PROBABILISTIC RISK ASSESSMENT OF OFFSHORE BLOWOUTS

A THESIS SUBMITTED TO
THE BOARD OF GRADUATE PROGRAMS
OF
MIDDLE EAST TECHNICAL UNIVERSITY, NORTHERN CYPRUS CAMPUS

BY

MUHAMMED ELSALİH

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN SUSTAINABLE ENVIRONMENT AND ENERGY SYSTEMS PROGRAM

JUNE 2021

Approval of the Board of Graduate Programs

Prof. Dr. Oğuz Solyalı
Chairperson

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Asst. Prof. Dr. Ceren İnce Derogar
Program Coordinator

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Asst. Prof. Dr. Doruk Alp
Supervisor

Examining Committee Members

Prof. Dr. Salih Saner	Petroleum and Natural Gas Engineering Department Near East University
Asst. Prof. Dr. Doruk Alp	Petroleum and Natural Gas Engineering Program METU NCC
Asst. Prof. Dr. Aykut Argönül	Chemical Engineering Program METU NCC

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Muhammed, Elsalih

Signature:

ABSTRACT

PROBABILISTIC RISK ASSESSMENT OF OFFSHORE BLOWOUTS

Elsalih, Muhammed
Master of Science, Sustainable Environment and Energy Systems Program
Supervisor: Asst. Prof. Dr. Doruk Alp

June 2021, 124 pages

A blowout is the eruption of underground reservoir fluids to the surface during drilling operations. This has devastating results, which are described by the serious impact on human health, environmental problems, and economic loss. Blowout events are unpredictable due to uncertainty of how they evolve. Blowout risk usually lies with parts of the safety system that are expected to function fully, and prevent blowouts. Fault Tree Analysis (**FTA**) is a graphical method offering a way to identify Causal Factors (**CF**) of the safety system failure, and to evaluate the contribution level of each event to blowout. In this study, an FTA model for offshore blowout probability is mapped to a Bayesian Network (**BN**). This BN-based model is utilized for Probabilistic Risk Assessment (**PRA**) of hazards, accounting for uncertainty in both safety system failure rates and subsurface formation pressures. To the best of our knowledge, this is the first time all of the commonly encountered safety barriers are combined in a single PRA analysis. The PRA is performed using importance measures of FTA roots. According to results herein, the blowout event is attributed mostly to human error in monitoring safety barriers. Also, blowout events are highly probable due to inability to precisely identify abnormal subsurface pressure zones. Finally, casing failure is found to be the third significant contributor to blowout.

Keywords: Probabilistic Risk Assessment, Bayesian Network, Fault Tree Analysis, Blowout, Drilling

ÖZ

DENİZ SONDAJI KUYU PATLAMALARININ OLASILIK BAZLI RİSK DEĞERLENDİRMESİ

Elsalih, Muhammed
Yüksek Lisans, Sürdürülebilir Çevre ve Enerji Sistemleri
Tez Yöneticisi: Dr. Öğr. Üyesi Doruk Alp

Haziran 2021, 124 Sayfa

Kuyu patlaması (blowout), sondaj sırasında yeraltı sıvılarının kontrolsüz olarak yüzeye püskürmesidir. Bu patlamaların insan sağlığına, çevreye ve ekonomiye yıkıcı etkileri vardır. Patlamalara pek çok farklı unsurun sebep olması, bu durumun tahmin edilmesini ve önlem alınmasını zorlaştırmaktadır. En büyük risk kaynağı, hatasız çalışması ve patlamaları önlemesi beklenen kuyu güvenlik sistemidir. Hata Ağacı Analizi (**HAA**), güvenlik sistemi arıza nedenelerini ve sistemin her bir öğesinin arızaya etkisini değerlendirmede kullanılan grafiksel bir yöntemdir. Bu çalışmada, deniz sondajı sırasında olabilecek patlamalar için Bayes Ağı (**BA**) üstüne kurulu bir **HAA** modeli geliştirilmiştir. Temelinde Bayes Ağı olan bu model, güvenlik sistemi arıza olasılığı ve yeraltı kayaç mayi basınçlarındaki belirsizlikleri de gözeterekten, kuyu patlamalarının Olasılık Bazlı Risk Değerlendirmesi (**OBRD**) için kullanılmıştır. Taranan kaynakçalardan görülebildiği kadarıyla, yaygın olarak bilinen güvenlik bariyerlerinin tümü ilk kez bu çalışmada bir arada incelenmiştir. Patlamanın ana nedenleri **HAA** ile saptandıktan sonra, "önem ölçütleri" bazında değerlendirilerek **OBRD** gerçekleştirilmiştir. Bu çalışmada elde edilen sonuçlara göre, patlamaların ana kaynağı güvenlik sistemini izlerken oluşan operatör hatalarıdır. Patlamaların ikinci derecede sebebi, aşırı

basınçlı katmanların kesin olarak tespit edilememesidir. Kuyu koruma borusu (casing) arızasının patlamaya üçüncü derecede sebep olduğu bulunmuştur.

Anahtar Kelimeler: Olasılık Bazlı Risk Değerlendirmesi, Bayes Ağı, Hata Ağacı Analizi, Kuyu patlaması, Sondaj

To My Parents

ACKNOWLEDGMENTS

The author wishes to express his deepest gratitude to his supervisor Asst. Prof. Dr. Doruk Alp for his guidance, advice, criticism, encouragements, and insight throughout the research.

I would like to extend thanks to Dr. Majeed Abimbola and Dr. Faisal Khan, who generously guided me through their publications and helped in the logical configuration of the Bayesian Network mapping procedures in this work.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

ABBREVIATIONS

AIChE	American Institute of Chemical Engineers
AND	Logic gate that indicates the conjunction between two or more events
API	American Petroleum Institute
BE	Basic Event
BI	Birnbaum Importance
BN	Bayesian Network
BP	British Petroleum
BOP	Blowout Preventer
CCOHS	Canadian Centre for Occupational Health and Safety
CCPS	Center for Chemical Process Safety
CF	Causal Factor(s)
CI	Criticality Importance
CPT	Conditional Probability Table
DAG	Directed acyclic Graph
DI	Diagnostic Importance
ETA	Event Tree Analysis
FMEA	Failure Modes and Effects Analysis
FT	Fault Tree
FTA	Fault Tree Analysis
GOM	Gulf of Mexico
HAZID	Hazard Identification
HAZOP	Hazard and operability study
HC	Hydrocarbon
HSE	Health, Safety, and Environment.
IE	Intermediate Event
IEA	International Energy Agency

IM	Importance Measures
KM	Kill Mud
MPD	Managed Pressure Drilling
MSG	Multi-State Gate
NL	No light in a room
OM	Old Mud Weight
OR	Logic gate that indicates the disjunction between two or more events
OSHA	Occupational Safety and Health Administration
OVAT	One Variable at a Time
PRA	Probabilistic Risk Assessment
RCD	Rotating Control Device
RP	Recommended Practices
ROP	Rate of Penetration
RRW	Risk Reduction Worth
TE	Top Event
WC	Well Control
Yr	Year

LIST OF SYMBOLS

SYMBOLS

A, B…	An event, e.g. getting number 6 after rolling the dice
P(A)	Probability of an event (event A, in this case)
A’	Complementary event of event A
∪	Union of two events, i.e. A ∪ B
∩	Intersection of two events, i.e. A ∩ B
P (A|B)	Probability, event A occurrence given that event B occurs
Pa (Di)	Probability of an event’s parent (BN) occurring simultaneously
$\prod_{i=1}^{n} P(D_i \| Pa(D_i))$	Chain rule and conditional probability formula to calculate a BN
P (C|A, B)	Probability of an event C given that A and B occurs
P_H	Hydrostatic Pressure
P_F	Formation Pressure
BE_i	Element of interest in the analysis
ΔP	Differential pressure i.e., $\Delta P = P_H - P_F$

CHAPTER 1

INTRODUCTION

Wells are drilled to reach and extract three valuable resources:

1) Fresh Water
2) Geothermal energy – a clean and renewable resource
3) Hydrocarbons – fuel and raw material for many products

Drilling industry faces major challenges sustaining continuity of operations that meet Health, Safety, and Environment (HSE) requirements (Tom, 2012). Drilling operations frequently slow down and halt, and some wells are completely abandoned due to accidents and hazards. Such interruptions also impact sustainable production of valuable resources mentioned above.

While renewable energy resources are most desired, they still cannot provide a complete substitute for hydrocarbon-based[1] products. Petrochemical products obtained through petroleum refineries are typically used in transportation as fuel for the engines of vehicles. Specifically, diesel, gasoline, and kerosene[2] are known for their high performance, efficiency, and safety as fuel for internal combustion engines (Furfari, 2016). As of 2012, gasoline held 39 % of global consumption in the transportation sector. According to International Energy Agency (**IEA**) (2016), gasoline is expected to have a share of 33 % by 2040. In addition, the share of diesel in transportation is the second-highest, with 36 % in 2012. And, it is expected to drop to ~33 % level in 2040, similar to gasoline. Moreover, jet fuels and kerosene held 12

[1] Hydrocarbon (HC): an organic chemical compound composed mainly of hydrogen and carbon atoms (Enerijiofi, 2021).
[2] Kerosene: a fuel formed from HCs and used widely in aviation (Gad, 2005).

% of consumption in the transportation sector by 2012, and their combined share is expected to increase to 14 % by 2040.

Further, petrochemical products are used in medicine formulation, for example, as cancer-fighting drugs. Also, they are used in making aspirin, which is used daily to lower the risk of heart attack for patients (Speight, 2020).

The need for hydrocarbon-based products, make it compulsory to pursue hydrocarbon extraction process (National Research Council, 1994). Extraction should be conducted in a way that does not have a negative impact in any regard. This could be achieved by applying industry best practices and complying with HSE requirements (Ibrahim et al., 2016). However, the main issue in drilling operation continuity lies with the uncontrolled violent discharge of high-pressure, high-velocity underground fluids to the surface. This is called a ***blowout***. Besides continuity of operations, blowouts have created a huge debate about sustainability in the industry. This is due to the high impact on human life, which is illustrated by life loss or physical damage that the workers experience at the worksite. Also, blowouts result in environmental damage, and severe contamination of the surroundings with chemicals, endangering the species around (Saha, 2010).

Blowouts result from a sequence of failed safety barriers[3]. A well-known example is the Gulf of Mexico (**GOM**) oil spill of Macondo well, being drilled by the Deepwater Horizon rig at the time (2010). The blowout occurred after a subsystem safety failure, hydrocarbon fluids reached the surface and met an ignition source that led to an explosion. Surface facilities continued burning for two days, resulting in 11 fatalities, 17 injured, and nearly 5 million barrels of oil spilled to the GOM before the well was successfully controlled (National Academy of

[3] Safety barriers: physical and/or non-physical means planned to prevent, control, or mitigate undesired events or accidents (Sklet, 2006).

Engineering & National Research Council, 2012). The Macondo blowout (2010) is a perfect example to show the consequences of blowouts.

The reason for safety system failure of Macondo (2010) was found after a comprehensive investigation by the British Petroleum (**BP**) team, which used event chronology and Fault Tree Analysis (**FTA**) methods to diagnose the causal factors[4] of failures (BP, 2010). The blowout was mainly attributed to the unforeseen cement failure along with a sequence of failures in other safety barriers.

1.1 Scope of the Thesis

In this study, blowout safety system for a typical offshore operation is assessed to estimate operation risk. Herein, FTA is implemented to identify the causal factors and contribution of drilling system components to the blowout, and to evaluate blowout prevention barriers that are typically applied in the field. This analysis yields the weak point of the safety system, and allows estimating probability of having a blowout during drilling operations. Due to the complexity of the drilling operations, it is unpractical to create a fault tree that represents the whole operational structure because we need to include the common cause and sequential of failure (Khan et al. 2018). Hence, a Bayesian Network (**BN**) is utilized to overcome this issue. BN offers a convenient environment to account for complicated processes using single nodes, called Multi-State Gate (**MSG**). After developing necessary fault trees for individual subsystems, these trees are mapped into a BN model that follows the operation sequence. Later, the BN model is analyzed using Importance Measures (**IMs**). These "measures" test each causal factor and rank them according to the risk level, i.e. contribution of each parameter to the blowout. The sequence of this work is organized into nine chapters, as shown in detail in Table 1.1:

---

[4]Causal Factors: A major unplanned, unintended contributor to an incident i.e., a negative event or undesirable condition (AIChE/CCPS, 2014).

Table 1.1: Scope of the thesis

Chapter	**Content**
Chapter 2	Brief introduction to: 1- Off-shore drilling operations 2- Kick & Blowout initiation 3- Safety system functionality, and sequence of hazard prevention
Chapter 3	The concept of risk, and risk assessment is explained, with a focus on drilling risk assessment tools, benefits, and limitations
Chapter 4	A review on statistics, and introduction to Bayesian Network
Chapter 5	Fault Tree Analysis, construction, and evaluation procedure
Chapter 6	Problem statement, blowout risk assessment, literature review
Chapter 7	Methodology
Chapter 8	Results and discussion on the risk mitigation process
Chapter 9	Conclusion & Recommendations: 1- Summary of results, leading causes of blowouts 2- Recommendation to mitigate blowout occurrence

CHAPTER 2

OFFSHORE DRILLING OPERATIONS

Deepwater drilling is the process of drilling in waters, which has a depth of 300 [m] or more (Cholteeva, 2020). Drilling at a location where seabed is at 1500 [m] or deeper is called ultra-deep water drilling (Rocha et al., 2003). In deep-water drilling, the drilling system is composed of four main sections. These are (1) sea-level platform that hosts the rig and facilities, (2) connection to the seabed (or seafloor), and (3) seabed/seafloor wellhead, and (4) wellbore below the seabed, as shown in Figure 2.1.

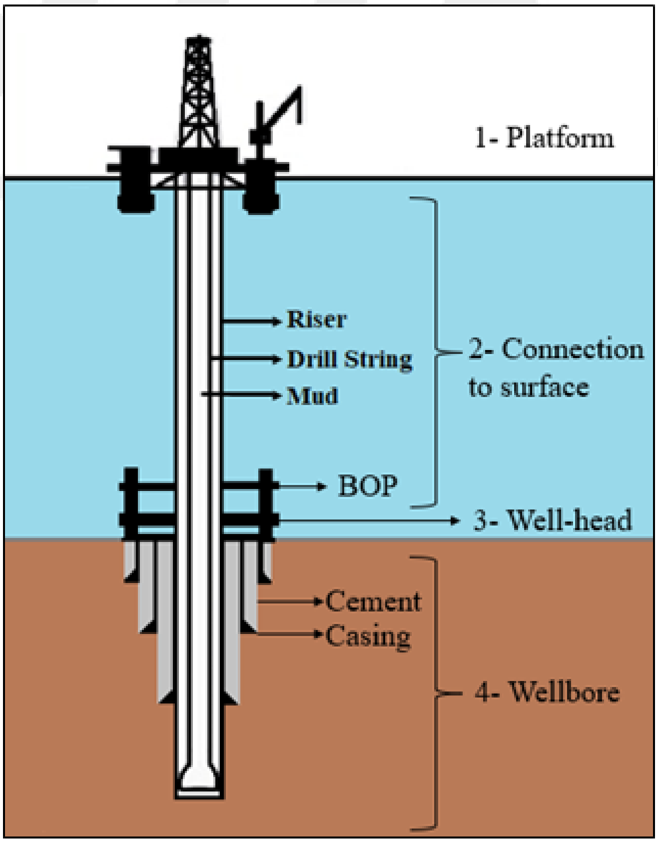


Figure 2.1: Schematic of deep-water drilling (Haghshenas et al., 2008)

Sea level equipment:

The sea level platform (the surface) is the part where most of the drilling facilities, fluids, pumps, engines, and personnel exist. All this equipment is set on a floating vehicle called an offshore rig (Bourgoyne, 1991).

Connections to Seabed:

In deep-water drilling, a drilling riser, a large diameter pipe, is used to connect the Blowout Preventer (**BOP**, explained in detail next) on the seafloor to the surface facilities. The function of the riser is to transmit drilling mud[5] returns to the surface. Inside the riser, another pipe is used for transmitting the required torque and weight to drill the formation[6], called drill pipe (Chandrasekaran, 2021). During ultra-deep drilling operations, these pipes are the only connections between the surface and seabed, and the position of the platform is maintained using tension cables anchored to the seafloor, and propellers mounted on the platform (Chakrabarti et al., 2005).

Seabed equipment:

The BOP is constructed on the seabed. There is no well drilled without the BOP. It is crucial for well safety to prevent the blowout in case of receiving a kick[7]. BOP is a combination of several valves constructed at the top of the well. These valves are controlled remotely from the surface facilities via hydraulic actuators. When kick is detected, the crew at the surface activates the BOP to shut the well in, i.e., stop the flow of fluids to the surface (Islam & Hossain, 2021). It has multiple flow preventer types; these are (1) Annular blowout preventers[8], which can seal

---

[5] Drilling mud: various mixtures of liquid, gaseous and solid ingredients are used to facilitate operations to drill boreholes into earth (Fink, 2015).
[6] Formation: a continuous body of subsurface rock that is sufficiently distinctive from surrounding strata (Earle, 2019).
[7] Kick: unplanned entry of low-density, high pressure formation fluids into the wellbore, posing blowout risk (Mitchell et al., 2011).
[8] Annular preventer: A large valve used to control wellbore fluids. Using a sealing element resembles a large rubber doughnut that is mechanically squeezed inward to seal on pipes (Crumpton, 2018).

around the non-cylindrical objects, and (2) Ram blowout preventers, which are three types as showing in Figure 2.2.

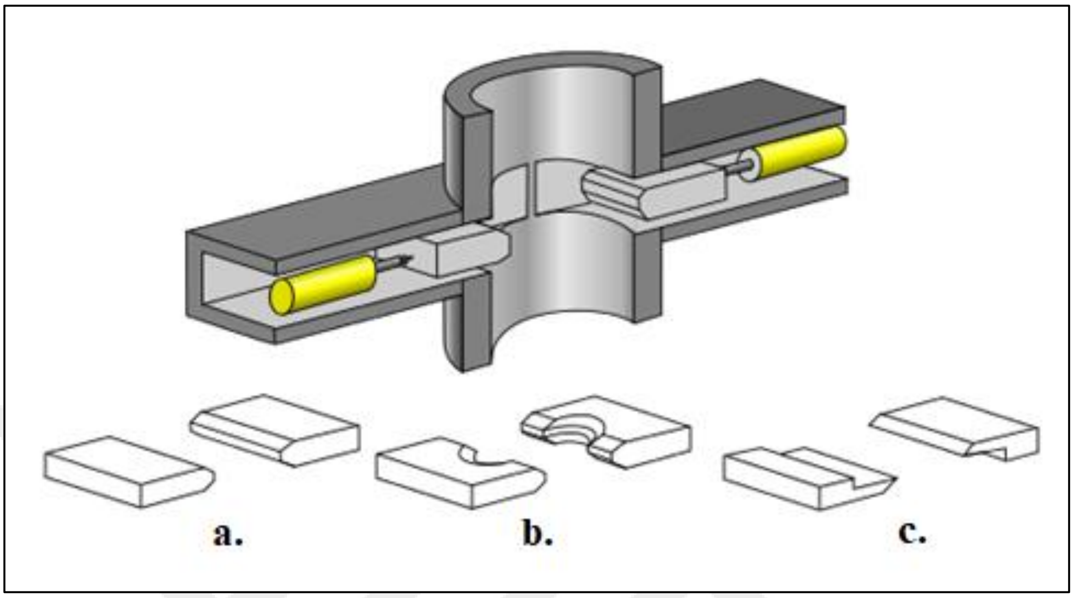


Figure 2.2: BOP rams: a) Blind ram, b) Pipe ram, c) Shear ram (Drillingformulas.com, 2012).

Blowout preventer rams, shown in Figure 2.2, are designed to be used according to the presence (or the absence) of drill pipe in a well. For example, blind rams shown in Figure 2.2 (part a) are used to seal the well, when there is no drill pipe in it. Another type, called pipe ram (Figure 2.2, part b), is used to seal around a drill pipe. Also, shear rams in Figure 2.2 (part c), are used to seal the well by cutting the drill string (Crumpton, 2018).

As the BOP system is one of the most important parts of a deep-water drilling system, it should be frequently tested, inspected, rejuvenated. These measures are a safeguard to ensure full and proper functionality of the BOP. Also, it is a part of risk mitigation and legal requirements (Mishra, 2019).

2.1 Drilling a Well

Drilling is the process of making a connection between underground rock formation and surface. This operation is not an arbitrary process, i.e., not only using a drilling machine to reach subsurface target depth, as if drilling a hole on the wall with a hand tool. The process ensures that the operations in different stages apply the required safety measures while reaching the target depth (Alnabhani, 2018).

Drilling operations are divided into several stages. These are illustrated in Figure 2.3. After deciding the location to drill, shown in Figure 2.3 (part 1), the platform hosting the rig is situated at the top of the targeted point. Drilling rig is the system of machines that drills the well. It conveys the rotational motion from surface to the drill bit at the end of the drill string, which is made up of a series of pipes called drill pipes. These pipes are connected to one after other while drilling continues to the target depth.

