Different risk-based inspection approaches have been accepted and developed in the petroleum industry in the past few years. These approaches have been used to determine the probability of failure and its consequences; then, the result optimizes the inspection intervals. However, there is not any integrated approach for RBI. In this research, to minimize the inspection cost, a new risk-based methodology has been developed by employing the Bayesian Network. Therefore, this study started with the most common risk analysis techniques such as fault tree and event tree and then tried to present a Bayesian network that can deal better with uncertainty.

The main objective of the thesis is to apply the result of BN to identification a risk-based strategy for ex electrical equipment in the offshore industry. Therefore, data has been collected from the rowan Viking rig. Then the BN has been developed based on the data from the case study and other relevant standards and regulations. The results of the analysis showed that applying a Bayesian network by sampling inspection could meet the RBI requirement. Still, there is some issues according to the result.

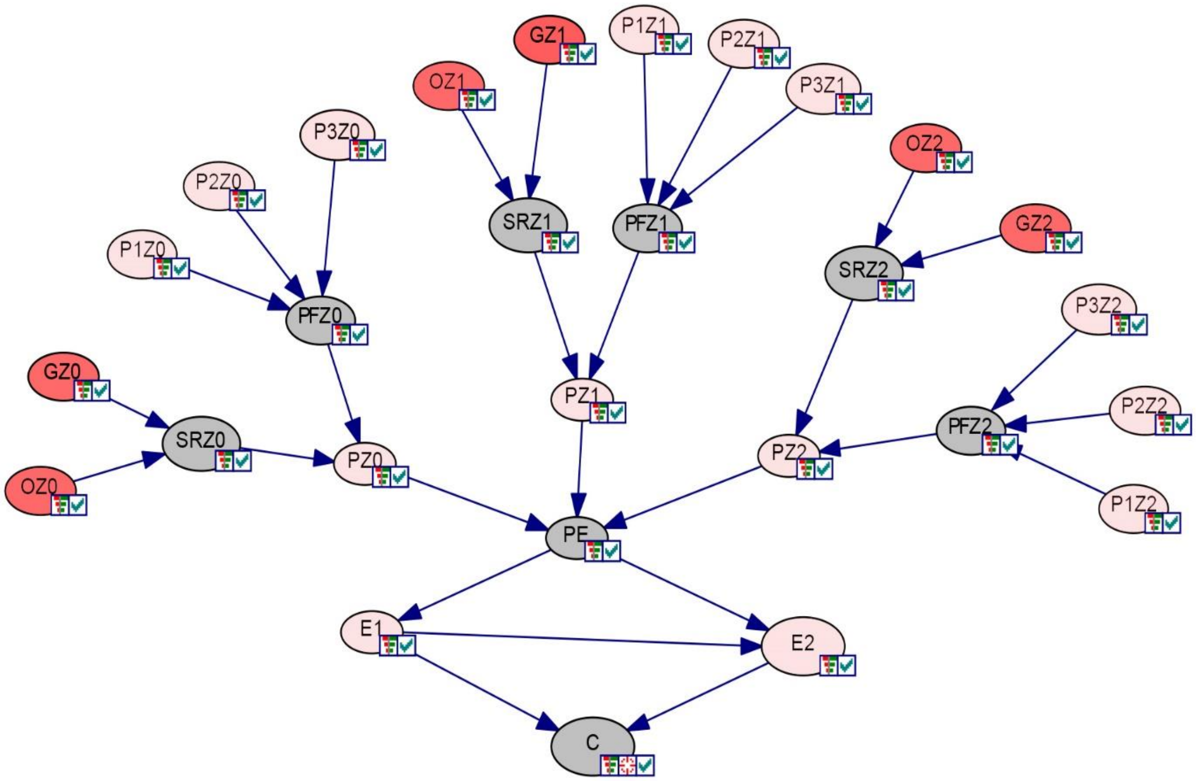


Figure 6.1: The sensitivity analysis for the end model (GeNIe academic version 3.0)

The main challenge for the model was converting qualitative risk zones to appropriate quantitative parameters for use in a BN. When the sensitivity analysis has been done for the end model (figure 6.1), still the target nodes C and PE influence significantly by a basic node of zones.

On the other hand, the inspection data does not explain how the zones are divided. In the inspection data, most of the equipment is installed in the safe zone. Based on the IEC 60079-17 definition, there is no chance for an explosive atmosphere in the safe area. Therefore, the risk of ignition does not make sense for these areas. In addition, the standards explain clearly that in the offshore operation process, it is essential to consider all safe zone as zone 2.

Consequently, this study suggests more precautionary approach regard to zone classification for the inspection data set because the probability of ignition of flammable releases is a critical factor in determining the risk of ignition.

Another challenge for the model was modeling the consequences node. Unfortunately, there is not sufficient data for the consequences of ignition, and the current data are sparse. Many risk-based techniques convert COP to monetary value. In the lack of systematic data, COF evaluation could be more based on analyzer taste and knowledge. The existing approach could not provide an integrated view of the COF value.

Referance

Abbasi, R. Bhandari, J. Khan, F. Garaniya, V. Chai, S. (2016): *Developing a Quantitative Risk-based Methodology for Maintenance Scheduling Using Bayesian Network* DOI: 10.3303/CET1648040, 48: 235

Aven, T. (2020): *The Science of Risk Analysis, Foundation and Practice*, 1 ed. New York: Taylor & Francis Group, 88-93, 20-44

Aven, T. Staff, W. (2015): *Risk Analysis*, 2 ed. India: John Wiley & Sons, Incorporated

Bai, J. Bai, Q. (2014): *Subsea Pipeline Integrity and Risk Management,* 1 ed. London: Elsevier Science & Technology

Bai, J. Jin, W-L. (2015): *Marine Structural Design*, 2 ed. Oxford: Elsevier Science & Technology

Bearfield, G. Marsh, W. (2005): *Generalising Event Trees Using Bayesian Networks with a Case Study of Train Derailment*, DOI:10.1007/11563228_5, 3688:52-66

Bhatia, K. Khan, F. Patel, H. Abbasi, R. (2019): *Dynamic risk-based inspection methodology,* doi.org/10.1016/j.jlp.2019.103974, Volume 62, November 2019, 103974

Bian, H. Zhang, J. Li, R. Zhao, H. Wang, X. (2021): *Risk analysis of tripping accidents of power grid caused by typical natural hazards based on FTA-BN model*, doi.org/10.1007/s11069-021-04510-5, Natural Hazards (2021) 106:1771–1795

Bobbio, A. Portinale, L. Minichino, M. Ciancamerla, E. (2001): *Improving the analysis of dependable systems by mapping fault trees into Bayesian networks*, PII: S0951-8320(00)00077-6, Reliability Engineering and System Safety 71 (2001) 249–260

Bottrill, G. Cheyne, D. and Vijayaraghavan,G. (2005): *Practical Electrical Equipment and Installations in Hazardous Areas*, 1 ed. Burlington: Elsevier Science & Technology

Casal, J. (2017): *Evaluation of the Effects and Consequences of Major Accidents in Industrial* Plants, 2 ed, London: Elsevier

Cooper, G. (1990): *The computational complexity of probabilistic inference using Bayesian belief networks*. Artifical Intelligence, 42(2-3):393-405

Energy Institute, (2008): *Guidelines for managing inspection of Ex electrical equipment ignition risk in support of IEC 60079-17*, 1 ed, London: Energy Institute

Kelly, D. Smith, C. (2011): *Bayesian Inference for Probabilistic Risk Assessment, A Practitioner's Guidebook*, ed 1, New York: Springer

IP Research. (2006): *Ignition Probability Review, Model Development and Look-up Correlations*, 1 ed, ISBN 10: 0852934548 ISBN 13: 9780852934548, London: Energy Institute

https://www.ikm.com/ikm-elektro/

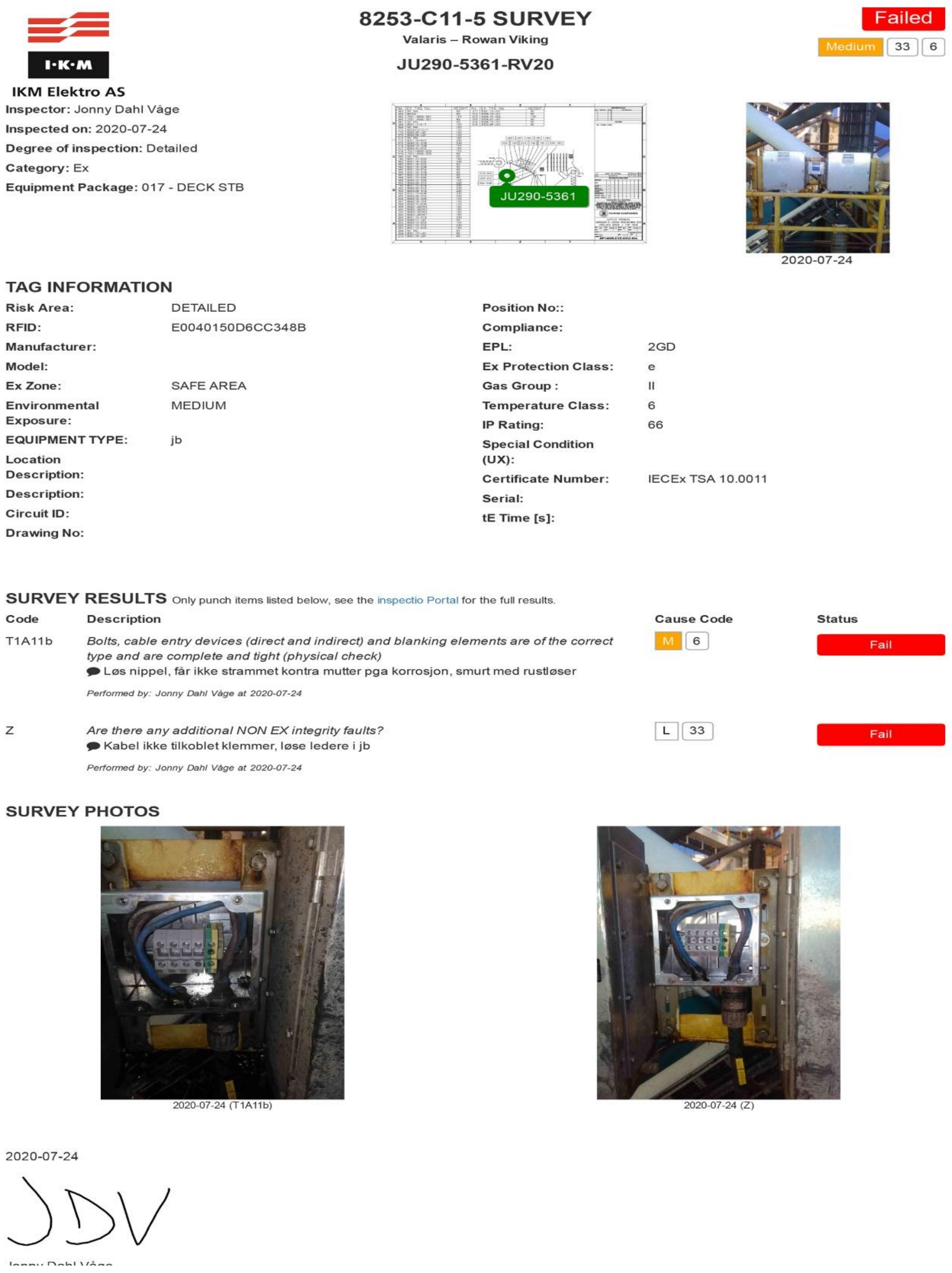
https://webstore.iec.ch/publication/631

https://www.iso.org/standard/72140.html

https://www.marinetraffic.com/en/ais/details/ships/shipid:6100385/mmsi:538004075/imo:8769664/vessel:ROWAN_VIKING

https://www-standard-no.ezproxy.uis.no/pagefiles/955/z-013.pdf

Annex A PDF Reports from Inspectio



IKM Elektro AS

Inspector: Jonny Dahl Våge
Inspected on: 2020-07-24
Degree of inspection: Detailed
Category: Ex
Equipment Package: 017 - DECK STB

8253-C11-5 SURVEY

Valaris – Rowan Viking

JU290-5361-RV20

Failed

Medium 33 6

2020-07-24

TAG INFORMATION

Risk Area:	DETAILED	**Position No::**	
RFID:	E0040150D6CC348B	**Compliance:**	
Manufacturer:		**EPL:**	2GD
Model:		**Ex Protection Class:**	e
Ex Zone:	SAFE AREA	**Gas Group :**	II
Environmental Exposure:	MEDIUM	**Temperature Class:**	6
		IP Rating:	66
EQUIPMENT TYPE:	jb	**Special Condition (UX):**	
Location Description:		**Certificate Number:**	IECEx TSA 10.0011
Description:		**Serial:**	
Circuit ID:		**tE Time [s]:**	
Drawing No:			

SURVEY RESULTS Only punch items listed below, see the inspectio Portal for the full results.

Code	Description	Cause Code	Status
T1A11b	*Bolts, cable entry devices (direct and indirect) and blanking elements are of the correct type and are complete and tight (physical check)* Løs nippel, får ikke strammet kontra mutter pga korrosjon, smurt med rustløser *Performed by: Jonny Dahl Våge at 2020-07-24*	M 6	Fail
Z	*Are there any additional NON EX integrity faults?* Kabel ikke tilkoblet klemmer, løse ledere i jb *Performed by: Jonny Dahl Våge at 2020-07-24*	L 33	Fail