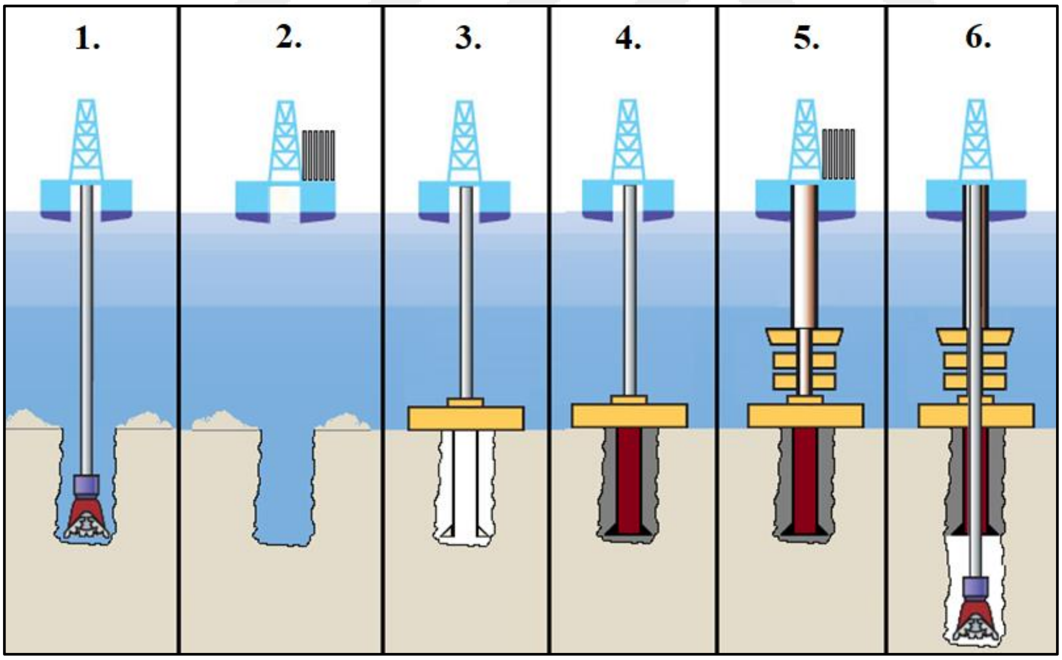


Figure 2.3: Deepwater drilling stages (modified from Mori et al., 2012)

The first phase of drilling starts by creating a hole, which is usually around 50 cm in diameter as shown in Figure 2.3 (part 1). This diameter of the first drilled hole depends on the depth of targeted formation. During this phase, sea water is pumped through the nozzles of the drill bit for cleaning (removing) the cuttings[9] from underneath the bit. Then, drill pipe is pulled back to surface (part 2) to install the wellhead and casing (Alnabhani, 2018).

Any hole drilled through soft formations is endangered by the caving phenomena, which is the collapse of formation into the wellbore. Same risk exists when drilling very deep. Even if formations are now hardened due to the overburden pressure exerted by the formations above the layer on interest, it is compulsory to create a support that prevents caving-in. Hence, the casing[10] is inserted into the hole to create a barrier between the drilling fluid and the walls of the hole, as seen in Figure 2.3 (part3). Moreover, casing also prevents the contamination of drilling fluids by formation fluids. A wellhead[11] is constructed at the top of casing (Singh, 2019). Then, casing is fixed in place using cement (part 4). Cementing is the process of pumping cement slurry[12] down to the bottom of the wellbore, then diverting it behind the casing, between outer surface of casing and the walls of well. The main purpose of using cement is:

1) To support casing; keeping the casing fixed in position.
2) To prevent the movement of fluid from formation into wellbore, and vice versa, (which reduces the probability of a blowout.)
3) To prevent casing corrosion by isolating it from the formation fluids.
4) To create isolation zones between formations to prevent the contamination of fluids.

---

[9] Cuttings: small pieces of rock that break away while drilling a formation (Huo et al., 2021).
[10] Casing: a hollow steel pipe configured to suit a specific wellbore (Azar & Samuel, 2007).
[11] Wellhead: the equipment installed on the seabed for suspending casing strings (Bourgoyne, 1991).
[12] Cement slurry: a mixture that is composed of cement, water, and various chemical additives (Mitchell et al., 2011).

Finally, the BOP is set at the top of wellhead. Above the BOP, the riser is inserted to connect the wellhead to the platform, as in Figure 2.3 (part 5). In (part 6) of Figure 2.3, drilling operation proceeds by drilling another depth interval, after which another casing is placed (smaller diameter than the previous one), and cemented in place. This procedure is repeated until the target depth is reached (Singh, 2019).

2.2 Subsurface Rocks & Abnormal Fluid Pressures

The major source of uncertainty in drilling operations is the abnormal fluid pressures in the subsurface rocks. The fluids enter into subsurface rocks:

1) After formation of the rock, through the pores of the rock
2) During deposition of the rock,

Due to porous structure of rocks, a hydrostatic pressure gradient is established within earth's crust. However, some rock layers are impermeable, and create a flow barrier between over-lying and under-lying layers, effectively disrupting the hydraulic communication, and the hydrostatic gradient. Such disruptions are observed as abnormal and subnormal pressures with respect to hydrostatic gradient (Chapman, 1983).

There are mainly three types of rock below the seabed. These are (1) the impermeable cap rock; which forms a seal that prevents HCs escape to surface, (2) permeable reservoir rock; which contains the HCs, and (3) the source rock, which is the origin of HC (Hustrulid, 2020). In fact, hydrocarbons (**HC**) are generated by conversion of solid organic materials that deposited with the rock grains. These rock types are shown in Figure 2.4.

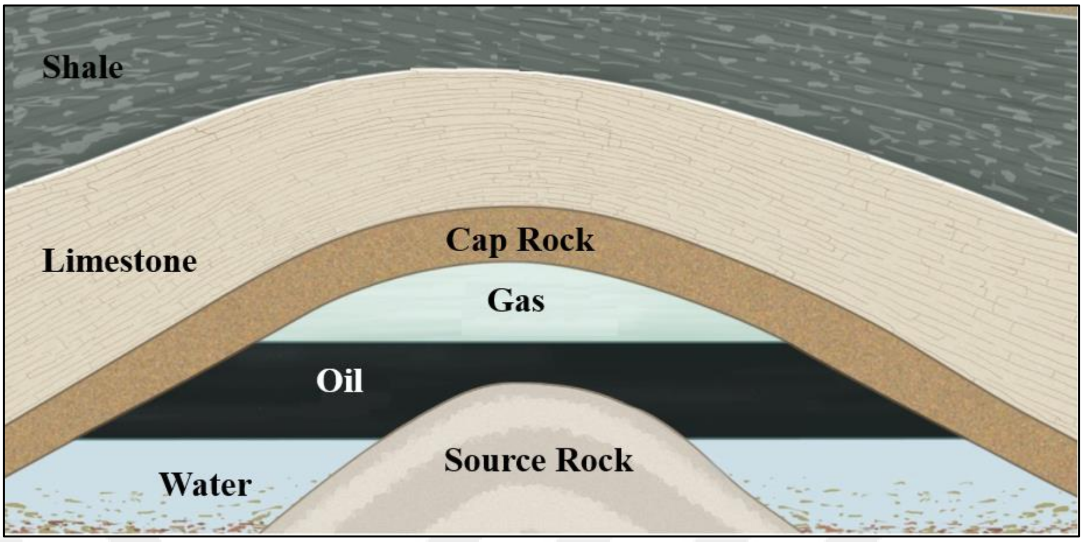


Figure 2.4: Petroleum system rocks (Hustrulid, 2020)

2.3 Fluids Involved in Drilling and the Kick

In drilling operations, two types of fluids exist at the bottom of the drilled hole. The first is the drilling fluid (mud); which is pumped from the surface through the drill string to the drill bit at the bottom of the hole. The second is the formation fluid that is present in the pores of geologic formations. These fluids are shown in Figure 2.5.

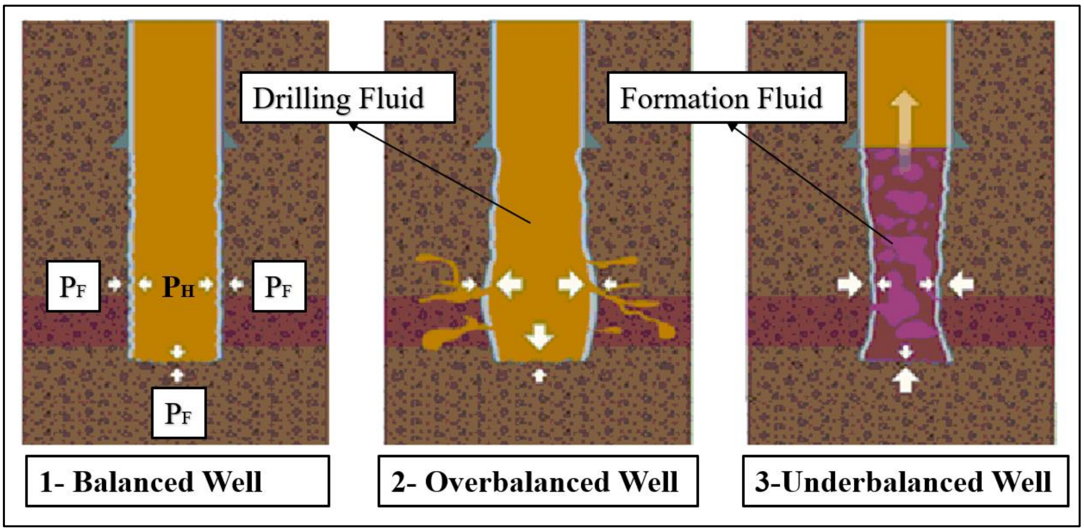


Figure 2.5: Well condition based on pressures (Aulicino & Timblin, 2018)

Formation fluids create a pressure within the pores of a reservoir rock called formation pressure (**P_F**). This pressure is balanced by the drilling fluid in order to prevent abnormally pressured formation fluids from erupting to surface.

As seen in Figure 2.5, the drilling fluids create a hydrostatic pressure (**P_H**) by the column of fluids accumulated from the surface until bottom of the hole. P_H is given in Eq 2.1:

$$P_H = 0.052(\mathrm{MD})\ (\mathrm{TVD}) \qquad \text{Eq 2.1}$$

Where,

P_H	Hydrostatic pressure [psi]
0.052	Conversion factor [ppg-ft] to [lb/in^2]
MD	Mud Density [ppg.]
TVD	True Vertical Depth [ft]

Kick is the intrusion of formation fluid to the wellbore (Bourgoyne, 1991). The intrusion is due to pressure balance problem that occurs when formation pressure is higher than the hydrostatic pressure. Usually, drilling operations are named according to the pressure conditions in the wellbore (Aulicino & Timblin, 2018). These are:

1- Balanced (P_H=P_F)

The case when the hydrostatic pressure is equal to the formation pressure as it keeps the well under control. In real field practices, wells may never reach the balanced conditions since there are lots of properties affected by heterogeneity of the geological formations.

2- Overbalanced (P_H>P_F)

The case when the pressure inside the wellbore is greater than the formation pressure indicates that there is no kick. Although most of the drilling operations are performed under overbalance situation, it is not preferable to have excessive overbalanced pressure as it results in drilling mud loss to the formation, which is expensive.

3- Underbalanced (P_H<P_F)

The case when the pressure inside the wellbore is lower than the formation pressure. Hence, the worst case of all pressure conditions as it indicates that kick is initiating (Mitchell et al., 2011). P_H may become less than the P_F due to several reasons:

1) Sudden drop in fluid level in the wellbore
2) High flow rates (P_H drop due to high circulation rate)
3) Sudden drop in drill-string inlet pressure
4) Sudden drop in casing outlet pressure
5) Unexpected abnormal pressure zone

2.4 Blowout

Blowout is the explosion caused by an uncontrolled kick, where formation pressure pushes wellbore fluids to the surface (more information about blowouts is introduced in Chapter 6). In such cases, intrusion of formation fluids may directly develop into a blowout when kick is not detected, or when the safety barriers (well control and BOP) fail (John & F, 2016).

2.5 Safety Systems

Drilling operations are subject to several safety barriers for each drilled section. The main aim of these barriers is to:

1- Prevent the intrusion of formation fluids into the wellbore, i.e. **cement and casing**.
2- Kick detection, i.e. **well monitoring system**.
3- Control the well, i.e. **circulation system**.

4- Seal the well, i.e. **BOP**.

If the kick is successfully controlled by any barrier, then the kick is considered to be killed; if the barriers failed to kill it, then fluid finds its way to the surface and results in a blowout (Lage et al., 1994). At the first stage, the cement creates a barrier to prevent HC influx into the wellbore. If this barrier does not function properly, a kick is received. The operation and wellbore pressures are monitored from the driller cabin at the surface for kick detection. However, if the system is not properly monitored, or a malfunction in the system is experienced and the final safety barrier (BOP) failed, the kick turns into a blowout. If it is properly detected, the blowout preventers are set to create a barrier between the subsurface and the surface. The casing holds the kick inside, and prevent release of fluids to surface or surrounding formation while kill operation[13] is in progress. However, this is the last barrier before kick development into a blowout.

2.6 Kick Detection and the Well Monitoring System

The drilling rig hosts variety of equipment which are used to monitor the drilling operation. This monitoring system is a crucial part of the drilling safety system. It is set to detect and mitigate kick initiation. Kick is detected upon recognizing changes in drilling parameters (such as fluid pressure, ROP[14], and mud tank levels). Mitigation is possible through required well control procedures applied to return to normal operations pathway.

In case of a kick, monitoring devices are continuously observed to detect the changes in drilling parameters such as circulations pressures, gas content in mud return, mud volume, density, and conductivity (Ahmed et al., 2016). That is, kick

---

[13] Kill operations: fluid circulation procedure to remove kick fluid and replace original mud with heavier kill mud (Fan et al., 2017).
[14] ROP: Rate of penetration

detection process is based on the observation of these parameters, which explain the movements of downhole fluids. For example, increase in mud return or increase in rate of penetration are considered as warning signs for a developing kick (Zhu et al., 2019).

Blowout mitigation implies that no kick detection leads to a direct blowout. Hence, when kick is not detected, operators at the surface would proceed drilling without putting on any Well Control (**WC**) procedures (explained in Section 2.7). If kick is detected, then the crew would stop drilling, and try to retain control of the well (i.e. restore pressure balance at the hole bottom) that is lost when kick is received.

2.7 Well Control and BOP

Well Control is the process of maintaining pressure balance (P_H=P_F) while circulating the kick fluid out of the well, before resuming regular drilling activity. There are several well control methods to monitor underground processes, detect kicks, and to cope with them. Usually, while conducting drilling operations, if a kick is detected, the direct action is to defer to the WC procedures. The well control procedure consists of two defensive barriers; these are (Hsieh, 2013):

1- Kill fluid (or kill mud), which is the primary well control barrier.

Usually, when the driller recognizes an unusual change in the formation parameters such as increase in Rate of Penetration (**ROP**), tank gain, and fluid return volumes on the monitoring system at the surface, he/she implements the primary barrier to regain pressure control over the well. Kick is received because the drilling fluid does not provide required pressure on the formation, as required by Eq 2.1. Hence, to overcome this issue, another fluid is prepared which is called Kill Mud

(**KM**), and circulated through the drill pipe to the annulus[15]. As shown in Figure 2.6, interior of the drill pipe and the annulus in fact establishes a U-tube connection. The KM is introduced to replace the Old Mud (**OM**). Hence, the new fluid gradually increases the P_H so that it is greater than or equal to P_F. If the pressure balance is maintained, the WC procedure continues to remove the kick out of the wellbore, and operations continue. If not, then the secondary defense barrier is activated (Lage et al., 1994).

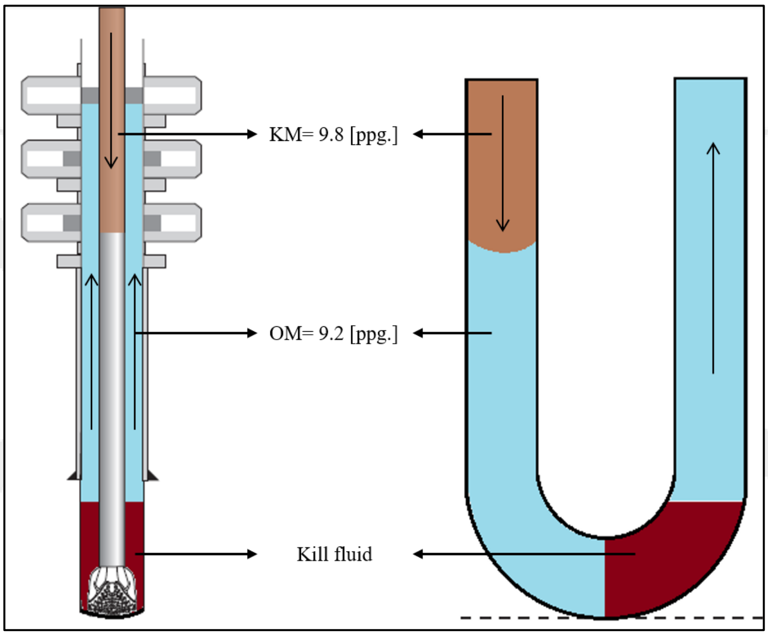


Figure 2.6: Circulation process (modified form Azar & Samuel, 2007)

2- BOP, also known as the secondary barrier.

If the first barrier (kill mud) does not achieve control, the secondary barrier is activated based on supervisor decision to shut-in a well. Moreover, if the situation is getting worse, the BOP shear rams seal the well by cutting the drill pipe.

[15] Annulus: the space between two concentric objects (O'Neill et al., 2015).

CHAPTER 3

RISK ASSESSMENT

3.1 Risk

Risk, by the simple dictionary definition, is the possibility of something bad happening, or "a situation that involves exposure to danger"(Cambridge, 2008). This term is developed with time and experience to include all daily life processes that led to the most logical definition to be *"**the probability**"* or threat ***of damage, injury, liability***, loss, or any other negative occurrence that is caused by external or internal vulnerabilities (Pal & Ghosh, 2017).

3.2 Risk Assessment

Risk assessment is the estimation of the likelihood and severity of hazardous events that might harm human health, environment, and economy (Kleijunas et al., 2006). According to the Canadian Centre for Occupational Health and Safety (**CCOHS**), it is also a general description of any process that includes:

1) Identification of hazards or factors that contribute to hazards
2) Analysis and evaluation of the hazards,
3) Determination of ways to control, reduce, convert, or eliminate hazards.

Precautionary actions, prior arrangement, and formal assessment help to avoid, mitigate, and even convert hazards to a better situation. The role of risk assessment as a systematic process is to include all available tools and methods to analyze hazards, and deal with outcomes (Silvianita et al., 2011). Looking through the literature of risk assessment practices in petroleum industry, there are a variety of methods. One answer to when, where, and how to use these methods is given by the Recommended Practices (**RP** 75) documentations developed by American Petroleum Institute (**API**). This standard recommends safety and environment programs to ensure compliance with safety system standards. RP 14J is another documentation that summarizes the recommended practice in the design and hazard analysis practices for the offshore facilities (Velez et al., 1995).

Each assessment study starts by identifying, analyzing, and evaluating risk in a project or an activity, and concludes by monitoring it (Farrell & Brandt, 2006). The three main subsections of the risk assessment process are shown in Figure 3.1.

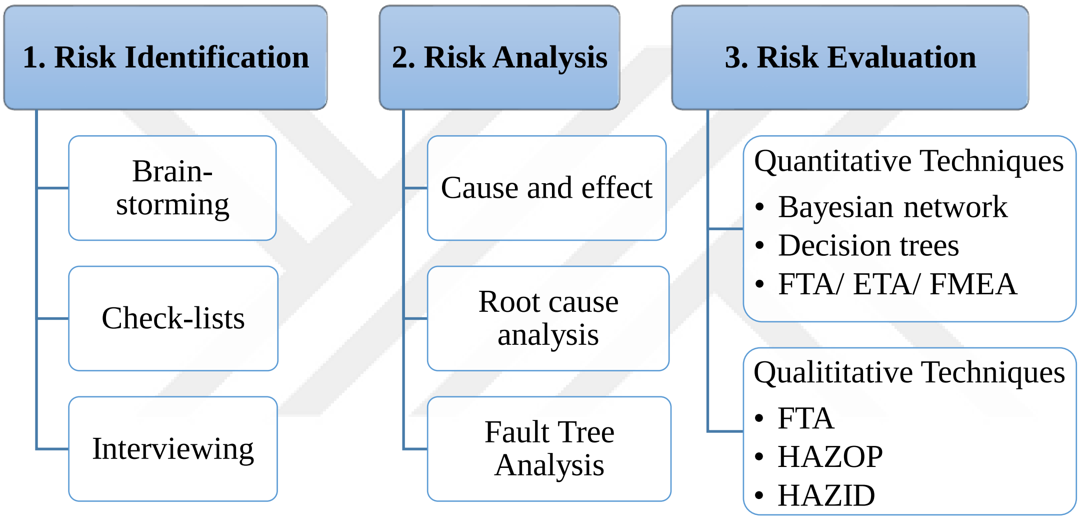


Figure 3.1: Risk assessment process (Dudek et al., 2020)

As shown in Figure 3.1, the risk assessment process goes through three stages:

1- Risk identification

It is essential to identify the hazards before conducting operations and to have an idea about what consequences can result from a specific action or procedure. Next step is to decide about who will probably be harmed by a certain hazard, set precautionary actions and safety measures. This stage is based on the observation of historically similar events, including expert knowledge, and preparing checklists to ensure that every part of a specific system is well identified (Dudek et al., 2020).

2- Risk analysis

After identifying the hazards, it is a must to implement the enough resources and appropriate tools to create a model that aids in diagnosing the weak point in the system that leads to the identified main event. For example, in the risk assessment of Macondo well by the BP investigation team, Fault Tree Analysis (explained in Chapter 5) was used to find the causal factors of the safety failure, and to consider various scenarios and possible factors contributing to the blowout (BP, 2010).

3- Risk evaluation

Risk evaluation is the process that completes the risk analysis. It is usually conducted by using qualitative or quantitative methods to observe the system behavior. Hence, after analyzing the system to find the potential risk points, the evaluation of these points is required to decide which point has the highest contribution to the system failure (Refsdal et al., 2015).

These three steps are connected to each other. Some methods like fault trees, decision trees, etc. are used in both analysis and evaluation. Hence, knowing the causal factors of failure is not enough to make a comprehensive analysis in fault trees. That is why the fault trees are furtherly evaluated to see how each element of the tree contributes to the main failure occurrence (Dudek et al., 2020). In this study the fault tree is used to analyze the system. Then, the evaluation is used based on fault tree importance measures (as explained in Section 5.4).

3.3 Risk Assessment Methods

Risk assessment includes a variety of tools to scientifically identify the risk associated with processes, operations, and reliability of systems (CCOHS, 2021).

3.3.1 Qualitative Risk Assessment

Qualitative Risk Assessment is a common method in risk assessment. To reach a judgment regarding a specific process, it looks for the qualities of the hazard-associated operations based on two main concepts, (1) the consequence (severity) and (2) the probability (likelihood) (Duvillard et al., 2021). However, there is no precise numerical application. Instead, there is a “scoring and rating process” to give a general idea about the risk level. That is, probability and severity are assigned qualifiers to compare multiple options when the numerical evaluation is not available (Yoe, 2016). Figure 3.2 shows a qualitative risk assessment example of the petroleum which shows the ranking matrix used to rank risk events based on probability and severity of outcome (low, medium, high). Herein, the risk is evaluated based on the probability (1 to 4) and the outcome severity. This can be separately evaluated based on impact to the economy, environment, safe operations (Ng, 2007).

Severity of outcome				Probability			
General terms	Financial or assets	Pollutant release	Well control	Very Unlikely 1	Unlikely 2	Likely 3	Very Likely 4
A Avoid at all costs	> $3,000k	Uncontained	Blowout needing relief well	M	H	H	H
B Definitely no	< $3,000k	Contained, < 1000 bbl equiv.	UGBO or blowout, relief well not needed	M	M	H	H
C Not desirable	< $1,000k	Contained, < 100 bbl equiv.	Well kick requires SI & circulate	L	M	M	H
D Part of the business	< $300k	Contained, < 10 bbl equiv.	Circulate and/or raise MW	L	L	L	M
Legend				L : Low	M: Medium		H: High

Figure 3.2: Qualitative risk assessment example (Ng, 2007)

3.3.2 Quantitative Risk Assessment

Unlike qualitative risk analysis, quantitative risk analysis is a risk measure when numerical values are assigned to causal factors of failures. It usually develops a probabilistic calculation to deal with uncertainty of hazards in operations and processes. With quantitative assessment, it is possible to analyze the reliability of the system by including the human error and machinery defect contribution to a specific system failure (Tauxe & Besser, 2014).

3.3.3 Comparison of Risk Assessment Methods

Silvianita et al. (2011) discusses most common risk assessment methods, as listed in Table 3.1. These methods are also implemented in offshore operations, where each one of them has its advantages as well as limitations. For example, HAZID and HAZOP methods are powerful methods in the design of safety systems, but they are limited with a qualitative analysis, giving instructions and suggestions to improve the safety system. FMEA is a highly structured assessment in the failure analysis of systems, but it is mainly used in the analysis of a single failure point of a system, limited to the examination of internal effects, and requires an extensive failure information. But methods are developed and combined to compensate for the limitation of each tool. ETA looks for the event and consequences which is a good method in terms of safety analysis. But it needs FTA as a foundation to conduct the analysis. FTA comes to be a very powerful and convenient method in finding the causal factors of failure in safety systems (Bai & Bai, 2019).

Table 3.1: Common risk assessment methods used in petroleum industry

Risk assessment method	**Type**
Failure Mode and Effects Analysis (**FMEA**)	Quantitative
Fault Tree Analysis (**FTA**)	Quantitative
Event Tree Analysis (**ETA**)	Quantitative
Hazard of Operability Study (**HAZOP**)	Qualitative
Hazard Identification (**HAZID**)	Qualitative

CHAPTER 4

BACKGROUND ON PROBABILITY

4.1 Fundamentals

The joint probability is used to calculate the likelihood of two events occurring at the same time (Kloeden et al., 1994). Each event has a probability index which varies between zero and one. The zero is an indication that event does not occur. Whereas the one indicates that event occurs. Also, the sum of probabilities of all possible outcomes of an event equals to one. Fundamental rules of evaluating joint probability are described next.

Rule of subtraction: The rule of subtraction states that the probability of occurrence of an event is 1 minus the probability of non-occurrence of the event, as given in Eq 4.1:

$$\mathrm{P(A)} = 1 - \mathrm{P(A')} \qquad \text{Eq 4.1}$$

Where (A’) is the complementary event of (A)

Rule of Addition (A or B): The probability of occurrence of (A) or (B) is equal to the probability of the sum of both (A) occurrence and (B) occurrence minus the probability of both (A) and (B) occurring simultaneously. The mathematical expression of addition rule is given in Eq 4.2:

$$\mathrm{P(A \cup B)} = \mathrm{P(A)} + \mathrm{P(B)} - \mathrm{P(A \cap B)} \qquad \text{Eq 4.2}$$

4.2 Joint Probability

Suppose we have three events (A), (B), and (C), and want to manipulate the addition rule to calculate joint probability. This can be done by implementing the general rule of addition for three events, which is given in Eq 4.3:

$$P(A \cup B \cup C) = P(A) + P(B) + P(C) - P(A \cap C) - P(B \cap C) + P(A \cap B \cap C) \quad \text{Eq 4.3}$$

4.3 Joint Probability of Independent Events

Rule of Multiplication (A and B): if events (A) & (B) are independent, the probability of (A) and (B) simultaneously occurring is multiplication of both (A) probability and (B) probability. The mathematical expression of addition rule is given in Eq 4.4:

$$P(A \cap B) = P(A) \ * \ P(B) \quad \text{Eq 4.4}$$

To understand the rule joint of probability, a case of throwing two dices is given in the following example, in Figure 4.1, that shows events, and joint probability of them. Note that event (A) and event (B) are independent, where rolling the first dice is not affecting rolling the second:

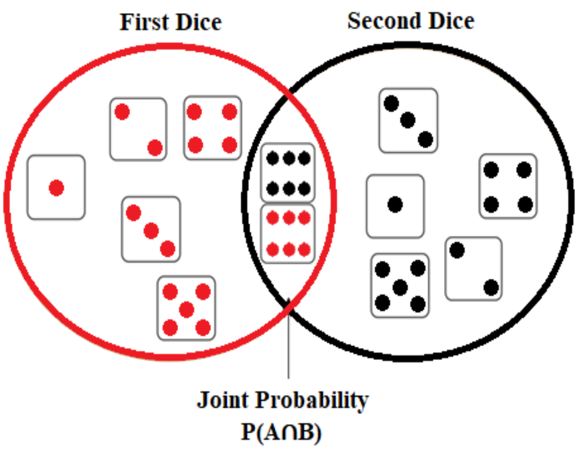


Figure 4.1: Joint probability of independent events: rolling two dices

The probability of outcome of throwing the dice are P(A) and P(B) for first and second dice, respectively. The probability of having number 6 on the topside of the first dice is $\mathrm{P(A)} = \frac{1}{6}$, and the probability of having number 6 on the second dice is $P(B) = \frac{1}{6}$. To illustrate, the probability of having number 6 on both sides is denoted as P(A∩B), and calculated using the multiplication rule as in Eq 4.4:

$$\mathrm{P(A \cap B) = P(A) * P(B)} = \frac{1}{6} * \frac{1}{6} = \frac{1}{36} = 0.0278 \text{ or } 2.78\ \%$$

However, to calculate the probability of the occurrence of any one of them i.e., the probability that either (A), or (B), or both are 6, is denoted as P(A∪B), and calculated using addition rule as in Eq 4.2 :

$$\mathrm{P(A \cup B) = P(A) + P(B) - P(A \cap B)} = \frac{1}{6} + \frac{1}{6} - \frac{1}{36} = \frac{11}{36} = 0.3056 \text{ i.e. } 30.56\ \%$$

4.4 Conditional Probability

Conditional probability implies that probability of an outcome (primary event) is dependent on the occurrence of another event. The probability of the primary event is updated based on the knowledge of the secondary event, as governed by the Bayes theorem shown in Eq 4.5:

$$\mathrm{P(A|B)} = \frac{\mathrm{P(A \cap B)}}{\mathrm{P(B)}} \qquad \text{Eq 4.5}$$

where,

P(A|B)	The probability of event (A) given that (B) occurs
P(A∩B)	The joint probability of (A) and (B)
P(B)	The probability of event (B)

4.5 Joint Probability of Dependent Events

Multiplication rule does not apply when calculating joint probability of dependent events. Consider, the probability that sum of numbers is greater than 10 when rolling a dice twice, given that the first roll shows number 6. The case of rolling the dice twice is presented in Figure 4.2.

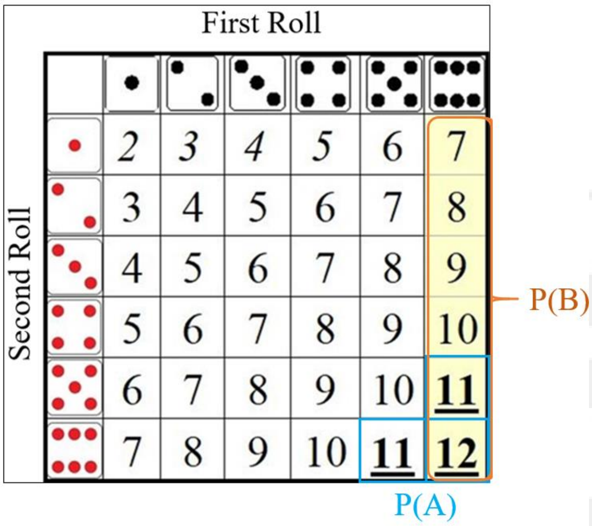


Figure 4.2. All possible outcomes of rolling the dice twice and sum of numbers

The case of having a number more than 10 is the case of having a result of 11, or 12, which is P(A)=3/36. Also, the case of having 6 in the first roll is represented by the last column of Figure 4.2, which is P(B)=6/36. That makes P(A∩B) = 0.5/36. Then,

$$P(A|B) = \frac{P(A \cap B)}{P(B)} = \frac{\frac{0.5}{36}}{\frac{6}{36}} = \frac{1}{12} \text{ or } 8.33\ \%$$

For events (A) and (B), the conditional probability is mathematically represented as follows:

1- $P(A|B) = \frac{P(A \cap B)}{P(B)}$, if (A) and (B) **are dependent**, as shown in Figure 4.2, then the probability of (A), given that (B) occurs is represented by Eq 4.5

2- If (A) and (B) are independent, as in Figure 4.1, then the probability of (A) given that (B) occurs is represented by Eq 4.6:

$$P(A|B) = P(A) \quad \text{Eq 4.6}$$

4.6 Bayesian View of Probability

Bayesian approach looks to an event based on some knowledge on its occurrence. It provides a reasoning of probability based on this knowledge, instead of the repetitions of the event that classical probability approach uses. Bayesian probability implement Bayes' rule to calculate the probability of an event (Holmes et al., 2008). Bayes' rule manipulates the conditional probability with the joint probability of (A) and (B) term in Eq 4.5 to give Eq 4.7 as follow:

$$P(A \cap B) = P(A|B)P(A) \quad \text{Eq 4.7}$$

It is known that the joint probability of (A) and (B) can be expressed in Eq 4.8 and Eq 4.9:

$$P(A \cap B) = P(A|B)P(A) \quad \text{Eq 4.8}$$

$$= P(B|A)P(B) \quad \text{Eq 4.9}$$

By solving both Eq 4.8 and Eq 4.9, and taking the term P(A|B) to one side we get Eq 4.10:

$$P(A|B) = \frac{P(B|A)P(B)}{P(A)} \quad \text{Eq 4.10}$$

Here, (A) corresponds to the hypothesis (evidence), and (B) is the data (prior probability). In Bayesian probability, the data is utilized to judge the relative truth of the hypothesis (the result is called the posterior probability)

To better understand Bayes' rule, an example about the defective item rate is introduced. A manufacturer produces items (A), (B), and (C), with shares of 25 %, 25 %, and 50 % of the total production, respectively. Manufacturer provides a table for equipment test results (Table 4.1). Equipment (A) has 8 % defective production rate, (B) has 6 % defective rate, and (C) has 2 % defective rate.

Table 4.1: Defective item rate

Equipment	Error	No error	Error function	Total
A	20	230	0.08	250
B	15	235	0.06	250
C	10	490	0.02	500
Total	45	955	0.045	1000

If we randomly select an equipment, and it malfunctions, the probability that it is equipment (C) can be estimated using Bayes rule. We denote random selection of an equipment with X, and that selection is malfunctioning with Y. From Table 4.1, we find the following probabilities:

$P(X_A)$ =	0.250	$P(X_B)$ =	0.250	$P(X_C)$ =	0.500
$P(Y\|X_A)$ =	0.080	$P(Y\|X_B)$ =	0.060	$P(Y\|X_C)$ =	0.020
$P(Y)$ =	0.045				

$P(X_A)$ represents probability of selection being equipment A

$P(Y|X_A)$ represents probability of equipment A malfunctioning

We find the probability that randomly selected malfunctioning item is equipment C, $P(X_C \mid Y)$ using Bayes' rule in Eq 4.10:

$$P(Xc|Y) = \frac{P(Y|Xc)P(Xc)}{P(Y)} = \frac{0.02 * 0.5}{0.045} = 0.2222 \text{ or } 22.22\ \%$$

4.6.1 Directed Acyclic Graph

Directed Acyclic Graph (**DAG**) is simply a graphical representation of a network. There are arrows indicating direction of flow (thus it is 'Directed'), and there are no loopbacks, thus it is ‘Acyclic’. DAG is a combination of circular nodes; illustrating the probabilities of events; and links (sometimes called arcs); where each arc represents a dependency of one parameter on another connected parameter (Atlas, 2015). The Bayesian network uses the DAG, to represent conditional probability and to account for the uncertainty of the occurrence of a specific event. An event occurs due to the occurrence of another single or couple of events (Yang, 2019). Figure 4.3 shows DAG representation of simple BN.

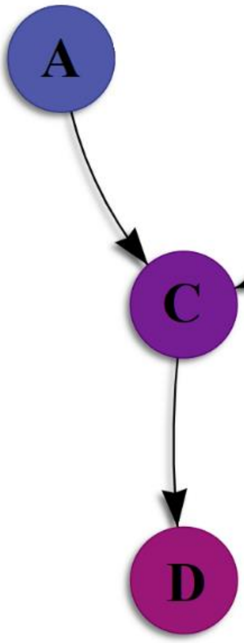


Figure 4.3: Generic Bayesian Network

The directed links in Figure 4.3 indicate the dependency of parameters. For example, the directed arc from node (A) to node (C), represents the dependency of event (C) on event (A). That is, (C) is consequence of (A). Similarly, node (C) results from Node (A). The DAG represents a dependency of node (C) on both (A) and (B). In conditional probability terms, both (A) and (B) are parents to (C), which makes it a child of (A) and (B).

4.6.2 Bayesian Network

The Bayesian Network (BN) is a powerful statistical/probabilistic tool. Bayesian, Bayes', belief, or decision network is a graphical representation of a set or combination of sets of parameters. These parameters are connected with each other via DAG to take the conditional dependency of them into consideration. BN mainly uses two kinds of approaches to calculate the probability of an event. These are forward and backward propagations. The forward propagation is done by prior knowledge of the parent(s) (i.e., A & B as in Figure 4.3) to observe the effect on the main event (D). Whereas backpropagation is done by prior knowledge of the event (D) to observe the contributions of parents (A and B). These forward or backward evaluations are calculated based on event probability supplied to the parents or to the child node, respectively.

4.6.3 Solving a Bayesian Network

Let us consider the Bayesian network illustrated in Figure 4.3. The network is composed of four elements (A), (B), (C), and (D). Probability of outcome at node (D) is calculated using the conditional probability and chain rule, per Eq 4.11:

$$P(D) = \prod_{i=1}^{n} P(D_i|Pa(D_i)) \quad \text{Eq 4.11}$$

Where,

P(D): Probability of an event (D)

$Pa(D_i)$ Probability of the main parent in the network i.e., A & B

That is, the occurrence of event (D) is dependent on the occurrence of event (D)'s parents i.e., (C), (B), and (A). For the Bayesian network in Figure 4.3, a simpler way to explain the implementation of Eq 4.11 is introduced in Eq 4.12 :

$$P(D) = P(D|C)P(C|A,B)P(A)P(B) \quad \text{Eq 4.12}$$

Where,

P(D): Probability of an event (D)

P (C|A, B): Probability of an event (C) given that (A) and (B) occurs

P(B): Probability of an event (B)

P(A): Probability of an event (A)

4.6.4 Bayesian Network in Risk Assessment

Since it provides the ability to link system components, the Bayesian network is applied for the operational risk assessment in many industries. It is used to analyze the risk that results from the failure of particular systems. Khakzad et al., (2013) investigate the vapor ignition of heating tanks by applying BN as a risk assessment tool. They were able to find the components that contribute to the system failure the most. Bayesian network is also applied in the oil & gas industry to minimize hazards. Barua et al., (2016) performed a case study on petroleum control systems, showing the ability of BN to capture dynamic operational changes in addressing time-dependent effects in risk calculation.

CHAPTER 5

FAULT TREE ANALYSIS

Fault Tree Analysis (FTA) is a graphical method based on qualitative analysis of system failure. It was developed in 1961 by the US military. Also, FTA experienced several developments to include the reconstruction failures, and failure frequency analysis. FTA, with these improvements, is used by many engineering operations/industries; aerospace, mining, oil field, chemical, and nuclear.

However, the most common use of FTA is the system safety engineering as a qualitative analysis tool for hazards and weaknesses in safety systems (Bahr, 2014). FTA gained a reputation due to its ability to logically identify, evaluate, and quantify different system performance problems and failures. The use of FTA in the safety analysis of mining indicates that it helps preventing problems by its ability to analyze a variety of systems, and its ability to find the root cause[16] of failure (Shoar et al., 2019).

5.1 Basic Elements

A typical Fault Tree (**FT**) is composed of notations and logical relationships called events and gates. These are the basis of the FTA; without them the fault tree has no sense of analysis. Figure 5.1 illustrates a simple fault tree.

[16] Root Cause: A fundamental, underlying, system-related reason why an incident occurred that identifies a correctable failure(s) in management systems (AIChE/CCPS, 2021).

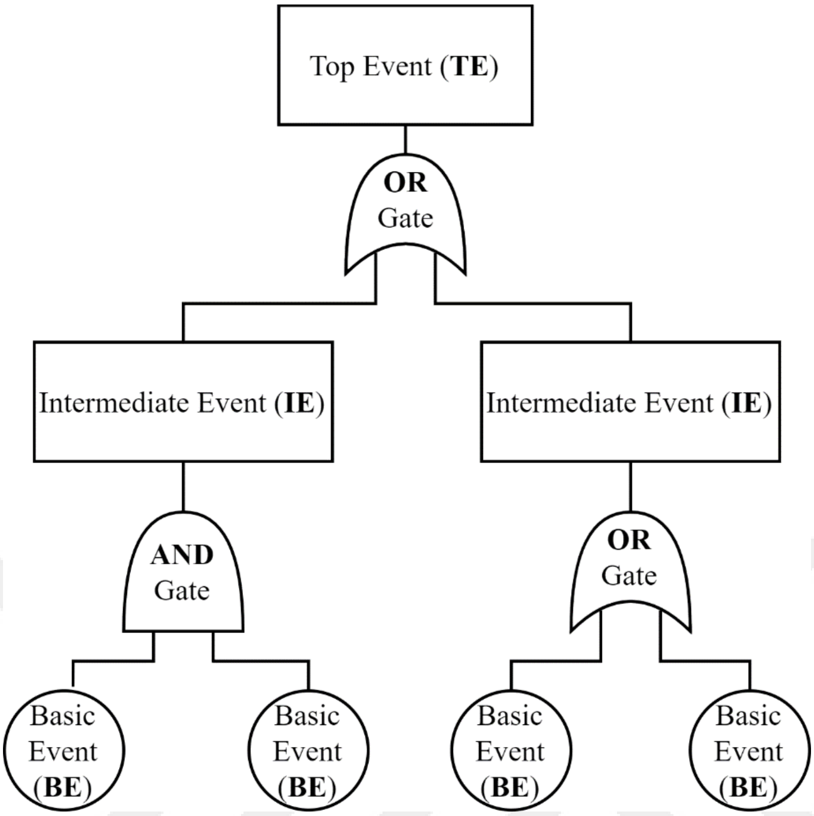


Figure 5.1: Simple Fault Tree

The FT events are usually classified as: (i) Top Event (**TE**), which is the undesired event; (ii) Intermediate Event (**IE**), usually placed in the second branch of the tree, is an event that occurs due to previous cause; lastly, (iii) the Basic Event (**BE**), which is the initiating fault requiring no further development of the tree, i.e., the tree branches have reached the possible root causes of the failure. FT has multiple gates such as **OR** gate, which means that the output (higher level IE or TE) occurs if at least one of the input faults (lower-level IE or BE) occur. There is also an **AND** gate which implies that an output fault occurs only if all the input faults occur.

5.2 Fault Tree Construction

Herein, FT construction is explained by describing the steps leading to the solution of a simple light switch problem (Lynch, 2021). Consider a room with two light bulbs, a switch to turn on/off the lights, and source power. The first step of the analysis is to (i) identify the main system failure, which is having “no light in the room”. The second step is (ii) understanding the system, the light system is based on the power source (voltage), switches to turn the lights on and a fuse; an electrical safety device that operates to provide overcurrent protection. The third step is the (iii) FT construction. As FTA is a representation of the possible causes of a particular system failure, it is better to have a limit of analysis, and not to deviate from the main failure which will lead to a very wide and complicated analysis. That is, only the tree routes that lead to the undesired event are assessed (Bahr, 2014).