SURVEY PHOTOS

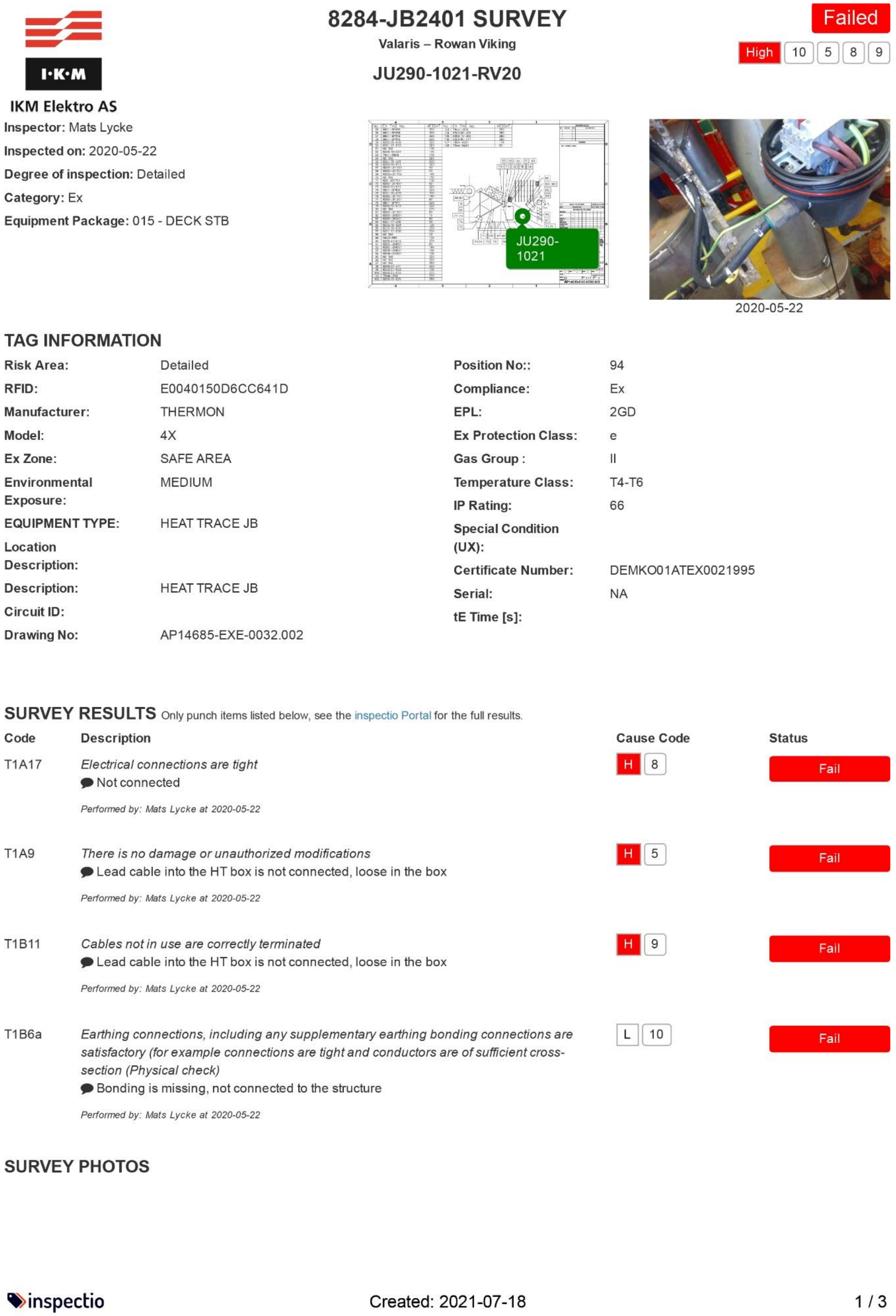
2020-07-24 (T1A11b)

2020-07-24 (Z)

2020-07-24

JDV

Jonny Dahl Våge



IKM Elektro AS

8284-JB2401 SURVEY

Valaris – Rowan Viking

JU290-1021-RV20

Failed

High 10 5 8 9

Inspector: Mats Lycke
Inspected on: 2020-05-22
Degree of inspection: Detailed
Category: Ex
Equipment Package: 015 - DECK STB

2020-05-22

TAG INFORMATION

Risk Area:	Detailed	**Position No::**	94
RFID:	E0040150D6CC641D	**Compliance:**	Ex
Manufacturer:	THERMON	**EPL:**	2GD
Model:	4X	**Ex Protection Class:**	e
Ex Zone:	SAFE AREA	**Gas Group :**	II
Environmental Exposure:	MEDIUM	**Temperature Class:**	T4-T6
		IP Rating:	66
EQUIPMENT TYPE:	HEAT TRACE JB	**Special Condition (UX):**	
Location Description:		**Certificate Number:**	DEMKO01ATEX0021995
Description:	HEAT TRACE JB	**Serial:**	NA
Circuit ID:		**tE Time [s]:**	
Drawing No:	AP14685-EXE-0032.002		

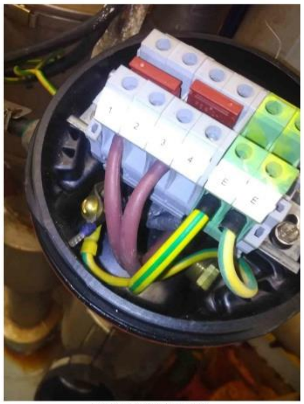
SURVEY RESULTS Only punch items listed below, see the inspectio Portal for the full results.

Code	Description	Cause Code	Status
T1A17	*Electrical connections are tight* Not connected *Performed by: Mats Lycke at 2020-05-22*	H 8	Fail
T1A9	*There is no damage or unauthorized modifications* Lead cable into the HT box is not connected, loose in the box *Performed by: Mats Lycke at 2020-05-22*	H 5	Fail
T1B11	*Cables not in use are correctly terminated* Lead cable into the HT box is not connected, loose in the box *Performed by: Mats Lycke at 2020-05-22*	H 9	Fail
T1B6a	*Earthing connections, including any supplementary earthing bonding connections are satisfactory (for example connections are tight and conductors are of sufficient cross-section (Physical check)* Bonding is missing, not connected to the structure *Performed by: Mats Lycke at 2020-05-22*	L 10	Fail

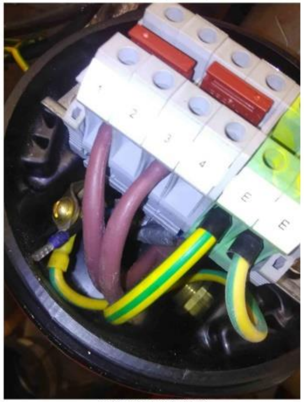
SURVEY PHOTOS

inspectio Created: 2021-07-18 1 / 3


2020-05-22 (T1A17)

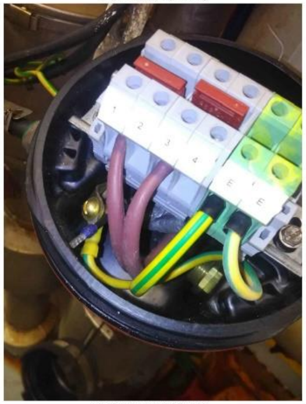

2020-05-22 (T1A17)


2020-05-22 (T1A9)

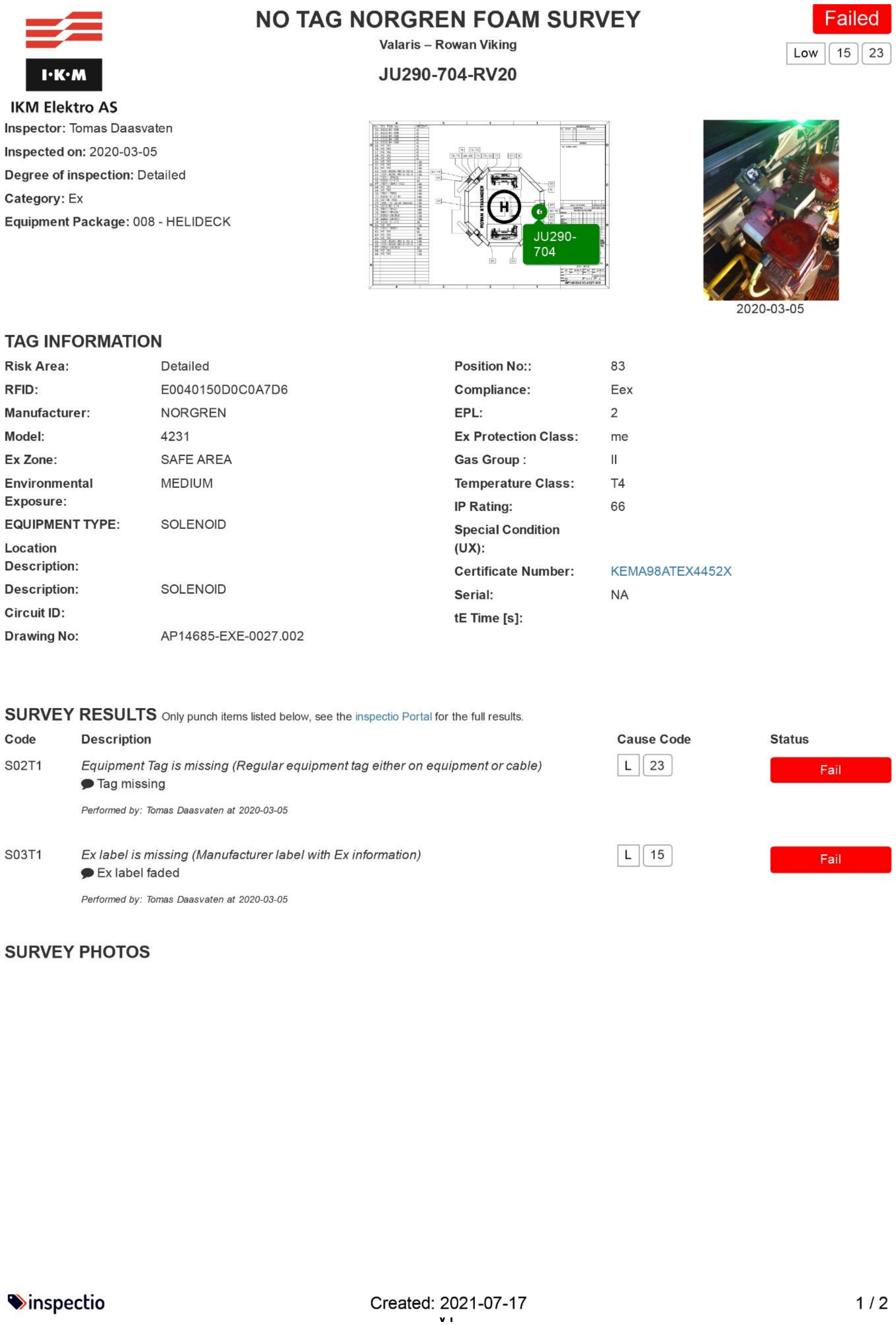

2020-05-22 (T1A9)


2020-05-22 (T1A9)


2020-05-22 (T1B11)


2020-05-22 (T1B11)


2020-05-22 (T1B6a)



IKM Elektro AS

NO TAG NORGREN FOAM SURVEY

Valaris – Rowan Viking

JU290-704-RV20

Failed

Low | 15 | 23

Inspector: Tomas Daasvaten

Inspected on: 2020-03-05

Degree of inspection: Detailed

Category: Ex

Equipment Package: 008 - HELIDECK

2020-03-05

TAG INFORMATION

Risk Area:	Detailed	**Position No::**	83
RFID:	E0040150D0C0A7D6	**Compliance:**	Eex
Manufacturer:	NORGREN	**EPL:**	2
Model:	4231	**Ex Protection Class:**	me
Ex Zone:	SAFE AREA	**Gas Group :**	II
Environmental Exposure:	MEDIUM	**Temperature Class:**	T4
		IP Rating:	66
EQUIPMENT TYPE:	SOLENOID	**Special Condition (UX):**	
Location Description:		**Certificate Number:**	KEMA98ATEX4452X
Description:	SOLENOID	**Serial:**	NA
Circuit ID:		**tE Time [s]:**	
Drawing No:	AP14685-EXE-0027.002		

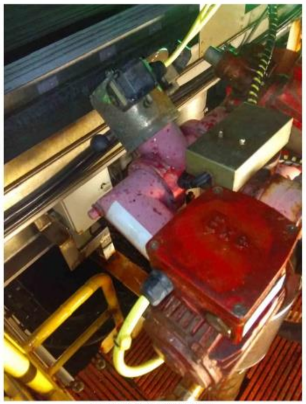
SURVEY RESULTS

Only punch items listed below, see the inspectio Portal for the full results.

Code	Description	Cause Code	Status
S02T1	*Equipment Tag is missing (Regular equipment tag either on equipment or cable)* Tag missing *Performed by: Tomas Daasvaten at 2020-03-05*	L 23	Fail
S03T1	*Ex label is missing (Manufacturer label with Ex information)* Ex label faded *Performed by: Tomas Daasvaten at 2020-03-05*	L 15	Fail

SURVEY PHOTOS

inspectio Created: 2021-07-17 1 / 2


2020-03-05 (S02T1)


2020-03-05 (S03T1)