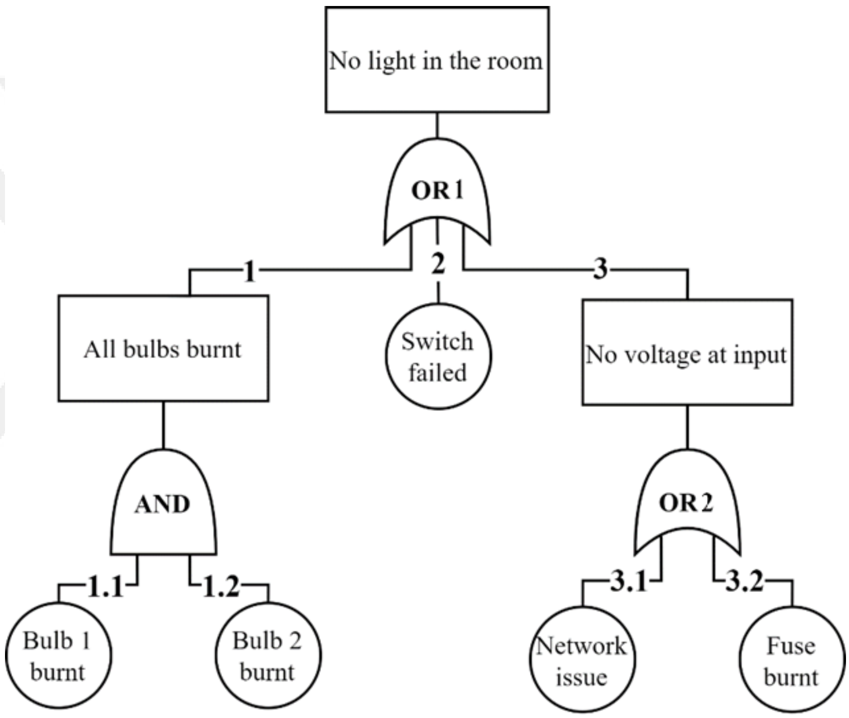


Figure 5.2: Fault Tree Example (no light in a room case)

For the case of having no light, the top event is drawn in a rectangle. The other rectangle that branches from the TE are the IEs, where the gate symbol explains the relation to the down branching events. The previously identified system has three possible reasons of failure, these are either (1), (2) or (3) as shown in Figure 5.2. In this Figure 5.2, the OR1 gate means that “No light in the room” occurs because either all bulbs are burnt, or because the switch has failed, or due to the absence of input voltage. Descending from the first IE, as the room has only two lamps, event (1) occurs when both lamps are burnt. Here the role of the AND gate explains that event (1) is true only if basic events of (1.1) and (1.2) occur. The basic events (with circular symbols) indicate no more development needed, i.e., further development is not the interest of analysis.

Fourth step of FTA is the (iv) identification of the cut sets; the basic events that, if simultaneously occurred, would lead to the main undesired event (AIChE/CCPS, 2010).

The final step of FTA is the (v) risk mitigation, the logical structure of the FT makes it easy to understand the combination of events that lead to a hazardous event. That is, the Boolean logic gates assist in the computation of the risk when the frequency of event occurrences is provided (Bahr, 2014). Based on the deviation from standard operations, necessary arrangement is made to mitigate the risk of the failure. For example, in the case of having higher impact than the acceptable risk of petroleum standards acceptable risk the root cause of failure is fixed (replaced or maintained) to reduce the impact.

5.3 Top Event Probability Calculation

The risk mitigation process is usually attached with probability analysis of the failure. These probabilities are assigned to the lowest level elements (BEs) of the tree from the frequency of occurrences. These probabilities can be reported in different units, depending on system type and preferred measure of occurrence. To illustrate, if we are looking for the probability of falling of an infant while walking for the first time, probabilities of failure can be recorded as 10 times per day or 300 times in a month. Yet, for correct evaluation of the FT, unit consistency is necessary. For instance, failure frequencies for the room lighting example in Figure 5.2, are given in Table 5.1; we use these values to calculate the probability of having no light in the room.

Table 5.1: Fault Tree Evaluation (no light in a room case)

Basic Event	BE1.1	BE1.2	BE2	BE3.1	BE3.2
Probability [Event/yr]	0.003	0.003	0.002	0.0055	0.0015

The Boolean logic for the OR gate utilizes the rule of addition to calculate the probability of an event. That is, the probability of having no light in the room P(NL) is calculated using Eq 4.3as follows:

$$P(NL) = P(IE1 \cup BE2 \cup IE3) \qquad \text{Eq 5.1}$$

However, this calculation requires the knowledge of IE1 and IE2 probability. Hence, the AND gate in IE1 indicates the need of using Eq 4.4 as follows:

$$P(IE1) = P(BE\ 1.1 \cap BE\ 1.2) = P(BE\ 1.1) * P(BE\ 1.2)$$

$$= 0.003 * 0.003 = 9 * 10^{-6} \left[\frac{event}{yr}\right]$$

Whereas, the OR gate in IE3 indicates the need of using Eq 4.2 as follow:

$$P(IE3) = P(BE\ 3.1 \cup IE\ 3.2) = P(BE\ 3.1) + P(BE\ 3.2) - P(BE\ 3.1 \cap BE\ 3.2)$$

$$= 0.0055 + 0.0015 - (0.0055 * 0.0015) = 6.99 * 10^{-3} \left[\frac{event}{yr}\right]$$

Plugging these numbers in Eq 5.1, and applying the rule of addition for three events i.e., Eq 4.3:

$$P(IE1 \cup BE2 \cup IE3) = P(IE1) + P(BE2) + P(IE3) - P(IE1 \cap IE3) - P(BE2 \cap IE3) + P(IE1 \cap BE2 \cap IE3)$$

$$P(NL) = 9 * 10^{-6} + 0.002 + 6.99 * 10^{-3} - (9 * 10^{-6} * 6.99 * 10^{-3}) - (0.002 * 6.99 * 10^{-3}) + (9 * 10^{-6} * 0.002 * 6.99 * 10^{-3})$$

$$P(NL) = 9 * 10^{-3} \left[\frac{event}{yr}\right]$$

It can be seen from the results that failure of the system is very sensitive to the AND gate, and the failure probability is reduced with more AND gates. So, a better and safer system could be designed in a way that has more AND gates (Bahr, 2014). For example, changing the AND gate in Figure 5.2 to OR gate would make the probability of IE1 as following:

$$\mathrm{P(IE1)} = \mathrm{P(BE\ 1.1 \cup BE\ 1.2)} = \mathrm{P(BE\ 1.1)} + \mathrm{P(BE\ 1.2)} - \mathrm{P(BE\ 1.1 \cap BE\ 1.2)}$$
$$= 0.003 + 0.003 - (0.003 * 0.003) = 6 * 10^{-3} \left[\frac{\mathrm{event}}{\mathrm{yr}}\right]$$

With this new configuration, the TE probability would change from $9*10^{-3}$ to $1.5*10^{-2}$, which is an increase in the failure rate of $\frac{9*10^{-3}}{1.5*10^{-2}} = 0.6$, i.e., 60% from the originally presented room system.

5.4 Evaluation Methods

After developing the required fault tree model, it is evaluated using the importance measures (IM). The main aim of the PRA is to maintain a system with acceptable risk. IM is implemented to identify which element of the system needs improvement, to maintain an acceptable risk, and to reduce the potential risk associated with each element. Two factors are considered when measuring the importance of a component. These are (1) element location in the system, and (2) element failure probability (Rausand & Hoyland, 2003). IMs are many, but the ones employed in this study are explained next.

5.4.1 Diagnostic Analysis

Diagnostic Importance (**DI**) analysis of a fault tree measures the effect of element of interest (**BE_i**) of the system, to the failure of the system (TE). This measure tests the whole system failure with the absence of (BE_i). The mathematical expression of diagnostic importance is given in Eq 5.2 (Rausand & Hoyland, 2003).:

$$DI = P(BEi)\frac{P(TE|P(BEi) = 1)}{P(TE)} \quad \text{Eq 5.2}$$

where,

$P(BE_i)$	The basic event's failure probability
$P(TE\|P(BE_i)=1)$	The TE failure probability given that BE_i totally failed
$P(TE)$	The TE failure probability without assumptions

When analyzing BE_i, the diagnostic importance describes the impact of (BEi) total failure (i.e., $P(BE_i)=1$) to TE, including the failure probability of BE_i. When ranking system components according to diagnostic measures, the lowest value indicates a negligible effect of BE_i failure on the system failure. Whereas, the highest value indicates a need to take precautions to fix the reliability issues of the component (Rausand & Hoyland, 2003).

5.4.2 Risk Reduction Worth

Risk Reduction Worth (RRW) is the ratio of the TE failure probability to the probability of the TE given that the component (BE_i) is optimized, assuming that the component has a zero-failure rate. The mathematical expression of RRW is given in Eq 5.3 (Van der Borst & Schoonakker, 2001):

$$RRW = \frac{P(TE)}{P(TE|P(BEi) = 0)} \quad \text{Eq 5.3}$$

where,

$P(TE\|P(BE_i)=0)$	The probability of (TE) given that the (BE_i) is optimized

RRW is set to test BEs one by one, and observe how each one affects the TE. Also, it explains the possibility of eliminating this risk. This is usually applied for a system where human failure takes place, or where substitution of a better component is possible (Tabassum et al., 2019).

Per Eq 5.3, impact of BEi is linearly proportional to the RRW value. For instance, RRW = 2 for BEi implies that eliminating the failure of BEi improves failure probability of TE by 2 folds (i.e., new P(TE) would be original P(TE) divided by 2).

The RRW analysis results may point to conclusions such as:

- Buying higher quality components
- Changing maintenance strategy
- Substituting personnel/operator with higher qualifications
- Providing additional or routine training for the personnel/operator, depending on the nature of errors he/she made.

When ranking the elements according to their RRW, it is possible to see the gap between elements, and how elements deviate from the normal situations. Because RRW values are calculated based on the assumption that components do not fail, the analysis can often rank some events equally. This is because the AND gate results in a ***failure state,*** even when one component is in ***safe*** state. RRW is a confirmation of the results from the diagnostic importance analysis, and illustrates the benefits of optimization of BE_i.

5.4.3 One Variable at a Time (OVAT) Analysis

In OVAT analysis, each causal factor of main failure event is altered separately while keeping other variables constant. This is done to test the system failure probability when the materials or equipment are changed with ones that have higher or lower failure rates (Razavi & Gupta, 2015). Also, to give an idea of how system reliability is affected when maintenance is missed, or low quality martials is utilized, assuming that the probability of causal factors of failure is increased by 10 % of the original probability value. The same assumption is made for the case of having frequent maintenance of system components, or the replacement with higher quality materials. Noting that when dealing with negative effect on the system, the failure probability is increased by a factor of (-10 %) since we are dealing with failures of the system. That is, if having a (2 %) probability of a specific failure in the system, the 10 % increment of the failure probability is calculated as in Eq 7.3:

$$\mathrm{P(new)} = \mathrm{P(old)} + (\mathrm{P(old)} * (-\mathrm{increment})) \qquad \text{Eq 5.4}$$

$$\mathrm{P(new)} = 2\ \% + \left(2\ \% * (-10\ \%)\right) = 1.8\ \% \qquad \text{Eq 5.5}$$

The negative sign is included because the Bayesian network is constructed to deal with failure state of the safety system, not the success state. That is, event probabilities (probability of failure of each element) are usually less than 1 %.

5.4.4 Evaluation Example

Consider the following fault tree in Figure 5.2. For this fault tree, the evaluation continued from Section 5.3 where TE value, **$9*10^{-6}$ [event/yr]**, represents the default failure probability of the system. Then, each BE_i set to the *safe* state (zero failure probability), and total *failure* state (one failure probability). Hence, TE values are recorded for (safe/failure) states. The final step is to apply plug these probabilities into (Eq 5.2 and Eq 5.3). Table 5.2 shows the evaluation of fault tree in Figure 5.2.

Table 5.2: Diagnostic Importance and RRW analysis results

Basic Event	**P(TE|P(BE$_i$)=1)**	**P(TE|P(BE$_i$)=0)**	**DI**	**RRW**
BE1.1	0.012	0.0090	0.004	1.00
BE1.2	0.012	0.0090	0.004	1.00
BE2	1	0.0070	0.223	1.28
BE3.1	1	0.0035	0.612	2.56
BE3.2	1	0.0075	0.167	1.20

According to DI analysis, in Table 5.2, fault tree elements are ranked from the highest to the lowest risk potential in the order of $BE_{3.1}$, BE_2, $BE_{3.2}$, and ($BE_{1.1}$ & $BE_{1.2}$) respectively. Similarly, the RRW calculated for each element using Eq 5.3 ranks the elements in the same order. The highest ranked element illustrates the need to improve this component, to reduce the risk of the system failure. Figure 5.3 shows the sensitivity analysis of this system.

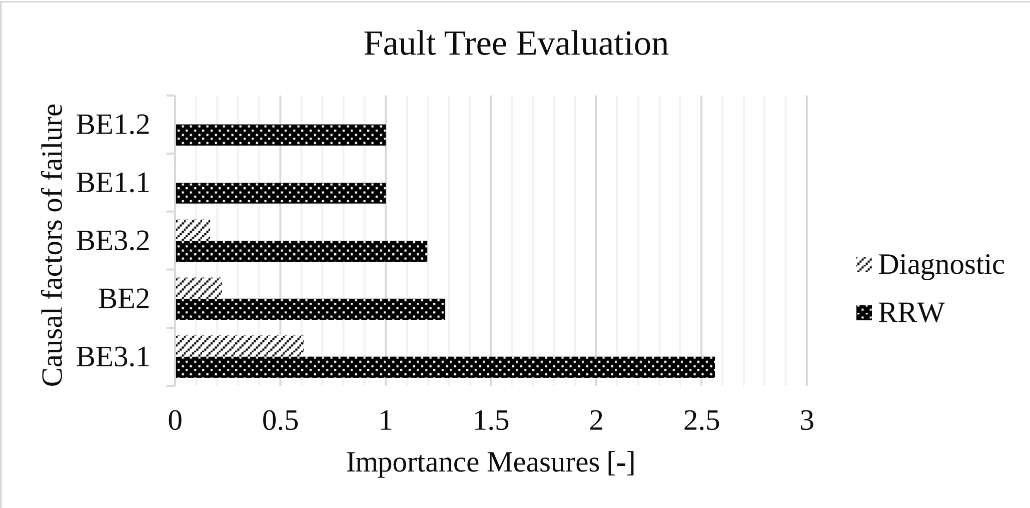


Figure 5.3: RRW & DI Evaluation Example

Failure of system is mostly attributed to $BE_{3.1}$. The RRW factor of $BE_{3.1}$, which 2.5, indicates that BE_3 has a higher potential of risk in the system, and it is preferable to find a substitute or improve this item if risk mitigation is applied.

CHAPTER 6

PROBLEM STATEMENT

Kicks and resulting blowouts are a major concern for health, safety, environment, and inter-generational equity[17] of the valuable resources. Due to inherent uncertainty[18] involved with drilling operations, it is critical to properly assess the probability of blowout occurrence, so that mitigating measures can be introduced. The aim of this study is to develop a model that aids in drilling safety analysis. This is based on the probability estimation of blowout occurrence.

According to the Occupational Safety and Health Administration (**OSHA**) records (2021), 489 of the workers in the oil and gas extraction industry were killed between 2013 and 2017. These fatalities were due to the direct and indirect exposure to the oil field hazards. Hazards in the industry include:

1- Chemical exposure
2- Falls
3- Explosions and fires
4- Struck-By/ Caught-in/ Caught between

These accidents are due to several reasons. Firstly, human error identified as the most common cause of accident in oil and gas industry (Nwankwo et al., 2021), that is usually reflected from the low-level situational awareness, i.e., failure to perceive, interpret and act on specific hazardous event (Raza et al., 2019). Also, equipment failure, which is the malfunction of the machinery in the field, due to

---

[17] Part of the inter-generational equity is the extraction of the natural resources without compromising the future generations needs of these resources (Mawejje & Bategeka, 2013)
[18] Subsurface pressure anomalies and formation fluid contents cannot be known with 100 % accuracy (Ma, 2011)

design or maintenance failures (Gilbert, 2015). Finally, the absence of operational guidelines in some companies. When looking throughout the petroleum literature, it is seen that hazard-leading incidents were reported earlier. But the absence of formal comprehensive risk assessment tools has resulted in aggravation of incidents to catastrophe (BP, 2010).

One of the most dangerous events that combines several of the aforementioned hazards is the blowout, which is the sudden release of high-pressure underground fluids to the surface. Blowouts occur due to losing control of the underground fluids, followed by a sequence of failures in the safety systems. Blowouts have resulted in very destructive outcomes throughout history. These are:

1- Environmental impact

The environmental impact of blowouts is depicted by the direct effect on the marine environment (offshore blowout) and the contamination of the shores around. Blowouts cause crude oil spill into the marine, which affects the habitants of the marine ecosystems by the toxic materials (Cordes et al., 2016).

2- Economic problems

The economic impact of offshore blowouts includes loss of oil industry revenues, profits, wages, and jobs. Also, the economic impact is depicted by the clean-up costs and damages to people and the environment by the government regulations (Kroh & Conathan, 2012).

3- Human health

Human health is mainly affected in two ways; directly by the fatal impact to workers on the rig site, which is highly in offshore drilling than onshore one (Holand, 1996). Also, a long-term impact, that is illustrated by the exposure to aerosolization[19]

---

[19]Aerosolization: the dispersion of a material (e.g., liquids, powders) in the air (Segen's medical dictionary, 2011).

of the agents that causes obesogenicity[20], toxicity, and illnesses (Eklund et al., 2019). Table 6.1 includes some of the major blowouts in the petroleum industry, and the number of fatalities resulted from each blowout.

Table 6.1: Major blowouts of the petroleum drilling operations (Holand, 1996)

Date	Place	Rig type	Results
1964	Gulf of Mexico	Drill barge	22 fatalities
1971	Peru	Drill barge	7 fatalities
1984	Rio de Janeiro	Platform	37 fatalities
1989	Nigeria	Jack-up	5 fatalities

According to Khakzad et al. (2014), only in the period between 1996 and 2012, on average, two blowouts per year occurred in the Gulf of Mexico. As explained in Chapter 2, the drilling industry has a set of safety barriers to cope with blowout events during operations. Casing, cementing, kick detection system, circulation system, and BOP are all set to defend against the blowouts. Usually, the system failure occurs in the respective failure of these barriers, as shown in Figure 6.1.

Each safety barrier is designed separately to minimize the overall risk of system failure. For example, at multiple sections along the wellbore, a casing is fixed in place with cement, which makes it hard to repair if the cement job failed. This may lead to undesired events such as blowouts if the last safety barrier, which is the blowout preventer, does not perfectly prevent the flow of underground fluids to the surface.

[20] Obesogenicity: tending to promote or contribute to obesity. It is said of unhealthy, calorie-rich diets and sedentary behavior (Segen's medical dictionary, 2011).

As seen from Figure 6.1, during drilling operations, there are several stages to deal with a kick. That is, when a kick occurs, we must look for the detection system. If a kick is not detected, then a direct ***blowout*** is expected. If it is detected, then well control operations are started by using the circulation system (as discussed in Section 2.4) to circulate the kick fluid out of the wellbore. Hence, if the circulation system failed to maintain pressure balance, the final solution is to activate BOP, which will result in a ***safe*** operation if it functions, and a ***blowout*** if it malfunctions (fails).

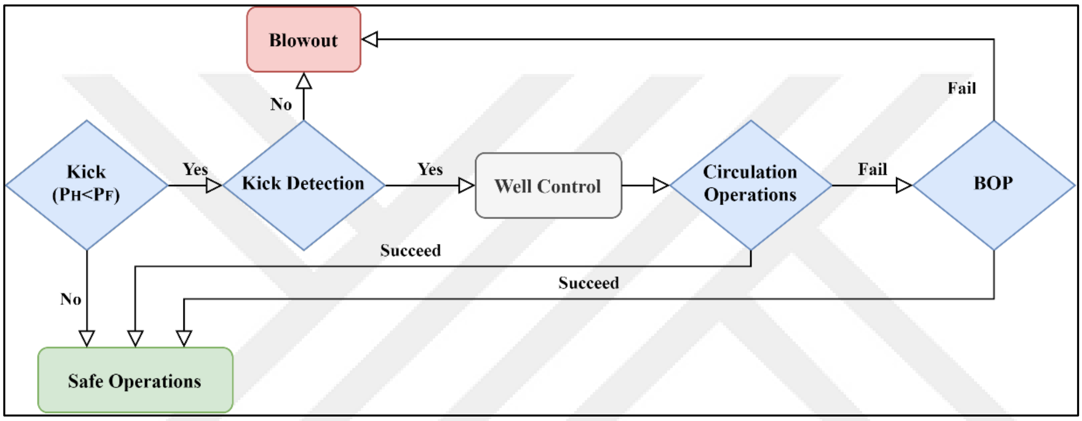


Figure 6.1: Blowout scenario in drilling operations

Besides the uncertainty associated with formation pressure, the main issue lies in the uncertainty with safety barriers perfectly functioning. Due to the limited information we have about underground formations, there is currently no perfect approach to predict kicks precisely. The blowout scenario starts with: (1) kick and (2) well control failure. Kicks occur due to hydrostatic mud pressure reduction at the hole bottom ($P_H < P_F$). This may be attributed to events such as casing or cement failures, swab[21], or unexpected abnormal formation pressures. Some of these incidents, known from previous blowout experiences, are detected using the surface monitoring system (Fraser et al., 2014). Yet, some are not detected due to human

[21] Swab: dynamic pressure reduction at hole-bottom due to pulling of the drill string out of the hole, this may lead to influx of formation fluids into the wellbore (Whittaker, 1985).

errors in interpreting the situation, or malfunction of the equipment (Nwankwo et al., 2021). Not detecting the kick is the less frequent situation, but it has the most severe outcome.

The aim of the drilling industry is to enhance the safety barriers, identify the weak points of each safety system, and maintain safe operations. Safety and risk analysis are very crucial parts of the drilling industry. That is, the drilling system is a complex machinery composed of a series of pipes, shafts, fluids, compressors & pumps, and motor-driven machines. Moreover, when drilling for hydrocarbons, the industry deals with highly flammable and toxic chemical components (Rosenfeld & Feng, 2011). Thus, sudden malfunction of any component will lead to a high impact accident on the people at the site of the operation, on the environment, and on the finances of the company.

6.1 Literature Review

Holand (1996) established an offshore blowout database for risk analysis. Also, he discussed the blowout trends and their frequencies based on the historical events, classified according to their stages (drilling, completion, etc.). Holland's study along with OREDA[22], the offshore reliability data handbook, are used as an index for the risk assessment studies of petroleum accidents. The significant studies which are made on the petroleum blowouts are mentioned next.

Andersen (1998) discussed the stochastic blowout modeling framework in offshore risk management in drilling operations. He indicated that a model that considers the physics of the blowout phenomenon is required to strengthen the decision making process.

---

[22] OREDA: An Offshore and Onshore Reliability Data index, established in 1981 in cooperation with Petroleum Safety Authority Norway.

Vinnem et al. (2010) used linear regression as an analysis tool to see the correlation between petroleum leaks and safety indicators. This tool is used to point out the causal factors of major accidents in the petroleum industry (including blowouts).

Eckle & Burgherr (2013) used the hierarchal BN models to analyze frequency trends of fatal accidents causes in different activities through the entire oil chain (from exploration until the final usage). They stated that correlation and risk assessment studies about accidents in the industry should be correlated yearly to observe the change of the accidents frequency. Their correlation of the accident data showed that lessons were not learned from previous accidents.

Khakzad et al. (2013) studied the kick and kick detection scenarios in offshore drilling by applying BN in risk analysis. Khakzad et al. (2014) used BN hierarchical models to overcome the uncertainty of the generic data using the likelihood function. They implemented the accident precursor data (events occurring prior to the undesired event, e.g., blowout) in their analysis. Per their analysis, the trend of kick and blowout probability increases with time (as illustrated in Figure 6.2). This is contrary to the expectation that as personnel gains experience in the same field (or region, or formation), they should be prepared to deal with similar accidents, and the frequency of failure should reduce.

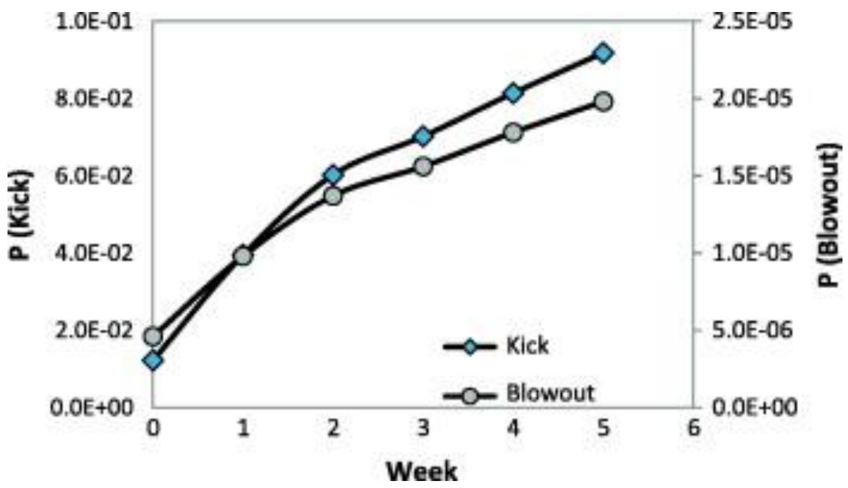


Figure 6.2: Kick and blowout probability trend with time (Khakzad et al., 2013)

Abimbola et al. (2014) introduce the failure of BOP and circulation system. They showed how fire prevention system barriers (after blowout occurrence) would function with time. Later, Abimbola et al. (2015) discussed BN implementation in assessing the effects of the MPD[23] system failure and change in bottom-hole pressure to the drilling safety system. Again, Abimbola et al. (2016) studied the well integrity failure effect to the blowout occurrences. This study includes the casing and cement effect.

Malika et al. (2017) showed the BN advantages in machines maintenance and diagnosis. He also mapped the FT to BN to illustrate how BN can provide a strong probabilistic method when dealing with uncertainty. This is illustrated by the dynamic interaction between elements that lead to undesired events.

Khan et al. (2018) studied the risk assessment methods in the drilling and production phases in the petroleum industry. They made a comparison between the risk assessment methods, explaining the capability of BN to handle uncertainty, multistate variables, complex causal relationships between the causal factors that lead to a blowout. They also showed the framework of risk assessment in the industry, which leveled from risk avoidance until risk retention.

Aydinli et al. (2019) studied the unsafe acts and the organizational safety climate in drilling operations. In their study, they showed that the oil and gas industry should always introduce unsafe practices as part of hands-on training so that drilling personnel learns from the experience.

These studies have shown the ability of BN in conducting a probabilistic risk assessment of the blowouts. Also, these studies are conducted using specific

[23] Managed Pressure Drilling (MPD): an adaptive drilling process used to precisely control the annular pressure profile throughout the wellbore (Frink, 2006)

components of the drilling system. In this study, the data is collected from several sources to create a comprehensive model for the offshore drilling system.

CHAPTER 7

METHODOLOGY

In this study, a Probabilistic Risk Assessment (PRA)[24] model is developed for deep water drilling operations using FTA. Bayesian Network is used to develop the required FTA using a Bayesian Network software. This will further allow the improvement of FTA as a dynamic model.

The BN is developed using Genie 3.0 software, available from https://www.bayesfusion.com/. Genie 3.0 offers a convenient environment for conducting BN mapping into fault trees. To be able to use a BN software for FTA, first FTA should be mapped to BN-based on a set of rules. The process is explained in Section 7.4.

Herein, based on the previous discussion in Section 6.1, the drilling system components are collected to create a comprehensive BN model that includes all major failures that may lead to a blowout. First, the fault tree of each component is mapped into a BN model to create an analysis environment. Then, each fault tree is analyzed by the importance measures. This is done to rank the fault tree elements based on the highest contribution to main component failure. Also, risk reduction worth analysis, one of the importance measures, is used to address which elements are worth in higher reduction of the blowout probability if these elements failure is totally removed. Then, based on these results, top contributors to each component failure are recorded. Later, MSGs are used to order components of the safety system barriers according to the sequence of operations. The highest contributor to each

---

[24] In the literature often mentioned as PSA: probabilistic safety analysis, e.g., (International Atomic Energy Agency report, 1997).

component is introduced to the MSG of BN to observe the impact of each on the blowout probability.

7.1 Definitions

System may refer to whole drilling machinery system, to just an individual "subsystem" that is part of this whole machinery system (e.g., circulation system, BOP system), or to an individual tree for the FTA.

Safety barrier refers to a system composed of any material, equipment, and/or operational procedure that are used to prevent a risky event from occurring.

Component refers to a "subsystem" of the FTA for blowout analysis. It includes:

1) Kick event
2) Kick detection system
3) Circulation system (includes cement & casing components)
4) BOP system

Element, or event, in the context of drilling system, refers to any material, equipment, and/or operational procedure of the system. In the FTA context, it refers to any event, as well as any material, equipment, and/or operational procedure of the system.

7.2 The Meaning and Units of Probability

Khakzad et al. (2013) extracted probability data from OREDA 2002, which provides statistical failure rates on a 10^6 (a million) service hour basis for the equipment. Therefore, a sample of final probability of 3% pump failure, obtained through the analysis applied herein can be interpreted as:

- Pump fails 3 times out of 100 hours of operation, or

- Pump fails N (= X*10*3 %) times out of 10 wells drilled, if drilling each well lasts about X hours.
- Pump fails M (= Y/100*3 %) times out of 100 ft drilled if drilling 10 ft takes about Y hours.

7.3 Model Construction Overview

First, the elements of the subsea drilling operation are analyzed by building the FT for each component separately, such as cementing, casing, circulation system, etc. The overall blowout FT includes human errors, as well as the failure of the material, and equipment is analyzed to see how the elements affect the system. Due to the complexity of drilling operations, a single parameter/element can lead to several scenarios, or create a ***common cause*** for different failure events. This is illustrated by the fact that casing (or cement) failures could directly lead to a kick, or directly lead to a circulation system failure, which in turn leads to a kick.

In normal FTA, it is not possible to conduct an analysis of the "multi-state gates" (explained in Section 7.4.3). For example, when constructing blowout FT, some events like kick, kick detection, and circulation operations are difficult to be contained in one gate, i.e., it is only possible to use the FT gates, which cannot account for the conditional dependencies among these components. Herein, the Bayesian network is implemented to design a gate that could contain all these parameters in one conditional gate, allowing the calculation of the blowout probability.

7.4 Mapping a Fault Tree into Bayesian Network

As explained in Section 5.1, the fault tree typically uses two types of gates; AND & OR gates. These gates help in the calculation of the Top Event (TE) failure probability. Fault tree connects the basic event into intermediate events, and then into the undesired event, which is the Top Event. Mapping of Fault Tree gates (OR

/ AND) using BN is explained in Khakzad et al. (2013) and was originally discussed in the work of Bobbio et al. (2001).

Figure 7.1 shows the process of mapping a generic fault tree into a Bayesian Network. The dashed lines illustrate the event that must be mapped. It is required to map each event (BE, IE, and TE) into an oval node in the software, called chance nodes. Nodes of BE is a place to define the failure probability. Nodes of (IEs) and (TE) are a place to insert the gate calculation.

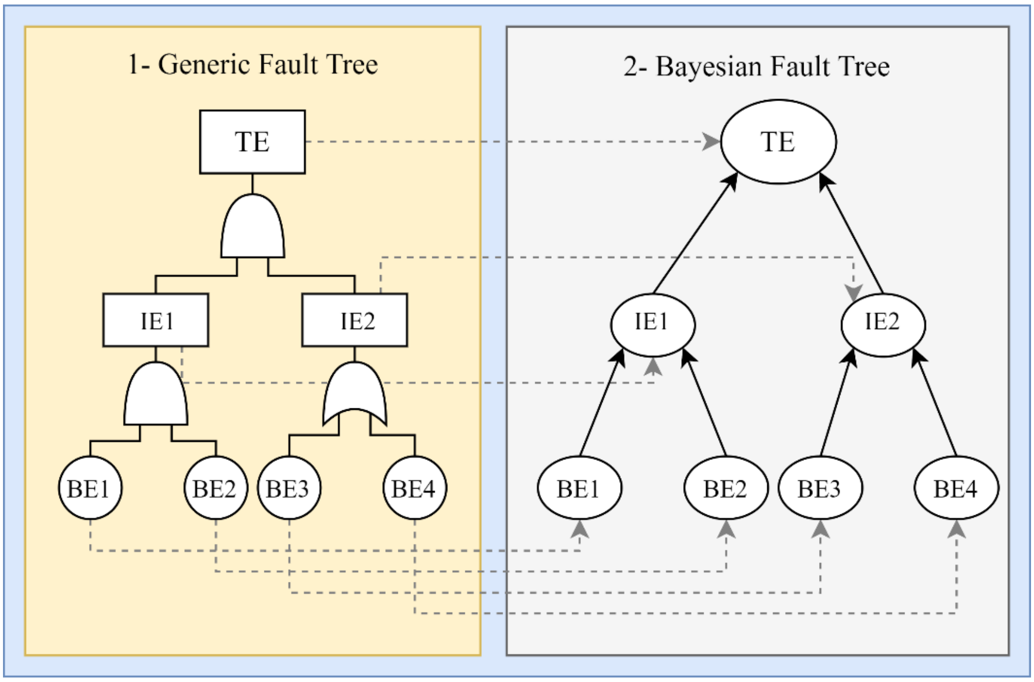


Figure 7.1: Fault Tree mapping to Bayesian network

7.4.1 Mapping AND Gate into BN

Figure 7.2 shows the mapping process of AND gates from a generic fault tree into Bayesian network. In gate section of Figure 7.2, the generic fault tree of Top Event (C), which resulted from two basic events (A) and (B), is illustrated. In Bayesian representation, events (A), (B), and (C) are created by three nodes with the same name of events. In (A) and (B) nodes, the failure probabilities are inserted. Then, (A) and (B) nodes are connected to (C) node using direct lines. Then, the

Conditional Probability Table (**CPT**) is filled based on the binary inputs, as seen in Figure 7.2. This CPT is a representation of the AND gate for the rule of multiplication (Eq 4.4) that is used to calculate the AND gate.

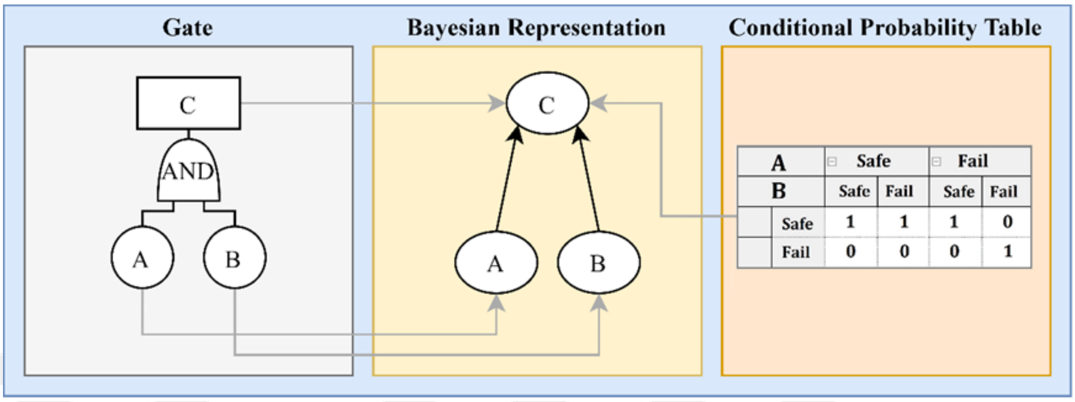


Figure 7.2: AND gate mapping into Bayesian network

7.4.2 Mapping OR Gate into BN

Similar to AND gate, the OR gate is mapped to BN, as shown in Figure 7.3. The only difference between OR and AND gates mapping is the CPT configuration, making it possible to use the rule of addition (Eq 4.2) for OR gate calculation.

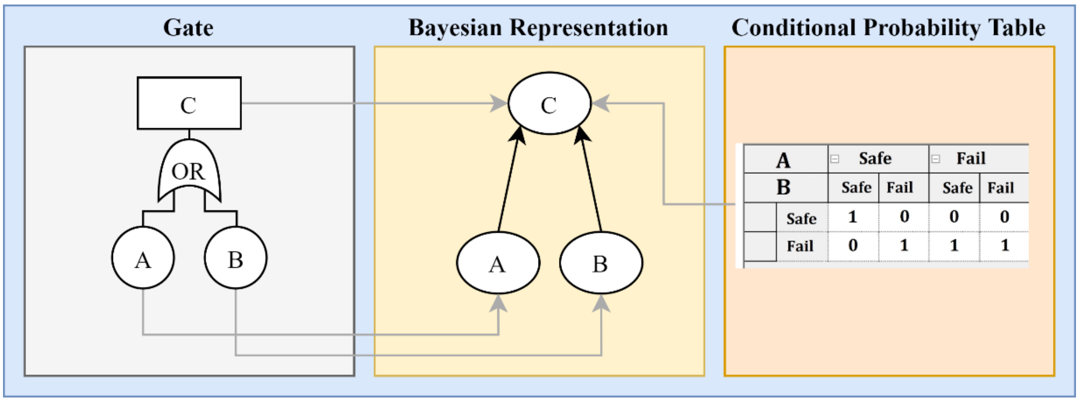


Figure 7.3: OR gate mapping into Bayesian network

7.4.3 Multi-State Gate Construction

BN makes it possible to get the exact evaluation of the Multi-State Gate (**MSG**) based on the CPTs configurations (Nadjafi et al., 2016), which is otherwise a complicated process with traditional fault trees. Figure 6.1 is a good example to illustrate how multi-state gate is used in BN. The fault tree that explains the drilling operation sequence (see Figure 6.1) is given in Figure 7.4. It is complicated to construct a traditional FT for such a system of interconnected elements. This is because ***common cause of failure*** (kick, and kick detection in Figure 7.4) should be modeled explicitly to avoid overestimating the system reliability (Ruijters & Stoelinga, 2015).

The nature of the safety system indicates an interaction between tree branches to reach a decision about how the blowout scenario progresses according to the correct chronology of the accident. This is possible using the BN as shown in Figure 7.5.

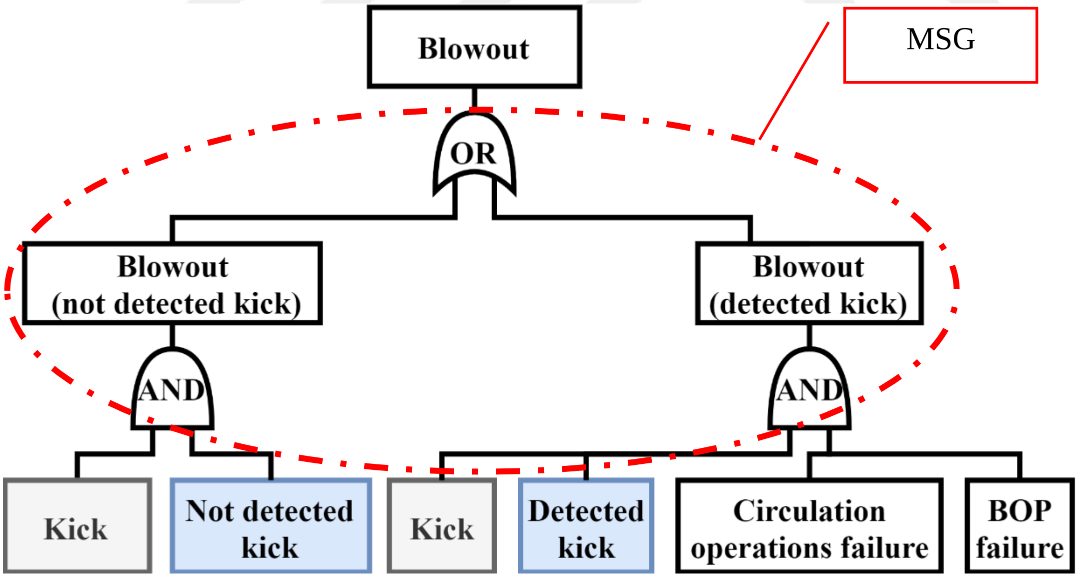


Figure 7.4: Blowout Fault Tree illustrating MSG

Figure 7.5 shows that MSG successfully accounts for the consecutive stages of operations in one node. The use of the gate is very important because, in drilling operations, the kick passes through multiple stages before developing into a blowout (explained in Chapter 6).

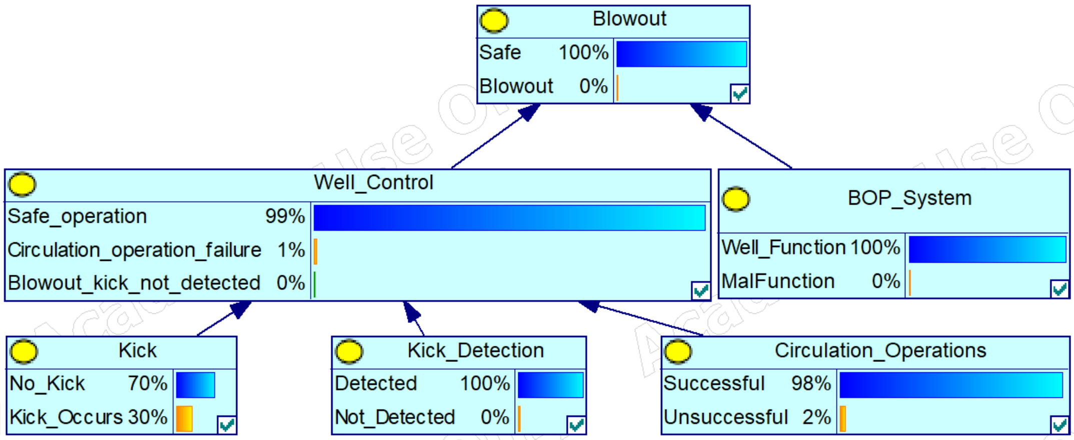


Figure 7.5: MSG of blowout Fault Tree using BN

To have the MSG, in Figure 7.5, the blowout and well control nodes are mapped as shown in Figure 9.7 in Appendix B

CHAPTER 8

RESULTS AND DISCUSSION

The main purpose of this analysis is (1) to assess the risk of having a blowout during drilling operations, and (2) to assess which parameters contribute to the blowout most. The analysis of the drilling safety system is divided into two sections. These are the (1) fault tree analysis for the safety system components, and (2) the model combination into a blowout analysis. After mapping the component fault trees into a Bayesian network, the Bayesian configuration helps in conducting a blowout safety analysis of drilling operations.

8.1 Safety System Analysis

Fault trees for drilling components are presented in the following sections. Elements and their ***default failure probabilities*** considered for all the separate FTAs in this study are presented in corresponding ***tables of Appendix A***. The probabilities given in these tables are utilized to evaluate corresponding BN at its default state. In addition to evaluating the default state of BN, three separate sensitivity analysis are applied using the BN: these are IMs (DI, & RRW), and OVAT.

8.1.1 Kick Fault Tree

Kick, as explained in Section 2.2, is the first sign of a probable blowout. Kick itself is also preceded by some signs, failures or misuse of equipment or procedures. Figure 8.1 includes the main reasons that contribute to kick initiation, these are:

1- Gas pocket (K3)
2- Abnormal pressure zones (K4)
3- Low hydrostatic pressure

a. Due to volume reduction (K5 to K8)

b. Due to density reduction (K9 to K12)

c. Surge (K1), and swab (K2)

The fault tree in Figure 8.1 explains the reasons for negative differential pressure ($\Delta P<0$ i.e., $P_H-P_F<0$ or $P_H < P_F$), which is the main reason for kick initiation.

The FT is mapped into a BN, Kick FT Bayesian model in Figure 9.1 in **Appendix B**, to create a model for safety analysis. The result of BN is (**30 %)**, which is the default probability of receiving a kick.