2020-03-05

TDa

Tomas Daasvaten

Annex B: ASL and ALARP-ASL Tables

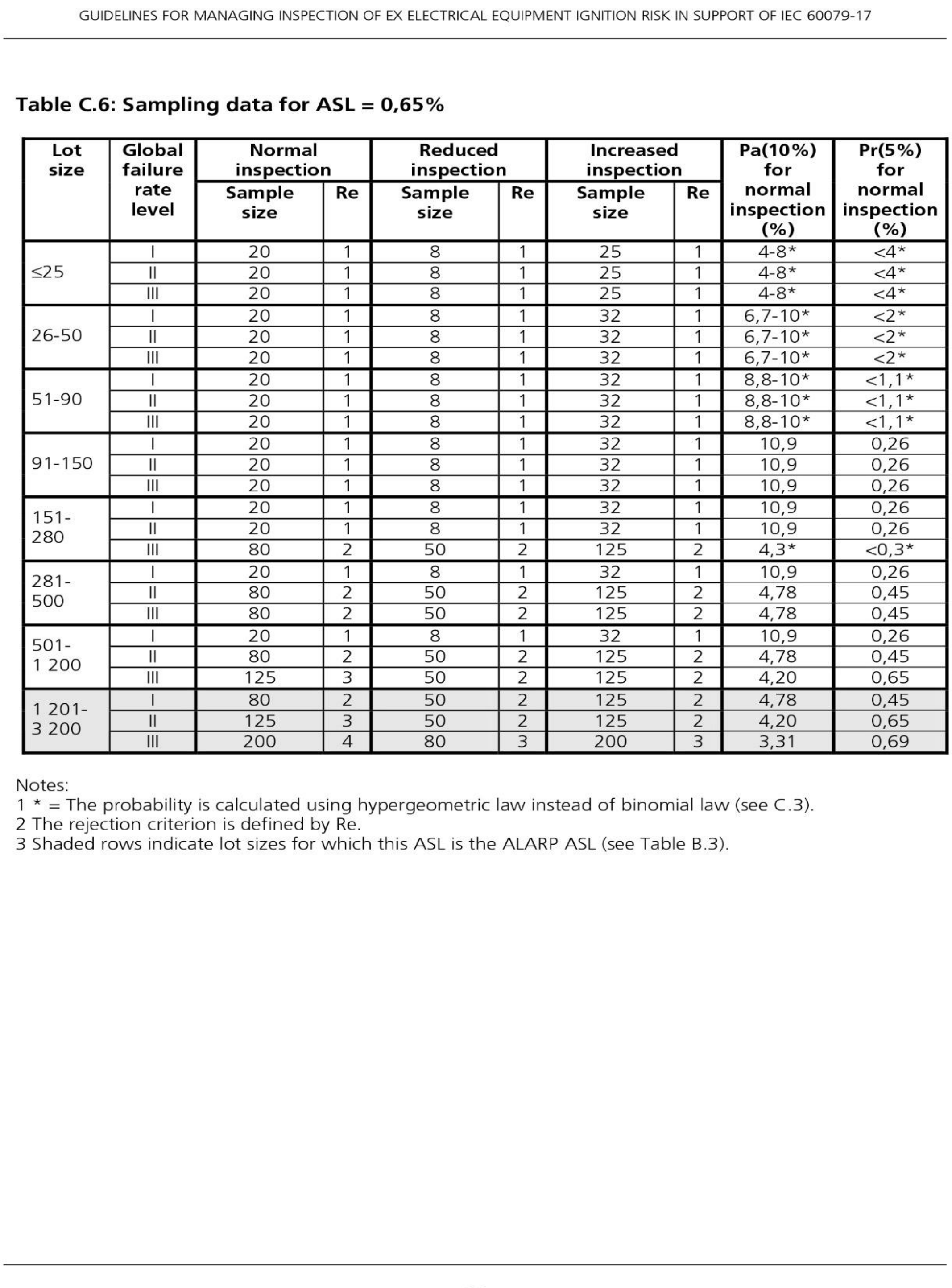


Table C.6: Sampling data for ASL = 0,65%

Lot size	Global failure rate level	Normal inspection		Reduced inspection		Increased inspection		Pa(10%) for normal inspection (%)	Pr(5%) for normal inspection (%)
		Sample size	Re	Sample size	Re	Sample size	Re		
≤25	I	20	1	8	1	25	1	4-8*	<4*
	II	20	1	8	1	25	1	4-8*	<4*
	III	20	1	8	1	25	1	4-8*	<4*
26-50	I	20	1	8	1	32	1	6,7-10*	<2*
	II	20	1	8	1	32	1	6,7-10*	<2*
	III	20	1	8	1	32	1	6,7-10*	<2*
51-90	I	20	1	8	1	32	1	8,8-10*	<1,1*
	II	20	1	8	1	32	1	8,8-10*	<1,1*
	III	20	1	8	1	32	1	8,8-10*	<1,1*
91-150	I	20	1	8	1	32	1	10,9	0,26
	II	20	1	8	1	32	1	10,9	0,26
	III	20	1	8	1	32	1	10,9	0,26
151-280	I	20	1	8	1	32	1	10,9	0,26
	II	20	1	8	1	32	1	10,9	0,26
	III	80	2	50	2	125	2	4,3*	<0,3*
281-500	I	20	1	8	1	32	1	10,9	0,26
	II	80	2	50	2	125	2	4,78	0,45
	III	80	2	50	2	125	2	4,78	0,45
501-1 200	I	20	1	8	1	32	1	10,9	0,26
	II	80	2	50	2	125	2	4,78	0,45
	III	125	3	50	2	125	2	4,20	0,65
1 201-3 200	I	80	2	50	2	125	2	4,78	0,45
	II	125	3	50	2	125	2	4,20	0,65
	III	200	4	80	3	200	3	3,31	0,69

Notes:
1 * = The probability is calculated using hypergeometric law instead of binomial law (see C.3).
2 The rejection criterion is defined by Re.
3 Shaded rows indicate lot sizes for which this ASL is the ALARP ASL (see Table B.3).