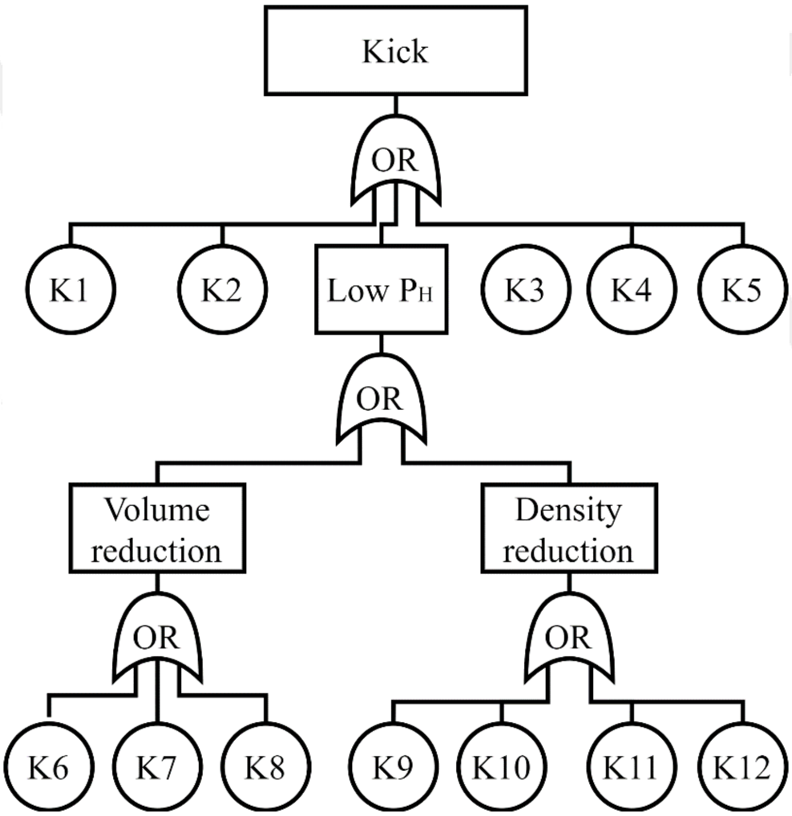


Figure 8.1: Kick Fault Tree (modified from Khakzad et al.,2013)

IMs Analysis:

Kick fault tree is analyzed using the importance measures (introduced in Section 5.4). First, **Diagnostic Importance (DI)** analysis of the tree is conducted using Eq 5.2. The diagnostic analysis of the system includes probability of the BE_i failure and tests the BE_i (as discussed in Section 5.4.1).

Per Table 8.1, results of diagnostic analysis of Kick FT given in Figure 8.1, concludes that:

- Abnormal pressure, denoted as (K4), has the highest contribution to kick initiation.
- Surge & swab (K1 & K2, respectively) contributes to kick initiation the second and third, respectively.
- The human error is ranked at the fourth place according to contribution to kick. This is represented by (K10), the operator failure to mix the right density mud for circulation.
- The circulation system (K12) is placed at the fifth stage.

The risk reduction worth (**RRW**) analysis of the system confirms these results, by giving the same ranking. The method does not consider the failure of BE_i. Instead, it assumes the optimization procedure for BE_i. The RRW analysis using Eq 5.3, that is shown in Table 8.2, illustrates that:

- Reduction in abnormal pressure probability, (K 4), which may be achieved by developing methods that precisely detect abnormal pressures zones, can reduce the kick probability from 30 % to 17 %, this reduces the risk by a factor of 1.7
- Reduction of surge & swab factor (pressure drop while pulling the drill string out of the hole) would reduce the kick probability from 30 % to 26 %, which is a reduction in the risk by a factor of 1.15
- Reduction of human errors in mud mixing stage would reduce the kick probability from 30 % to 27.8 %, which corresponds to a risk reduction by a factor of 1.08
- Enhancing the circulation system would reduce the kick probability from 30 % to 28.5 %, this points to a decrease in risk by a factor of 1.05

Table 8.1: Diagnostic risk analysis of Kick leading elements

Basic event	**DI** [-]	**Basic event**	**DI** [-]
K_03	0.0001	K_06	0.0236
K_08	0.0005	K_12	0.0491
K_05	0.0047	K_10	0.0722
K_11	0.0059	K_02	0.1330
K_09	0.0165	K_01	0.1333
K_07	0.0236	K_04	0.4121

Table 8.2: RRW analysis of Kick leading elements

Basic event	**RRW** [-]	**Basic event**	**RRW** [-]
K_03	1.00	K_06	1.02
K_08	1.00	K_12	1.05
K_05	1.00	K_10	1.08
K_11	1.01	K_02	1.15
K_09	1.02	K_01	1.15
K_07	1.02	K_04	1.70

OVAT Analysis:

OVAT is based on the hypothesis that each parameter is either enhanced/improved or diminished/degraded by 10 %. OVAT analysis, results of which are presented in Figure 8.2, is conducted using the BN model in Figure 9.1.

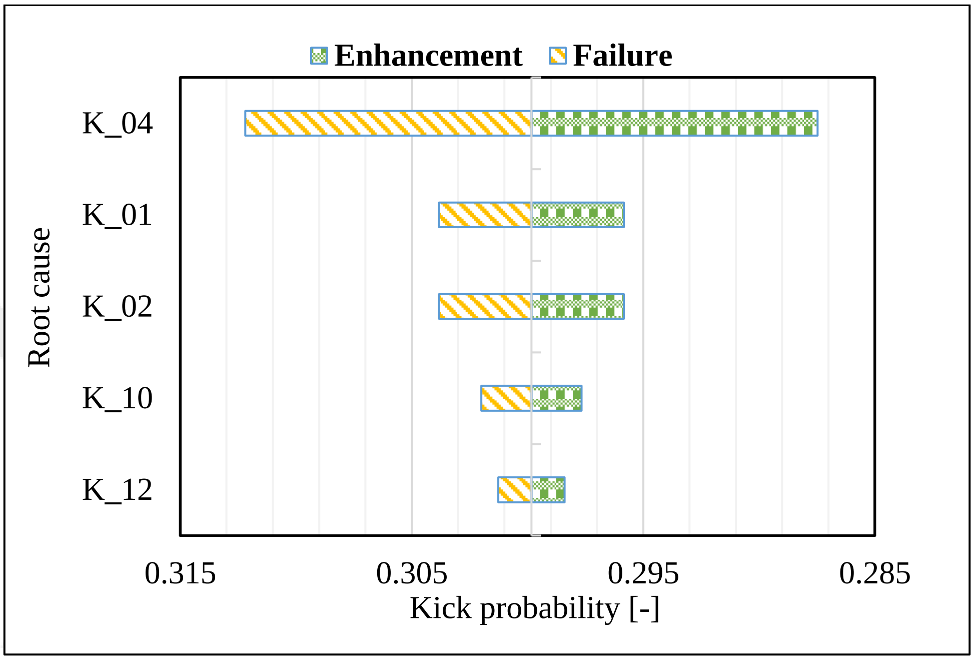


Figure 8.2: OVAT analysis for kick

OVAT illustrates that ± 10 % increment of the default failure probability of each basic event separately, would result in the following changes in kick probability:

- Abnormal pressure zone detection methods (K4):
    - ± 4.30 % change in the kick probability
- Surge and swab (K1 and K2):
    - ± 1.35 % change in the kick probability
- Human error (K10):
    - ± 0.73 % change in the kick probability
- Circulation system (K12)
    - ± 0.48 % change in the kick probability

8.1.2 Kick Detection Fault Tree

Kick detection failure results from failure to notice any combination of changes in mud volume, circulation pressure, formation gas content, and mud property (This is illustrated in Figure 8.3). Each node that descends from these IEs is separated into several parts that include equipment failure, and operator error to notice the failure. Hence, the kick detection FT is composed of 14 basic events. These are denoted as (KD1 to KD14) and explained in detail in **Appendix A**. The FT is first mapped into a BN, kick detection FT Bayesian model in Figure 9.2 in Appendix B, to create a model for safety analysis. The model shows that the kick detection failure probability is (**8.68E-04 %**)

IM Analysis:

The kick detection fault tree is analyzed using the ***importance measures*** described in Section 5.4. Results of this in Table 8.3 shows that the failure of the operator to notice gas (KD10), and failure of the operator to notice tank level (KD2) has the highest impact. Graphical presentation of the data as in Figure 8.4 illustrates the gap between failing BEi.

Based on diagnostic analysis of kick detection FT, it is concluded that the kick detection system is affected by:

1. Operator failure to notice gas (kick gas)
2. Operator failure to notice tank level (pit volume)
3. Operator failure to notice pump pressure change.
4. Operator failure to notice mud conductivity and density changes.
5. Operator failure to notice the increase of ROP.
6. Equipment failure, which contributes by a very little effect to the kick detection failure.

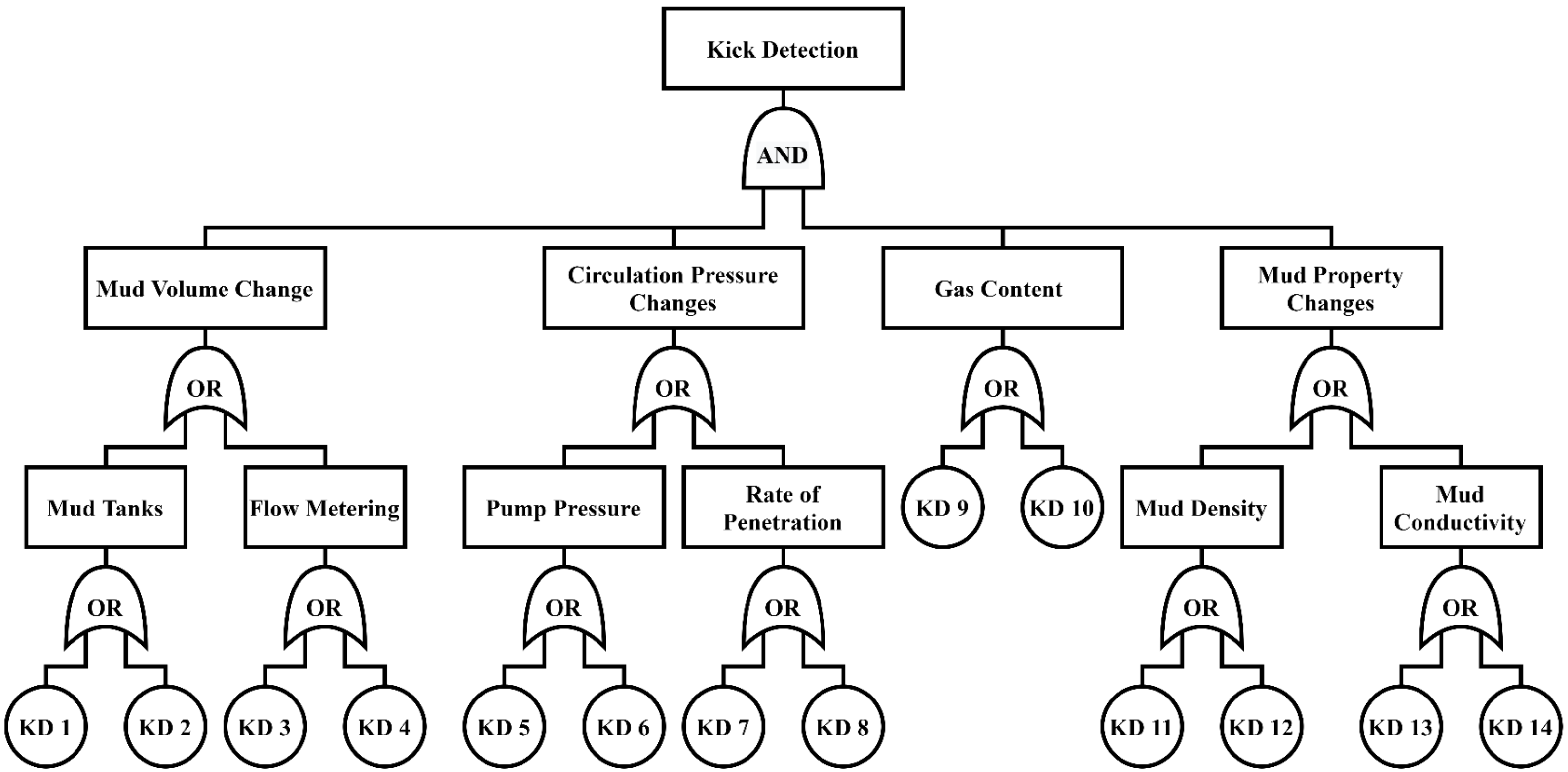


Figure 8.3: Kick detection FT (modified from Khakzad et al.,2013)

Table 8.3: Diagnostic analysis of elements that lead to kick detection failure.

Basic event	**DI** [-]	**Basic event**	**DI** [-]
KD 03	0.0011	KD 05	0.1036
KD 07	0.0013	KD 08	0.3139
KD 01	0.0013	KD 12	0.4821
KD 09	0.0040	KD 14	0.4821
KD 11	0.0193	KD 06	0.6278
KD 13	0.0193	***KD 02***	***0.9549***
KD 04	0.0477	***KD 10***	***0.9962***

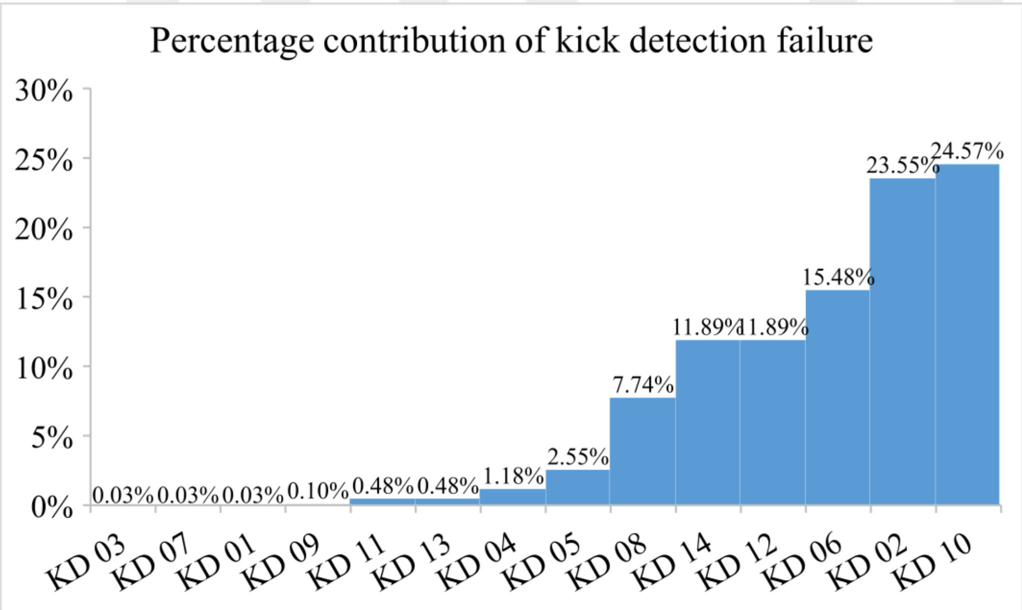


Figure 8.4: Diagnostic Analysis of Kick detection elements

RRW analysis of the system confirms DI ranking. The RRW analysis presented in Table 8.4 illustrates that increasing the situational awareness[25] or better training of operators who monitor the detection system, would reduce the probability of failing to detect kicks by a RRW factor of:

- 250, for (KD10), represented by the change of kick detection failure probability from 3.46E-08 [-] to 1.73E-04 [-]
- 20, for (KD2), represented by the change of kick detection failure probability from 3.46E-08 [-] to 4.35E-07 [-]
- 2.4, for (KD6), represented by the change of kick detection failure probability from 3.46E-08 [-] to 3.59E-06 [-]
- 1.9, for (KD12 & KD14), represented by the change of kick detection failure probability from 3.46E-08 to 4.52E-06 [-]
- 1.4, for (KD8 & KD5), represented by the change of kick detection failure probability from 3.46E-08 [-] to 6.27E-06 [-]

Table 8.4: RRW analysis of elements that lead to kick detection failure.

Basic event	**RRW** [-]	**Basic event**	**RRW** [-]
KD 03	1.0009	KD 05	1.0972
KD 07	1.0011	KD 08	1.3847
KD 01	1.0012	KD 12	1.9213
KD 09	1.0038	KD 14	1.9213
KD 11	1.0195	KD 06	2.4183
KD 13	1.0195	***KD 02***	***19.950***
KD 04	1.0449	***KD 10***	***250.95***

[25] Situational Awareness: part of the petroleum training courses to increase the crew ability to conceive, interpret, and react on the abnormal situations in well operations (Raza et al., 2019).

OVAT analysis

OVAT analysis (shown in Figure 8.5) illustrates that ± 10 % increment of the original failure probability of each basic event separately would require replacement or better training of the operator who is responsible for:

- Gas detection:
    - 10.0 % change in the kick detection probability
- Tank level:
    - 9.50 % change in the kick detection probability
- Pump pressure change observation:
    - 5.87 % change in the kick detection probability
- Mud property change:
    - 4.80 % change in the kick detection probability
- ROP observation:
    - 2.70 % of the kick detection probability

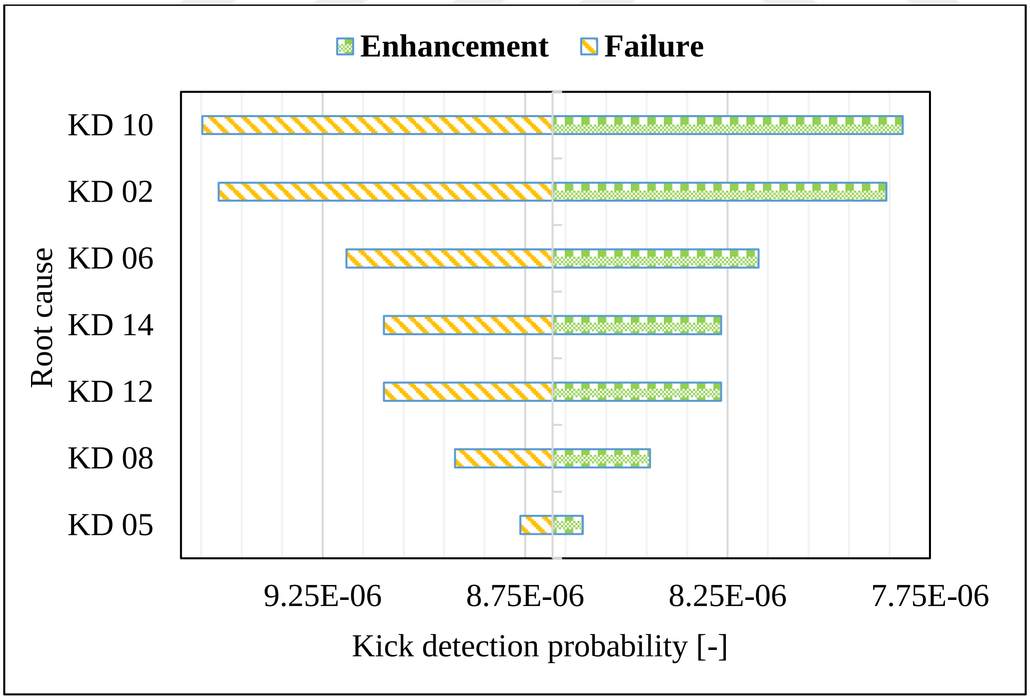


Figure 8.5: OVAT analysis for kick FT

Analysis on the kick detection system shows that human error contributes the most to the kick detection failure. This is very critical and, human error needs to be minimized, as the detection system is the first safety barriers in blowout mitigation. However, equipment failure contribution to kick detection failure is negligible comparing by the human error. Hence, it is required to provide better training, better qualified operators, or even a better alarm system that notifies the operator when parameters that signal kick occurrence. This is because kick detection system is the first and the most important barrier when well is threatened by a kick.

8.1.3 Casing Fault Tree

The casing fault tree is shown in Figure 8.6 illustrates that casing failure is attributed to two intermediate failures. These are:

1. Failures while introducing the casing to the formation, which includes the surge, swab, and Managed Pressure Drilling (**MPD**) system, represented by (BE1 to B3 respectively)
2. Failures of the casing component. That includes the casing string components failure and the failure in the casing setting evaluation, which branches to 7 basic events (BE4 to BE10).

The FT is first mapped into a BN as shown in Figure 9.3 in **Appendix B**, to create a model for safety analysis, which shows that the casing failure probability is (0.8 **%**)

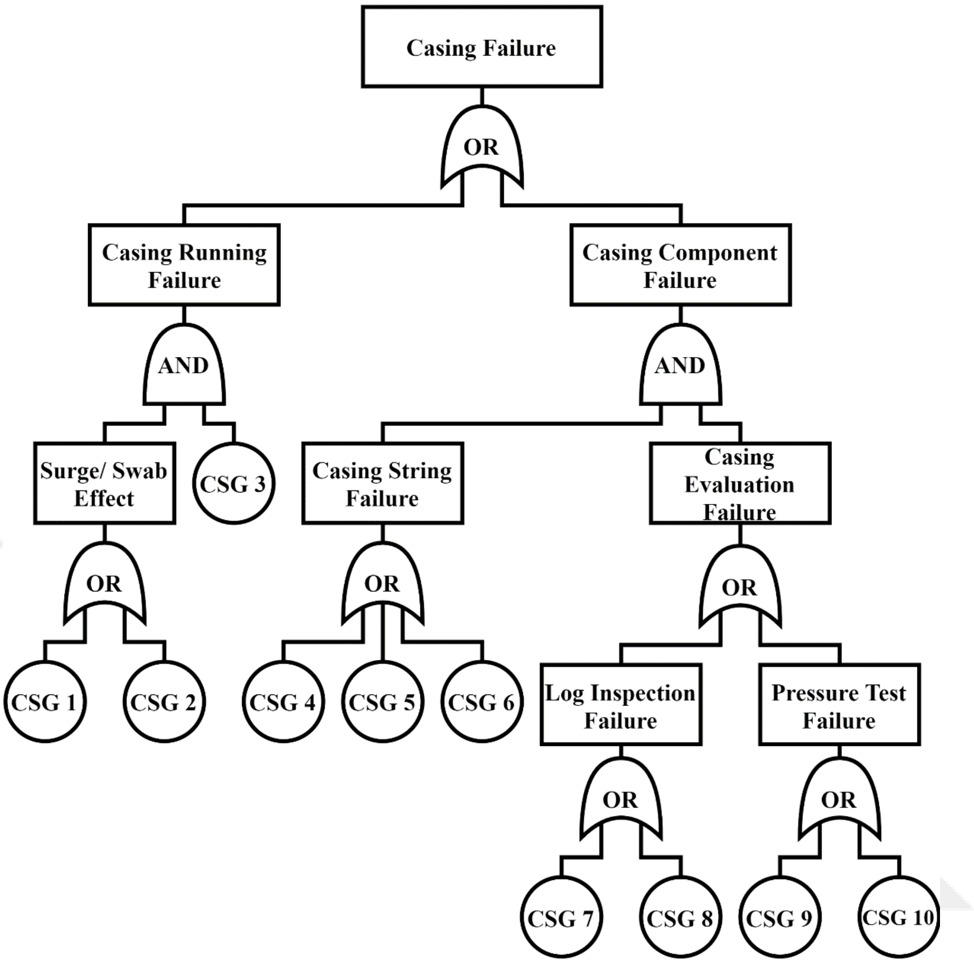


Figure 8.6: Casing failure Fault Tree (modified from Abimbola et al., 2016)

IMs Analysis

The diagnostic analysis of casing FT, using the BN model in **Appendix B**, is given in Table 8.5.

Table 8.5: Diagnostic analysis of elements that lead to casing failure.

Basic event	DI [-]	Basic event	DI [-]
CSG 01	0.0112	CSG 04	0.2141
CSG 03	0.0147	CSG 08	0.2176
CSG 07	0.0218	CSG 10	0.2176
CSG 02	0.0601	CSG 09	0.5440
CSG 06	0.2141	CSG 05	0.6148

DI analysis of the casing fault tree, concludes that:

- Wellhead failure, denoted as (CSG5), contributes the most to the casing failure.
- Pressure test failure, denoted as (CSG9), contributes the second to the casing failure.
- Inaccurate interpretation of test results and inaccurate interpretation of logs, denoted as (CSG10 & CSG8 respectively), contributes the third and fourth respectively to casing failure.
- Casing collapse and casing coupling failure, denoted as (CSG6 & CSG4 respectively), contributes the third and fourth respectively to casing failure.

RRW analysis, in Table 8.6, of the system confirms these results, by giving the same ranking.

Table 8.6: RRW analysis of elements that lead to circulation system failure.

Basic event	**RRW [-]**	**Basic event**	**RRW [-]**
CSG 01	1.0066	CSG 04	1.2219
CSG 03	1.0067	CSG 08	1.2653
CSG 07	1.0138	CSG 10	1.2653
CSG 02	1.0212	CSG 09	2.1380
CSG 06	1.2219	CSG 05	2.3130

The RRW analysis illustrates that:

- The priority of risk reduction goes to the Wellhead (CSG5), where the optimization of it reduces the failure probability by a factor of 2.3.
  - Casing failure probability reduces from 8.43E-03 to 3.65E-03
- Then, risk reduction of pressure test failure (CSG9), would reduce the failure probability by a factor of 2.13
  - Casing failure probability reduces from 8.43E-03 to 3.94E-03

- Also, risk reduction of inaccurate interpretation of test results and inaccurate interpretation of logs, denoted as (CSG10 & CSG8 respectively), would reduce the failure probability by a factor of 1.27
    - ➢ Casing failure probability reduces from 8.43E-03 to 6.66E-03
- Finally, risk reduction of casing collapse and casing coupling failure, denoted as (CSG6 & CSG4 respectively), would reduce the failure probability by a factor of 1.22
    - ➢ Casing failure probability reduces from 8.43E-03 to 6.90E-03

OVAT Analysis

The OVAT analysis are presented in Figure 8.7 illustrate that ± 10 % increment of the original failure probability of each basic event separately would result in:

- Wellhead failure (CSG5)
    - ➢ ± 6.2 % of the casing failure probability
- Pressure test failure (CSG9)
    - ➢ ± 5.9 % of the casing failure probability
- Interpretation of casing test results and casing logs
    - ➢ ± 2.6 % of the casing failure probability
- Casing collapse and casing coupling
    - ➢ ± 2.3 % of the casing failure probability

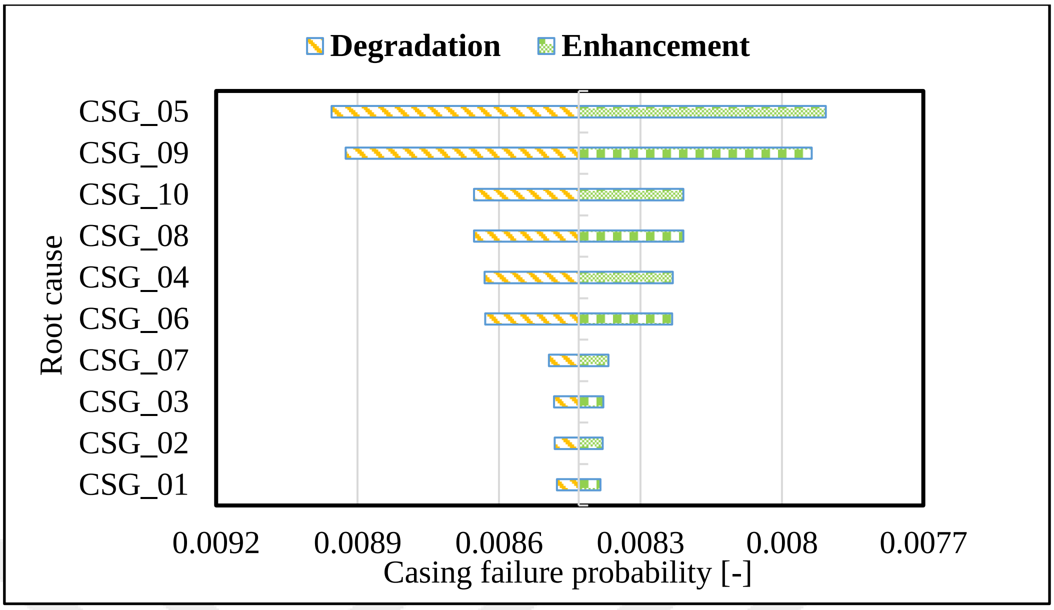


Figure 8.7: OVAT for Casing FT

8.1.4 Cementing Fault Tree

The cementing fault tree (shown in Figure 8.8) illustrates that the failure of cement component is a result of failure in improper cement job, or inaccurate evaluation of the cement job (that aims to confirm the success of the cement operations).

In cementing operations, the failure is the result of either not creating a good bond of the cement or incomplete cementing process. This failure branches into 17 basic events (C 1 to C 17). Also, inaccurate evaluation of cement job is the result of inability to interpret the logs or pressure test, which are represented by the basic events (C 18 to C 20).

The BN model used for the evaluation of importance measures is presented in Figure 9.4 in **Appendix B.** The model shows that the default probability of cementing job failure, which is (**0.4 %**).

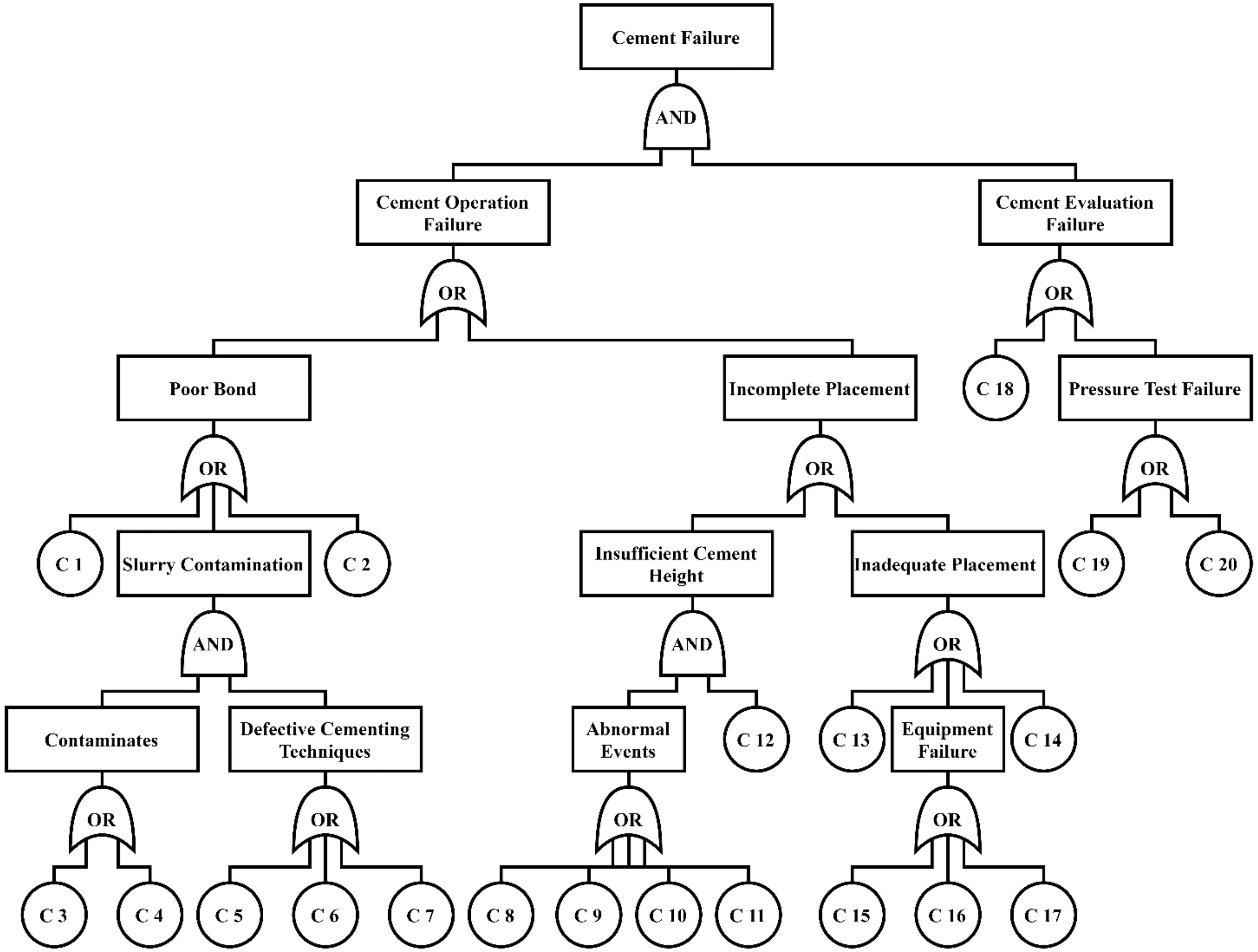


Figure 8.8: Cement Fault Tree (modified from Abimbola et al.,2016)

IMs Analysis

First, the diagnostic analysis is conducted to observe the contribution of each basic event to the totally failure of each basic event to the cement failure. Yet, because DI analysis considers the failure probability of BE_i, results in irregularities in the DI calculation[26]. For this reason, other importance measures can be used to correct the rank of risk results from each basic event. For instance, these are Birnbaum Importance (**BI**) and Criticality Importance (**CI**) explained in detail in **Appendix C**[27].

Table 8.7 is showing the criticality importance index of cement fault tree, Table 8.7 indicates that:

- Pressure test failure, denoted as (C 19), is the major contributor to the cementing failure.
- Pumping system failure, denoted as (C 15), contributes the second to the cementing failure.
- Inaccurate interpretation of the test results, denoted as (C 20), contributes the third to the cementing failure.
- Poor formulation of cementing slurry denoted as (C 01) ranked as the fourth contributor to the cement failure.
- Human error denoted as (C 13) ranked as fifth.

---

[26] An example showing the issue is given in **Appendix C**.
[27] In this study, we used CI measure.

Table 8.7: Criticality analysis of elements that lead to cement failure.

Basic event	CI [-]	Basic event	CI [-]
C 11	1.42E-08	C 06	0.043
C 10	5.39E-07	C 14	0.053
C 09	8.62E-06	C 05	0.072
C 02	2.85E-05	C 03	0.097
C 08	0.001	C 16	0.121
C 12	0.001	C 13	0.129
C 18	0.003	C 01	0.162
C 17	0.009	C 20	0.280
C 07	0.032	C 15	0.330
C 04	0.043	C 19	0.710

The CI analysis used to evaluate the model confirms the ranking with RRW, which is shown in Table 8.8. RRW analysis illustrates that to reduce the casing failure risk:

- An optimization/enhancement in the pressure testing (C 19) methods would reduce the risk by a factor of 3.5
- More reliable pumping system, denoted as (C 15) would reduce the risk by a factor of 1.5
- Raising the awareness among the cementing team about the danger of wrong interpretation (C 20) of tests conducted during cementing job and ensuring better training for the team would reduce the risk by a factor of 1.4
- Preparing perfect cementing slurry (C 1) would reduce the risk by a factor of 1.19
- Human error (C 13) should be reduced by better training or higher situational awareness to reduce the failure probability by a factor of 1.5

Table 8.8: RRW analysis of elements that lead to cement failure.

Basic event	RRW	Basic event	RRW
C 11	1.000	C 06	1.045
C 10	1.000	C 14	1.056
C 09	1.000	C 05	1.078
C 02	1.000	C 03	1.107
C 08	1.001	C 16	1.137
C 12	1.001	C 13	1.148
C 18	1.003	C 01	1.193
C 17	1.009	C 20	1.388
C 07	1.033	C 15	1.492
C 04	1.045	C 19	3.445

OVAT Analysis

For better observation of the risk reduction process, OVAT analysis is conducted as shown in Figure 8.9. OVAT analysis, illustrate that ± 10 % increment of the original failure probability of each basic event separately would result in:

- Pressure testing (C 19)
  - ± 7.1 % of the cementing failure probability
- Pumping system testing (C 15)
  - ± 3.3 % of the cementing failure probability
- Test interpretation (C 20)
  - ± 2.7 % of the cementing failure probability
- Cementing slurry formulation (C 1)
  - ± 1.6 % of the cementing failure probability
- Human Error (C 13)
  - ± 1.3 % of the cementing failure probability

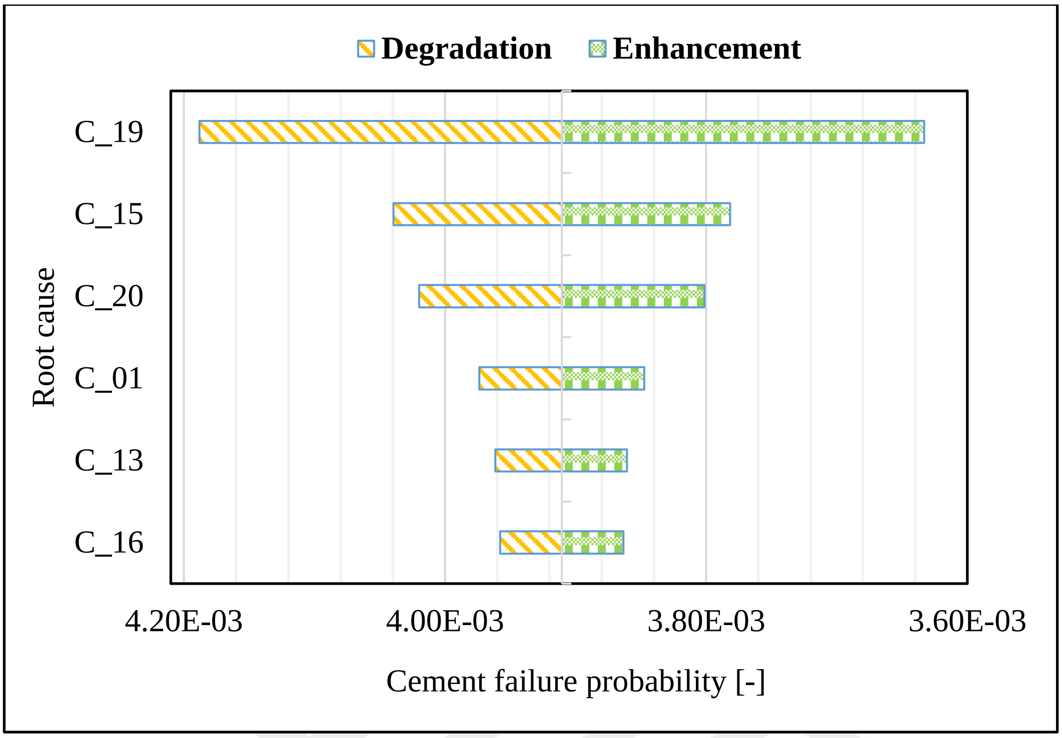


Figure 8.9: OVAT for cement operation

8.1.5 Circulation System Fault Tree

The circulation system fault tree is shown in Figure 8.10. The FT descends to 18 basic events, explaining the failure possibility through the logical gates. Circulation system failure is attributed to:

- Pump control failure (Circ 1)
- Pump failure (Circ 2)
- Power failure (Circ 3)
- Lines and valves failure:
    - Emergency Shut Down (**ESD**) valve (Circ 4), kill line (Circ 5), nonreturn valve (Circ 6), failsafe valve (Circ 7), and choke manifold (Circ 8)
- Equipment failures. These are:
    - Drill pipe (Circ 9), float shoe (Circ 10), and riser (Circ 11)
- Control panel failure
    - Tank level indicator (Circ 12), pump strokes (Circ 13), and flow meter failure (Circ 14)
- Wellhead failure
    - Wellhead connector (Circ 15), and wellhead housing (Circ 16)
- Major barriers failures such as casing (Circ 17) and cementing (Circ18)
    - probabilities of these are evaluated in corresponding FTA in previous sections, then substituted in this analysis)

The BN model used for the evaluation of casing FT is presented in Figure 9.3 in Appendix B. The model is evaluated to give the default casing failure rate, which is (**2.06 %**).

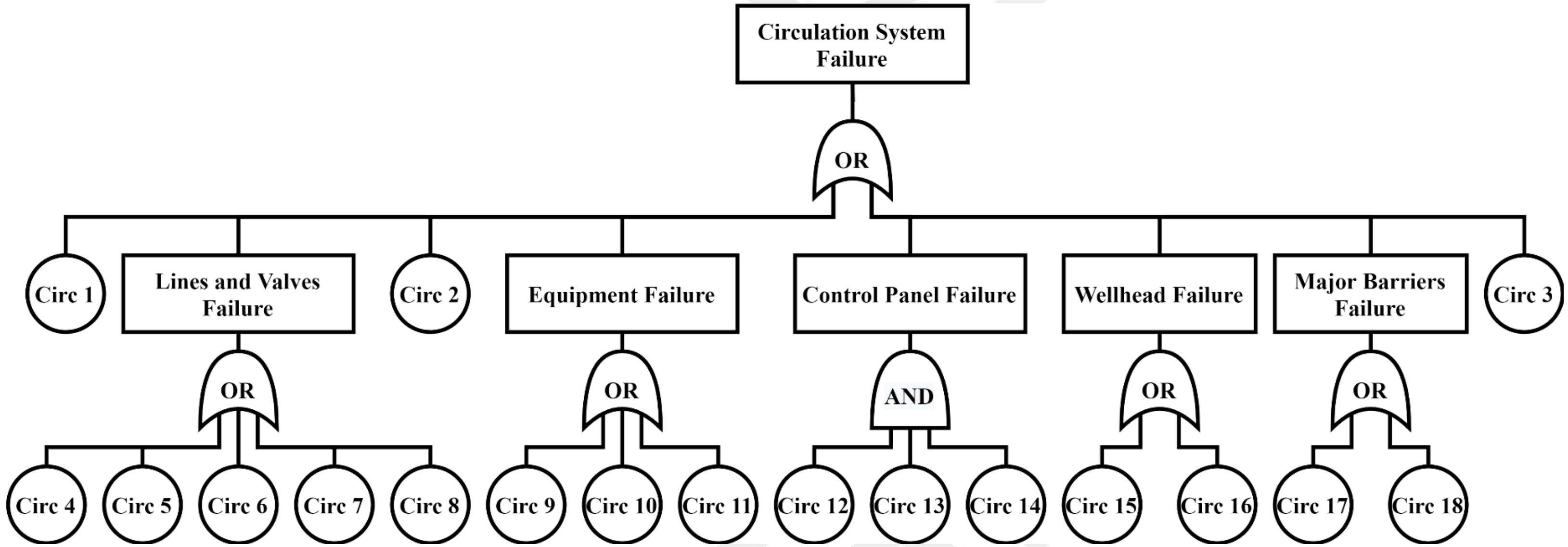


Figure 8.10: Circulation system fault tree (modified from Abimbola et al.,2014)

IMs analysis

The diagnostic calculation shown in Table 8.9 ranks contribution to circulation failure as follows:

- First, cement failure, denoted as (Circ 17), as significant contributor.
- Second, choke manifold failure denoted as (Circ 8)
- Third, casing failure, denoted as (Circ 18)
- Equally ranked as the fourth and fifth, float shoe and pump control failure, denoted as (Circ 10 & Circ1 respectively)

Table 8.9: Diagnostic analysis of elements that lead to circulation system failure.

Basic event	**DI [-]**	**Basic event**	**DI [-]**
Circ 13	1.43E-10	Circ 07	0.0107
Circ 12	1.44E-10	Circ 05	0.0175
Circ 14	1.46E-10	Circ 09	0.0243
Circ 03	1.19E-05	Circ 11	0.0248
Circ 15	0.0005	Circ 01	0.0486
Circ 16	0.0005	Circ 10	0.0486
Circ 02	0.0009	Circ 18	0.1900
Circ 04	0.0063	Circ 08	0.2192
Circ 06	0.0063	Circ 17	0.4097

The RRW analysis in Table 8.10 shows that the optimization or enhancement of basic event:

- Circ 17, would highly reduce the risk by a factor of 1.7
- Circ 8, would reduce the risk by a factor of 1.27
- Circ 18, would reduce the risk by a factor of 1.23
- Circ 1 or Circ 10, would reduce the risk by a factor of 1.05

Table 8.10: RRW analysis of elements that lead to circulation system failure.