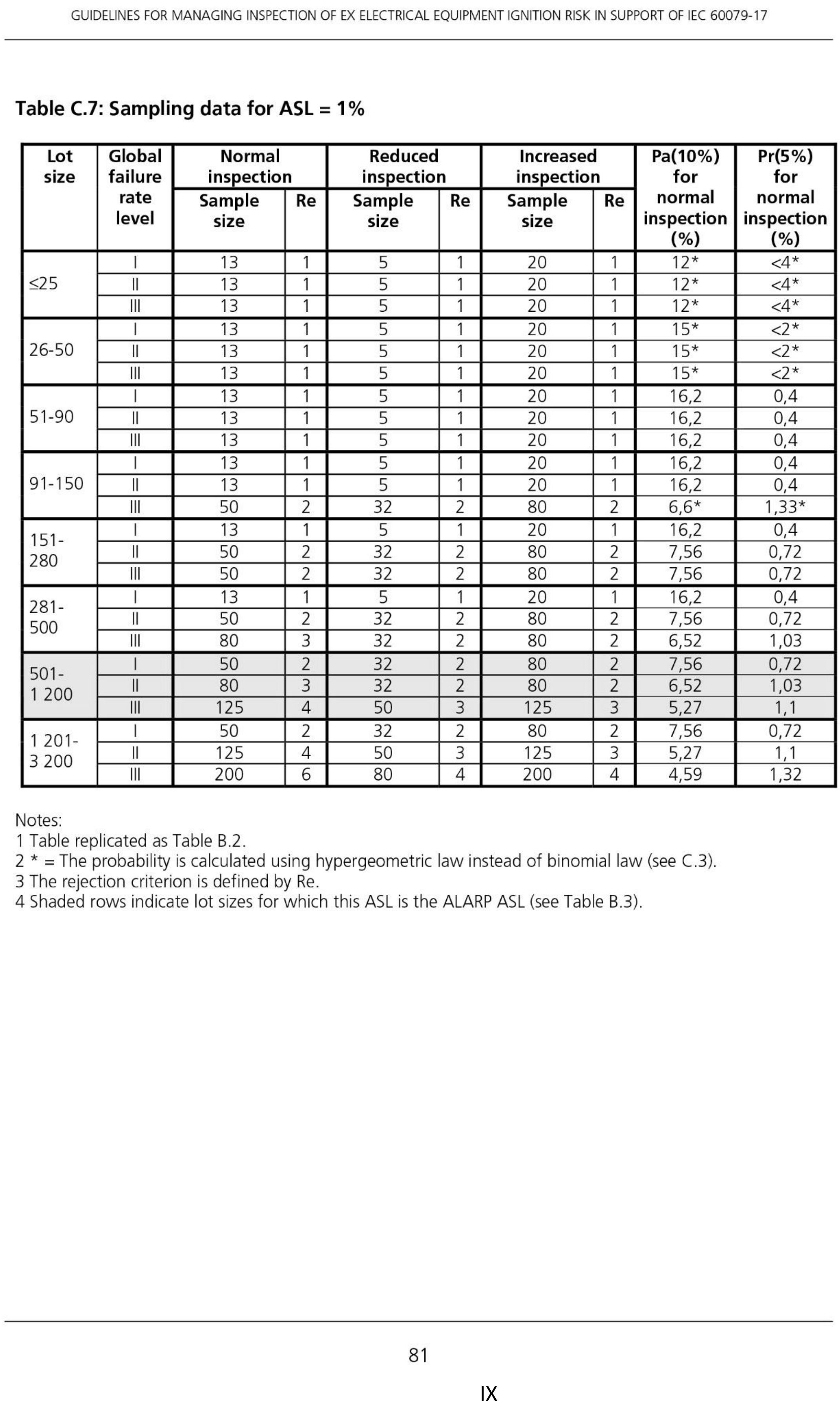
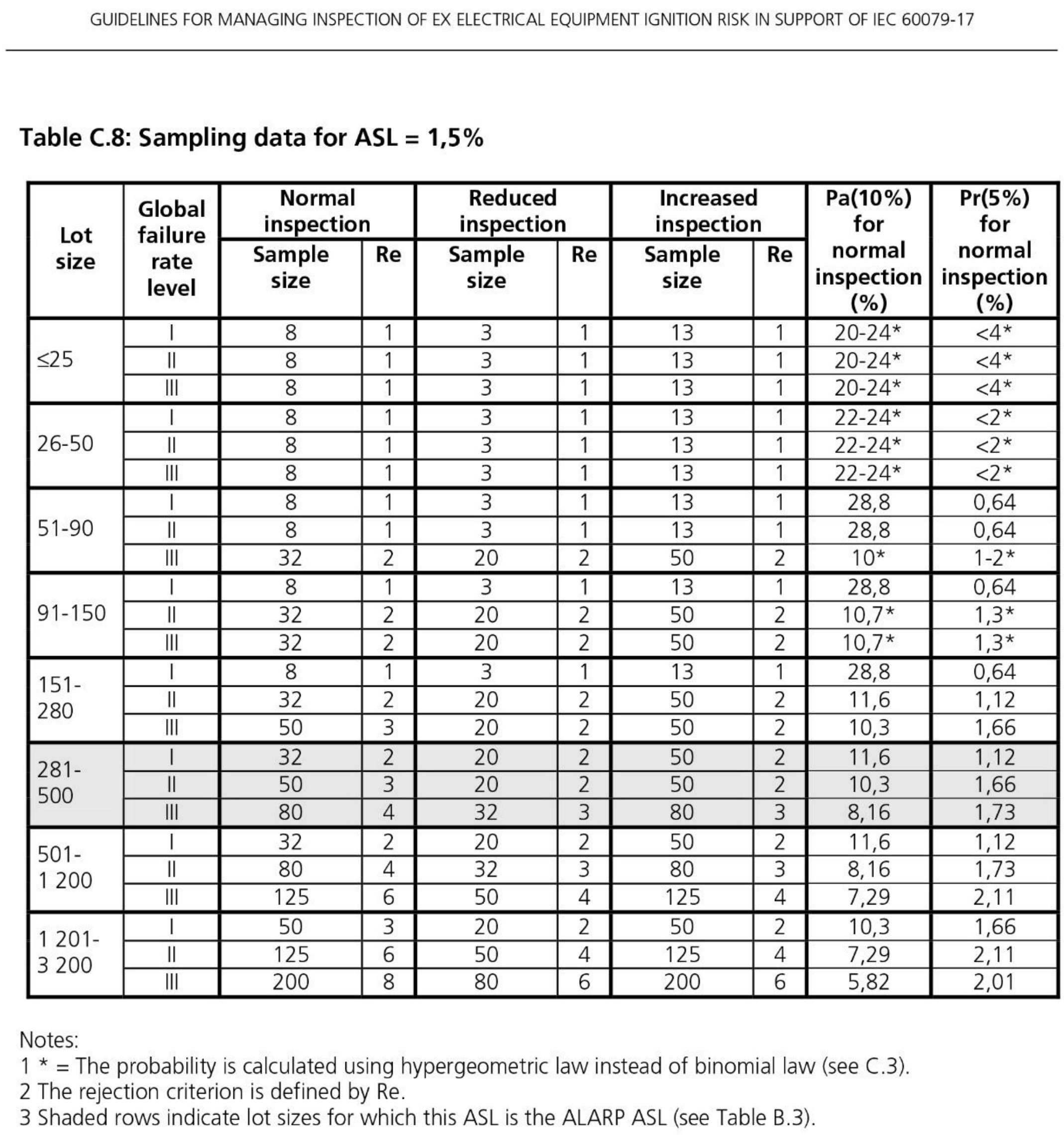


Table C.7: Sampling data for ASL = 1%

Lot size	Global failure rate level	Normal inspection		Reduced inspection		Increased inspection		Pa(10%) for normal inspection (%)	Pr(5%) for normal inspection (%)
		Sample size	Re	Sample size	Re	Sample size	Re		
≤25	I	13	1	5	1	20	1	12*	<4*
	II	13	1	5	1	20	1	12*	<4*
	III	13	1	5	1	20	1	12*	<4*
26-50	I	13	1	5	1	20	1	15*	<2*
	II	13	1	5	1	20	1	15*	<2*
	III	13	1	5	1	20	1	15*	<2*
51-90	I	13	1	5	1	20	1	16,2	0,4
	II	13	1	5	1	20	1	16,2	0,4
	III	13	1	5	1	20	1	16,2	0,4
91-150	I	13	1	5	1	20	1	16,2	0,4
	II	13	1	5	1	20	1	16,2	0,4
	III	50	2	32	2	80	2	6,6*	1,33*
151-280	I	13	1	5	1	20	1	16,2	0,4
	II	50	2	32	2	80	2	7,56	0,72
	III	50	2	32	2	80	2	7,56	0,72
281-500	I	13	1	5	1	20	1	16,2	0,4
	II	50	2	32	2	80	2	7,56	0,72
	III	80	3	32	2	80	2	6,52	1,03
501-1 200	I	50	2	32	2	80	2	7,56	0,72
	II	80	3	32	2	80	2	6,52	1,03
	III	125	4	50	3	125	3	5,27	1,1
1 201-3 200	I	50	2	32	2	80	2	7,56	0,72
	II	125	4	50	3	125	3	5,27	1,1
	III	200	6	80	4	200	4	4,59	1,32

Notes:
1 Table replicated as Table B.2.
2 * = The probability is calculated using hypergeometric law instead of binomial law (see C.3).
3 The rejection criterion is defined by Re.
4 Shaded rows indicate lot sizes for which this ASL is the ALARP ASL (see Table B.3).



GUIDELINES FOR MANAGING INSPECTION OF EX ELECTRICAL EQUIPMENT IGNITION RISK IN SUPPORT OF IEC 60079-17

Table C.8: Sampling data for ASL = 1,5%

Lot size	Global failure rate level	Normal inspection		Reduced inspection		Increased inspection		Pa(10%) for normal inspection (%)	Pr(5%) for normal inspection (%)
		Sample size	**Re**	**Sample size**	**Re**	**Sample size**	**Re**		
≤25	I	8	1	3	1	13	1	20-24*	<4*
	II	8	1	3	1	13	1	20-24*	<4*
	III	8	1	3	1	13	1	20-24*	<4*
26-50	I	8	1	3	1	13	1	22-24*	<2*
	II	8	1	3	1	13	1	22-24*	<2*
	III	8	1	3	1	13	1	22-24*	<2*
51-90	I	8	1	3	1	13	1	28,8	0,64
	II	8	1	3	1	13	1	28,8	0,64
	III	32	2	20	2	50	2	10*	1-2*
91-150	I	8	1	3	1	13	1	28,8	0,64
	II	32	2	20	2	50	2	10,7*	1,3*
	III	32	2	20	2	50	2	10,7*	1,3*
151-280	I	8	1	3	1	13	1	28,8	0,64
	II	32	2	20	2	50	2	11,6	1,12
	III	50	3	20	2	50	2	10,3	1,66
281-500	I	32	2	20	2	50	2	11,6	1,12
	II	50	3	20	2	50	2	10,3	1,66
	III	80	4	32	3	80	3	8,16	1,73
501-1 200	I	32	2	20	2	50	2	11,6	1,12
	II	80	4	32	3	80	3	8,16	1,73
	III	125	6	50	4	125	4	7,29	2,11
1 201-3 200	I	50	3	20	2	50	2	10,3	1,66
	II	125	6	50	4	125	4	7,29	2,11
	III	200	8	80	6	200	6	5,82	2,01

Notes:
1 * = The probability is calculated using hypergeometric law instead of binomial law (see C.3).
2 The rejection criterion is defined by Re.
3 Shaded rows indicate lot sizes for which this ASL is the ALARP ASL (see Table B.3).

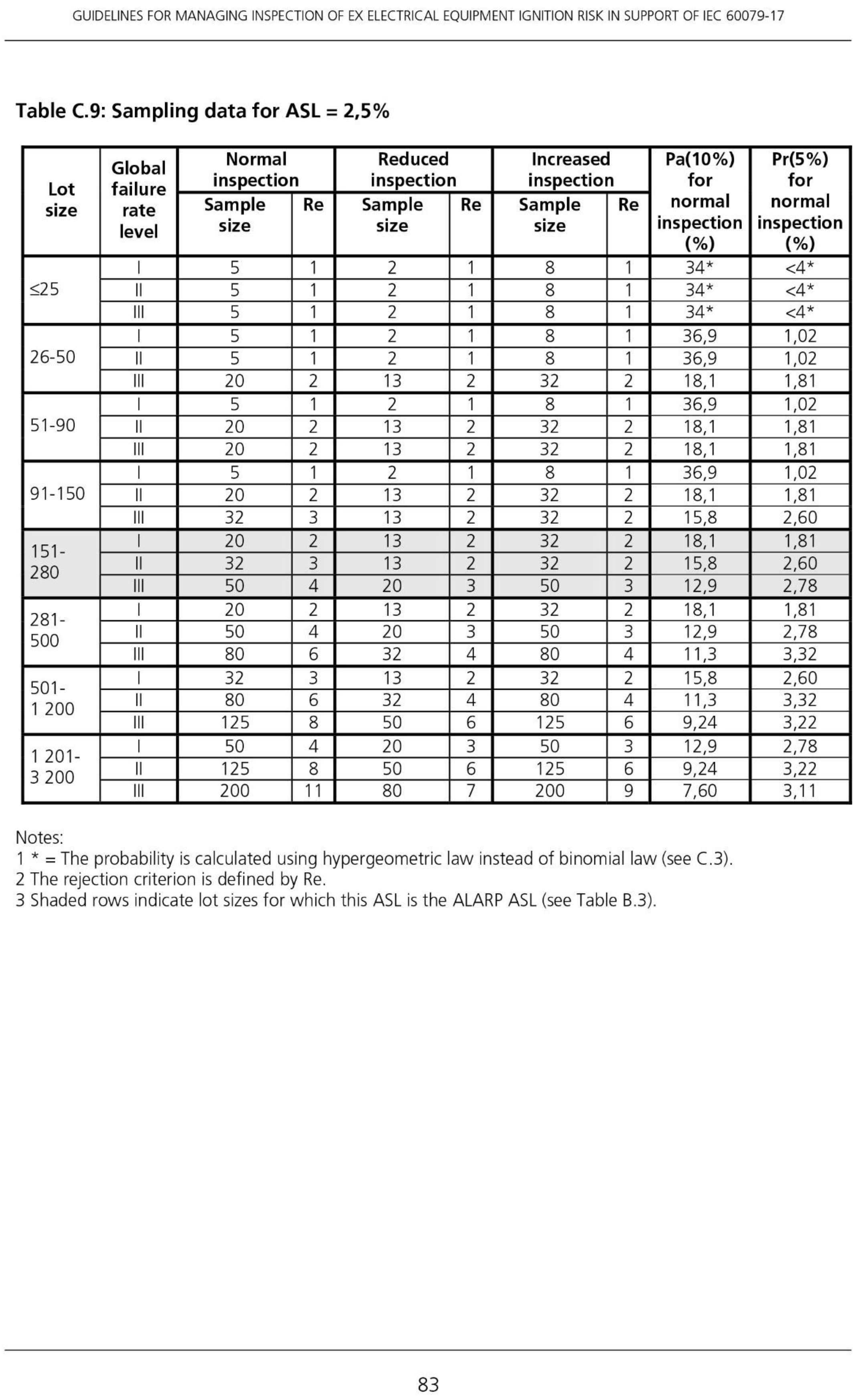


Table C.9: Sampling data for ASL = 2,5%

Lot size	Global failure rate level	Normal inspection		Reduced inspection		Increased inspection		Pa(10%) for normal inspection (%)	Pr(5%) for normal inspection (%)
		Sample size	Re	Sample size	Re	Sample size	Re		
≤25	I	5	1	2	1	8	1	34*	<4*
	II	5	1	2	1	8	1	34*	<4*
	III	5	1	2	1	8	1	34*	<4*
26-50	I	5	1	2	1	8	1	36,9	1,02
	II	5	1	2	1	8	1	36,9	1,02
	III	20	2	13	2	32	2	18,1	1,81
51-90	I	5	1	2	1	8	1	36,9	1,02
	II	20	2	13	2	32	2	18,1	1,81
	III	20	2	13	2	32	2	18,1	1,81
91-150	I	5	1	2	1	8	1	36,9	1,02
	II	20	2	13	2	32	2	18,1	1,81
	III	32	3	13	2	32	2	15,8	2,60
151-280	I	20	2	13	2	32	2	18,1	1,81
	II	32	3	13	2	32	2	15,8	2,60
	III	50	4	20	3	50	3	12,9	2,78
281-500	I	20	2	13	2	32	2	18,1	1,81
	II	50	4	20	3	50	3	12,9	2,78
	III	80	6	32	4	80	4	11,3	3,32
501-1 200	I	32	3	13	2	32	2	15,8	2,60
	II	80	6	32	4	80	4	11,3	3,32
	III	125	8	50	6	125	6	9,24	3,22
1 201-3 200	I	50	4	20	3	50	3	12,9	2,78
	II	125	8	50	6	125	6	9,24	3,22
	III	200	11	80	7	200	9	7,60	3,11

Notes:
1 * = The probability is calculated using hypergeometric law instead of binomial law (see C.3).
2 The rejection criterion is defined by Re.
3 Shaded rows indicate lot sizes for which this ASL is the ALARP ASL (see Table B.3).

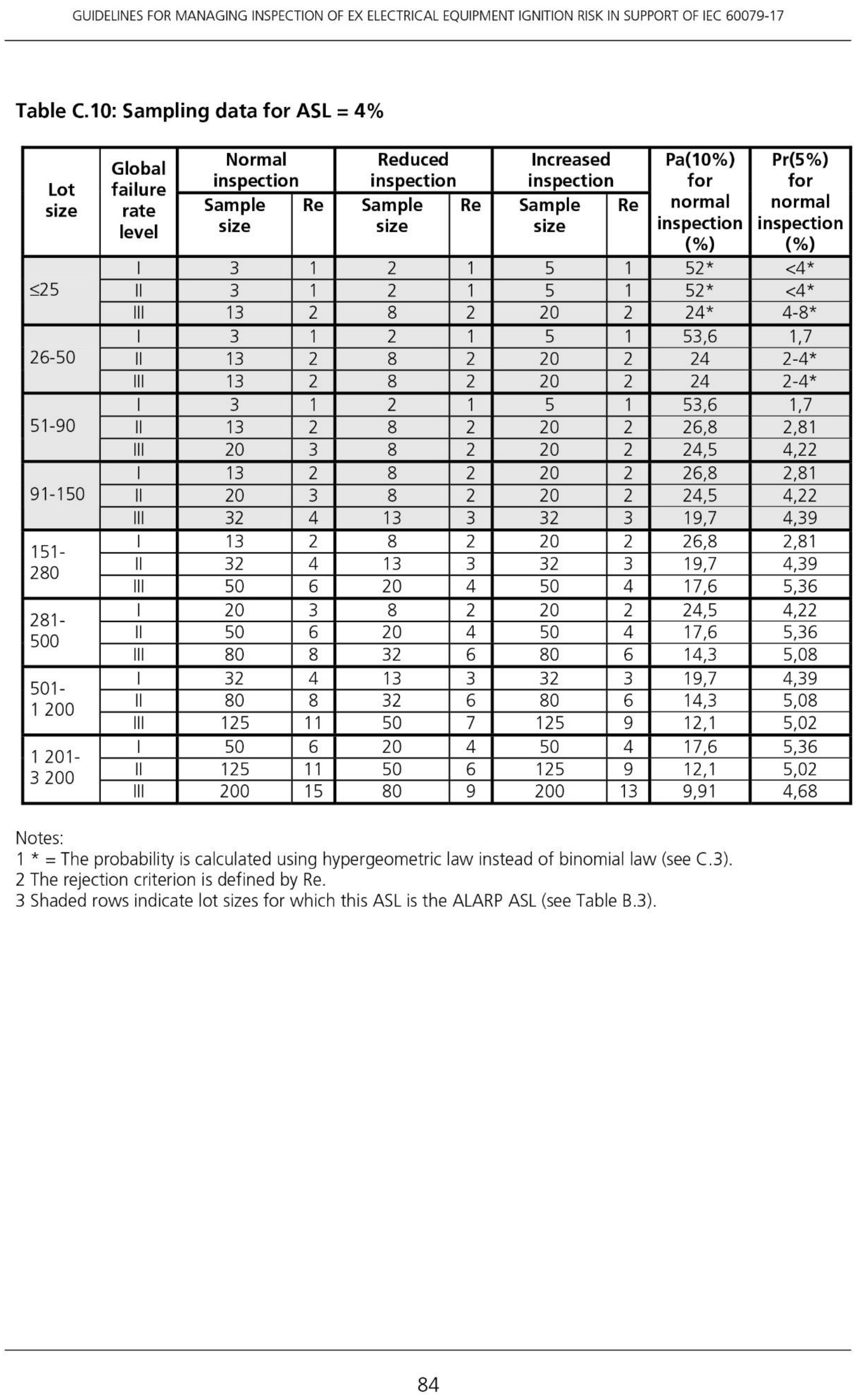


Table C.10: Sampling data for ASL = 4%

Lot size	Global failure rate level	Normal inspection		Reduced inspection		Increased inspection		Pa(10%) for normal inspection (%)	Pr(5%) for normal inspection (%)
		Sample size	Re	Sample size	Re	Sample size	Re		
≤25	I	3	1	2	1	5	1	52*	<4*
	II	3	1	2	1	5	1	52*	<4*
	III	13	2	8	2	20	2	24*	4-8*
26-50	I	3	1	2	1	5	1	53,6	1,7
	II	13	2	8	2	20	2	24	2-4*
	III	13	2	8	2	20	2	24	2-4*
51-90	I	3	1	2	1	5	1	53,6	1,7
	II	13	2	8	2	20	2	26,8	2,81
	III	20	3	8	2	20	2	24,5	4,22
91-150	I	13	2	8	2	20	2	26,8	2,81
	II	20	3	8	2	20	2	24,5	4,22
	III	32	4	13	3	32	3	19,7	4,39
151-280	I	13	2	8	2	20	2	26,8	2,81
	II	32	4	13	3	32	3	19,7	4,39
	III	50	6	20	4	50	4	17,6	5,36
281-500	I	20	3	8	2	20	2	24,5	4,22
	II	50	6	20	4	50	4	17,6	5,36
	III	80	8	32	6	80	6	14,3	5,08
501-1 200	I	32	4	13	3	32	3	19,7	4,39
	II	80	8	32	6	80	6	14,3	5,08
	III	125	11	50	7	125	9	12,1	5,02
1 201-3 200	I	50	6	20	4	50	4	17,6	5,36
	II	125	11	50	6	125	9	12,1	5,02
	III	200	15	80	9	200	13	9,91	4,68

Notes:
1 * = The probability is calculated using hypergeometric law instead of binomial law (see C.3).
2 The rejection criterion is defined by Re.
3 Shaded rows indicate lot sizes for which this ASL is the ALARP ASL (see Table B.3).

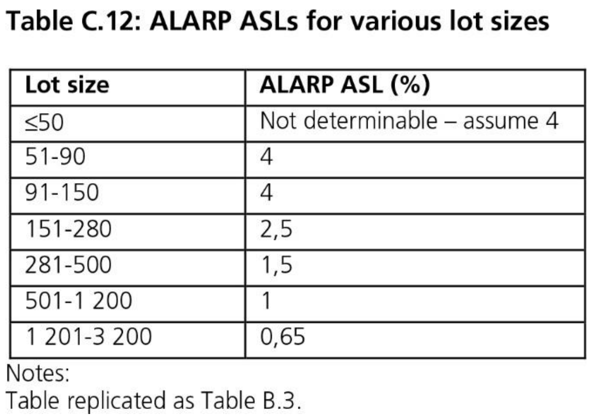


Table C.12: ALARP ASLs for various lot sizes

Lot size	ALARP ASL (%)
≤50	Not determinable – assume 4
51-90	4
91-150	4
151-280	2,5
281-500	1,5
501-1 200	1
1 201-3 200	0,65

Notes:
Table replicated as Table B.3.