Basic event	RRW [-]	Basic event	RRW [-]
Circ 13	1.0000	Circ 07	1.0106
Circ 12	1.0000	Circ 05	1.0174
Circ 14	1.0000	Circ 09	1.0244
Circ 03	1.0000	Circ 11	1.0249
Circ 15	1.0005	Circ 01	1.0500
Circ 16	1.0005	Circ 10	1.0500
Circ 02	1.0009	Circ 18	1.2298
Circ 04	1.0062	Circ 08	1.2749
Circ 06	1.0062	Circ 17	1.6799

OVAT Analysis

To have an idea about the how risk is reduced or increased during operations, OVAT analysis is carried out as shown in Figure 8.12. OVAT analysis illustrate that ± 10 % increment of the default failure probability of each basic event separately would result in:

- Cement, denoted as (Circ 17)
  - ± 4.1 % of circulation system failure probability
- Choke manifold, denoted as (Circ 8)
  - ± 2.2 % of circulation system failure probability
- Casing, denoted as (Circ 18)
  - ± 1.9 % of circulation system failure probability
- Float shoe and pump control, denoted as (Circ 10 & Circ1 respectively)
  - ± 0.5 % of circulation system failure probability

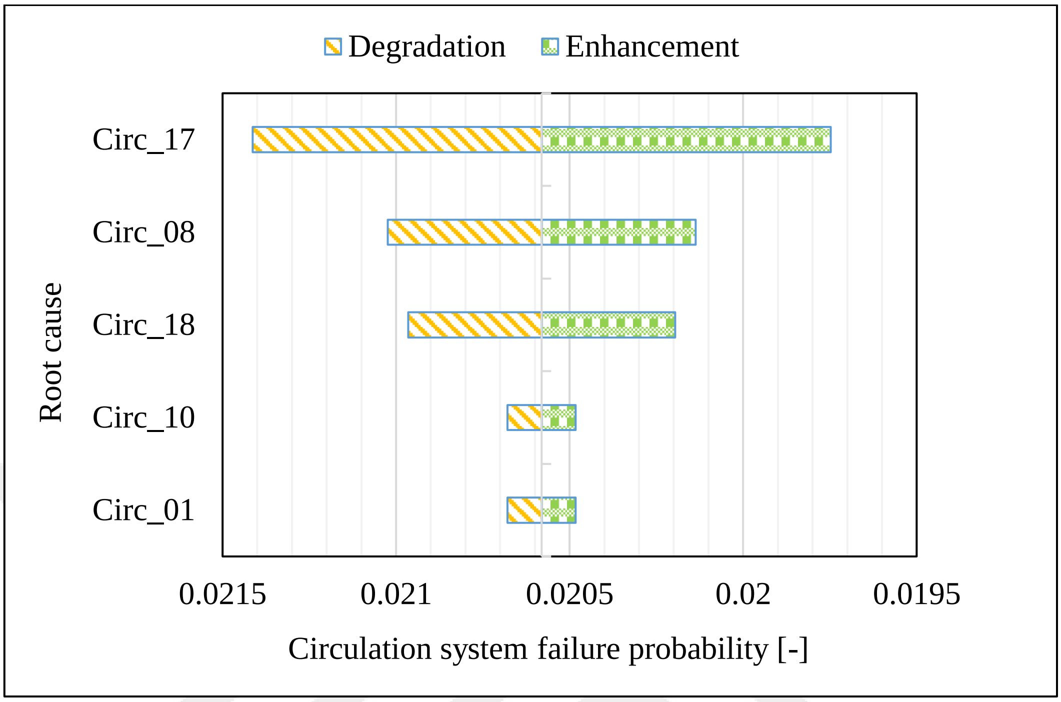


Figure 8.11: OVAT for Circulation system

8.1.6 Blowout Prevention System Fault Tree

The blowout prevention fault tree is shown in Figure 8.12, is composed of 16 basic events, denoted as (B 1 to B 16). The FT shows the typical paths that lead to malfunction of the prevention system. These are:

- Failure of the surface BOP failure such as Rotating Control Device (RCD), used to seal around drill-string located at the platform,)
- Subsea BOP system failure (located at the wellhead on seabed)
- Communication system failure (such as accumulator unit, which is used to hydraulically operate the BOP rams)

The BN model in Figure 9.6 shows that the BOP default failure probability is (**0.26 %**)

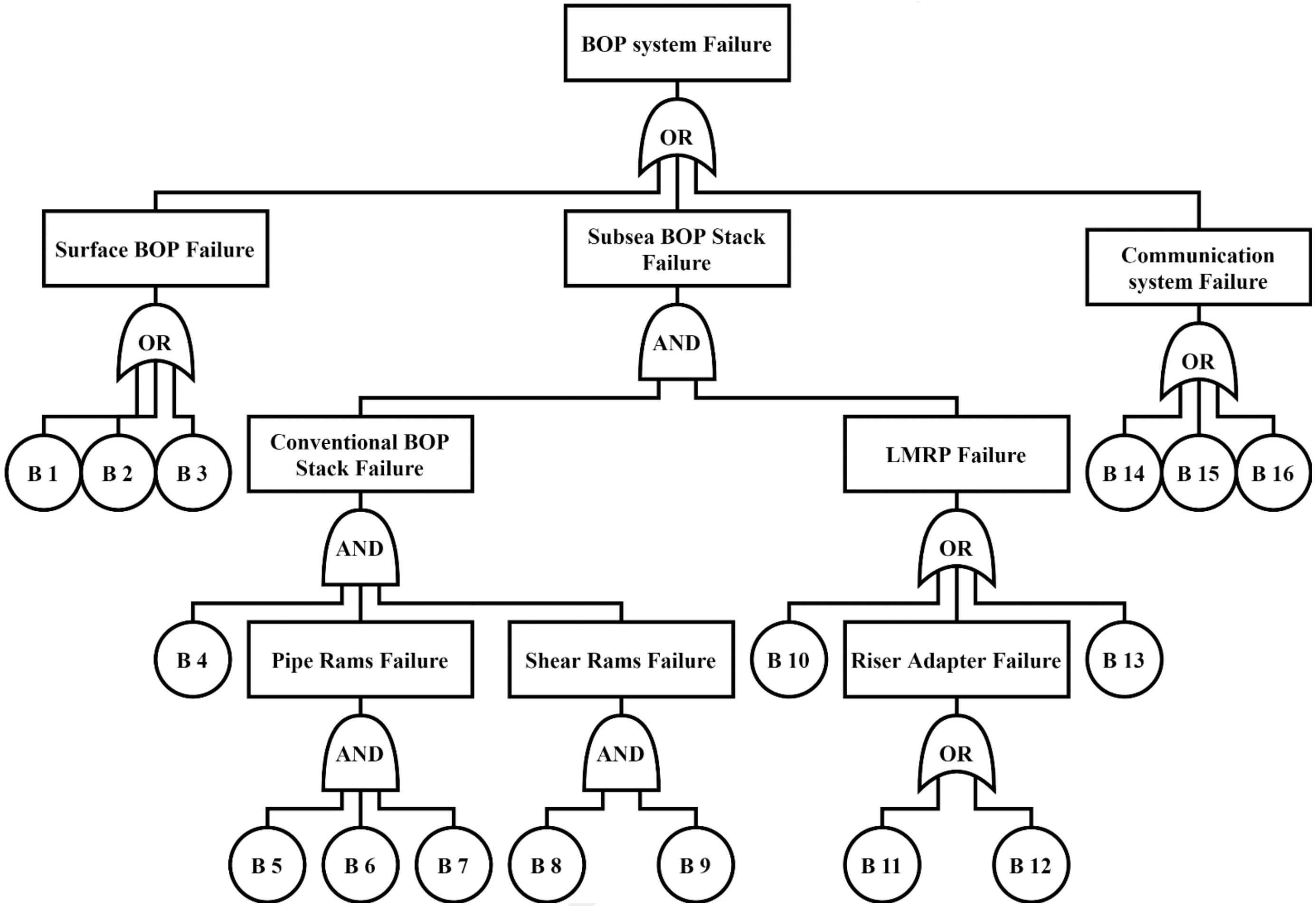


Figure 8.12: BOP system Fault Tree (modified from Abimbola et al.,2014)

IMs Analysis

The BOP fault tree is analyzed using the diagnostic importance measure, which is given in Table 8.11. DI ranks contribution to BOP failure as follow:

- First, operator error, denoted as (B 14), as significant contributor.
- Second, the control system failure, denoted as (B 16)
- Then. the rest of the BOP machinery part with a very low probability.

Table 8.11: Diagnostic analysis of elements that lead to BOP system failure.

Basic event	**DI [-]**	**Basic event**	**DI [-]**
B 01	4.00E-05	B 06	2.50E-05
B 15	3.80E-08	B 07	2.50E-05
B 09	1.00E-06	B 04	2.60E-04
B 08	1.00E-05	B 10	2.60E-04
B 11	1.00E-05	B 02	3.65E-03
B 12	1.00E-05	B 03	4.30E-03
B 13	1.00E-05	B 16	2.41E-01
B 05	2.50E-05	B 14	7.59E-01

The RRW analysis of elements that lead to BOP system failure are given in Table 8.12 shows that the optimization or enhancement of basic event:

- B 14, would highly reduce the risk by a factor of 4.15
- B 16, would reduce the risk by a factor of 1.3
- The remaining elements of the BOP system would result in insignificant reduction in BOP failure

Table 8.12: RRW analysis of elements that lead to BOP system failure.

Basic event	RRW [-]	Basic event	RRW [-]
B 01	1.00	B 06	1.00
B 15	1.00	B 07	1.00
B 09	1.00	B 04	1.00
B 08	1.00	B 10	1.00
B 11	1.00	B 02	1.00
B 12	1.00	B 03	1.00
B 13	1.00	B 16	1.32
B 05	1.00	B 14	4.15

OVAT analysis

The RRW analysis results are confirmed by the OVAT analysis as shown in Figure 8.13. OVAT analysis illustrate that ± 10 % increment of the default failure probability of each basic event separately would result in:

- Operator, denoted as (B 16)
  - ± 7.9 % of the BOP failure probability
- Control system, denoted as (B 14)
  - ± 2.4 % of the BOP failure probability

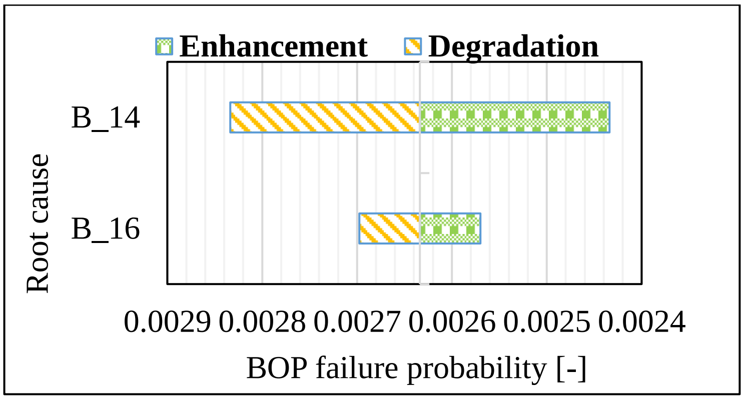


Figure 8.13: OVAT for BOP system

8.2 Blowout Analysis

Blowout analysis is conducted using a combined BN. A combined BN requires us to use the multistate gate, as explained in Section 7.4.3. The MSG includes the conditional probability distribution of multiple components in the system. The components used in the system are:

1- Kick leading elements.
2- Kick detection failure elements.
3- Circulation system, which includes:
    a. Cement failure elements
    b. Casing failure elements
4- BOP system.

The final model is combined according to the operation sequence (as discussed in chapter 6 and section 7.4.3). The BN model (which is used for the probabilistic analysis) is shown in Figure 8.14, shows the connections between the safety barriers discussed in Section 8.1. Failure probabilities of different components are evaluated within corresponding modules i.e., kick, kick detection nodes etc.

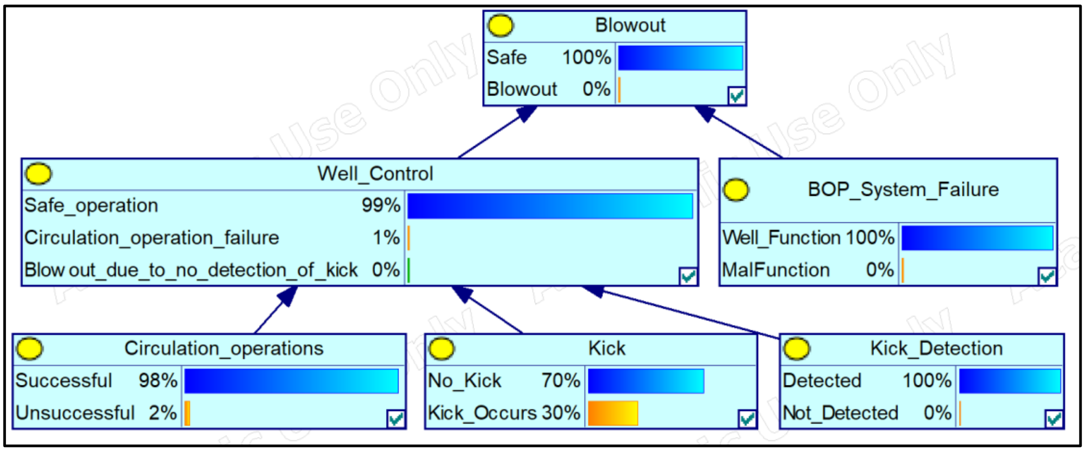


Figure 8.14: Blowout BN model

The blowout probability based on the configuration in Figure 8.14 is found to be (**1.63E-03 %)**. Component probabilities are evaluated separately before (in Section 8.1) as:

1- 3.00E-01 [-], kick probability
2- 8.68E-06 [-], kick detection failure probability
3- 2.06E-02 [-], circulation failure probability
4- 2.63E-03 [-], BOP failure probability

The process for PRA of blowout is explained in the following steps:

i. One component e.g., kick, kick detection etc., is set to ***failure*** state at a time to observe the failure contribution to blowout, and the resultant blowout probability is recorded.
ii. Same procedure is repeated for 100 % ***safe*** state.
iii. Failure probabilities of each fault tree (*section 8.1*) are inserted in the BN model in Figure 8.14. to observe the change of blowout failure probability. The most critical and risk potential elements that threaten the drilling operations are given in Table 8.13.

Table 8.13: Top contributors to blowout

Safety Barrier	**Elements**
Kick initiation	K12, K10, K2, K1, K4
Kick Detection system	KD5, KD8, KD14, KD12, KD6, KD2, KD10
Circulation system	Circ11, Circ1, Circ10, Circ18, Circ8, Circ17
BOP system	B14, B16

iv. Finally, the elements are evaluated based on BI & RRW.

These elements are analyzed with BI in Appendix C, as DI results deviate from the real risk ranking (as explained in Section 8.1.4)

The BN is analyzed using RRW to see how much the optimization of each element would reduce the blowout probability. The results from RRW analysis are presented in Table 8.14 (we only show 13 out of 23 elements, which we identified as top contributors to blowout).

Table 8.14: RRW analysis for blowout

Basic event	**RRW [-]**	**Description**
B 14	4.15	Operator error in BOP operations
K 04	1.70	Abnormal pressured zone
Circ 17	1.68	Casing failure
B 16	1.32	Control system failure
Circ 08	1.27	Choke manifold failure
Circ 18	1.23	Cementing failure
K 01	1.15	Surge
K 02	1.15	Swab
K 10	1.08	Operator failure in mixing right density
K 12	1.05	Circulation system failure (kick induction)
Circ 10	1.05	Float shoe
Circ 01	1.05	Pump control failure (drilling fluid pump)

Summary of the blowout analysis:

According to the probabilistic analysis on drilling operation, it has been observed that, with respect to the order of contribution:

1- Operator error (B 14) in operating the BOP contributes the most to blowout occurrence.
   - The full elimination of (B 14) would reduce the blowout probability by 4.15 RRW factor.

2- Abnormal pressure zones (K 04) are a big threat to sustainable drilling operations.
   - Removing (K 04) would reduce the blowout probability by 1.7 RRW factor.

3- Casing failure (Circ 17)
   - Eliminating the casing failure would reduce the blowout probability by1.68 RRW factor.

4- Choke manifold failure (Circ 8)
   - Eradicating (Circ 8) would result in 1.32 RRW factor.

5- Surge & swab (K 1 & K 2 respectively)
   - Eliminating (K 1 & K 2) would result 1.15 RRW factor.

6- Failure in mixing the right density when preparing drilling fluids (K 10)
   - Eliminating (K 10) would result 1.08 RRW factor.

7- Circulation system failure that induced a kick, float shoe failure, and pump control failure
   - Eliminating failure of these elements would result in reduction of blowout by 1.05 RRW factor.

CHAPTER 9

CONCLUSIONS

Inability to contain formation pressures by controlling drilling fluid bottom-hole pressures is the main reason for blowouts. The major challenge is the uncertainty in the underground formation pressures. Prior risk assessment allows us to include factors contributing to blowout altogether with well safety systems, and connect them to make an informed decision about the risk level. As it is not possible to eliminate the risk, risk assessment is used to create an analytical model to mitigate these risk causing factors based on the Health, Safety, and Environmental (HSE) aspects, which ensures optimal operations with the least outcome severity. In this study, a probabilistic risk assessment model for deep water drilling operations is developed by mapping FTA on a Bayesian Network. First, separate fault trees of the drilling system components were analyzed. Then, the elements that threaten the components most are identified. These elements are introduced to the blowout model through Multi-State Gate (MSG). MSG allows us to put the logical sequence of drilling safety system failure in correct order. Then, based on the fault tree importance measures, each element of the drilling system is analyzed to decide which one should be reduced to maintain an acceptable risk level (which reduce the possibility of blowout occurrence). The study also includes a one variable at a time (OVAT) analysis assuming that the failure rate of each parameter enhanced or degraded by 10 %.

Major conclusions from this study are:

- Human error represented by the operator inability to operate BOP contributes the most to blowout occurrence. Reduction of human error will reduce the blowout probability by 400 % form the default probability.

- False interpretation of the geological formations represented by the inability to precisely predict abnormally pressures zones is the second major contributor to blowout occurrence. Eliminating the uncertainty in the geological predictions would reduce blowout probability by almost 200 % compared to the default blowout probability.
- Equipment failure represented by casing, or choke manifold failures. Reduction in these parameters mitigate the blowout by 68 % and 32 % of the default blowout probability, respectively.
- Effect of surge & swab while operation. Eliminating these parameters would result 15 % reduction of the default blowout probability.
- Human error in fluids mixing. Eliminating such failure reduces the blowout probability by 8 % of the default blowout probability.
- Circulation system (assuming that it only reduced the pressure and function properly when well control procedure carried out), float shoe failure, and pump control failure. Eliminating these elements failure reduces the blowout probability by 5 % of the default blowout probability.

9.1 Recommendations

In this study, we used failure probabilities of fault tree elements from literature to evaluate blowout probability. However, element probabilities should be updated for each new well to be drilled, based on the experience of the engineers and rig personnel, company operational policies, and information and data gathered regarding the geographic region. Based on the current study, the following are recommended for future research:

- Re-examine the genesis of probability data based on statistical failure rates from industry databases, e.g. OREDA (2002), and confirm the implication of failure rate on probability assessment.
- Certain IM types (e.g. DI) failed to assign different ranks for different BEs. Instead, they resulted in same rank for different BEs, due to AND gates

present in the FTA. A suitable IM that properly ranks BEs regardless of how they are introduced to the FTA, should be established.

- Include economic aspects for risk assessment in the study.
- Develop time dependent models that can simulate the drilling process and update probabilities in real time.
- Conduct a study on a specific variable of the blowout elements, e.g., RCD, bottom-hole pressure, based on a previous blowout event
- Expand the study to include very detailed parts of the drilling system.

REFERENCES

Abimbola, M., Khan, F., & Khakzad, N. (2014). Dynamic Safety Risk Analysis of Offshore Drilling. *Journal of Loss Prevention in the Process Industries*, *30*, 74–85. https://doi.org/10.1016/j.jlp.2014.05.002

Abimbola, M., Khan, F., & Khakzad, N. (2016). Risk-based safety analysis of well integrity operations. *Safety Science*, *84*, 149–160. https://doi.org/10.1016/j.ssci.2015.12.009

Aerosolisation. (n.d.) *Segen's Medical Dictionary*. (2011). Retrieved June 26 2021 from https://medical-dictionary.thefreedictionary.com/Aerosolisation

Agency, International Atomic Energy Agency. (1997). *Workshop on PSA applications, Sofia, Bulgaria, 7-11 October 1996. Lecturing materials* (IAEA-RU--6699). International Atomic Energy Agency. http://inis.iaea.org/Search/search.aspx?orig_q=RN:28059556

Ahmed, M. A., Hegab, O. A., & Sabry, A. (2016). Early detection enhancement of the kick and near-balance drilling using mud logging warning sign. *Egyptian Journal of Basic and Applied Sciences*, *3*(1), 85–93. https://doi.org/10.1016/j.ejbas.2015.09.006

AIChE/CCPS (2010). Appendix D: Minimal Cut Set Analysis. In Guidelines for Chemical Process Quantitative Risk Analysis, (Ed.). https://doi.org/10.1002/9780470935422.app4

AIChE/CCPS. (2014, December 17). Causal factor (CF). https://www.aiche.org/ccps/resources/glossary/process-safety-glossary/causal-factor-cf

AIChE/CCPS. (n.d.). Root Causes. *CCPS Process Safety Glossary | AIChE*. Retrieved July 4, 2021, from https://www.aiche.org/ccps/resources/glossary?title=root+cause#views-exposed-form-glossary-page

Alnabhani, K. (2018). Chapter Five—Safety During Offshore Drilling Operation. In F. Khan & R. Abbassi (Eds.), *Methods in Chemical Process Safety* (Vol. 2, pp. 207–268). Elsevier. https://doi.org/10.1016/bs.mcps.2018.04.007

Andersen, L. B. (1998). Stochastic modelling for the analysis of blowout risk in exploration drilling. *Reliability Engineering & System Safety*, *61*(1–2), 53–63. https://doi.org/10.1016/S0951-8320(97)00067-7

Aulicino, B., & Timblin, D. (2018, May 10). *In Deep: Deepwater Well Control*. American Scientist. https://www.americanscientist.org/blog/from-the-staff/in-deep-deepwater-well-control

Azar, J. J., & Samuel, G. R. (2007). *Drilling engineering*. PennWell Corp.

Bahr, N. J. (2014). System safety engineering and risk assessment: A practical approach, second edition. In System Safety Engineering and Risk Assessment: A Practical Approach, Second Edition (p. 418). https://doi.org/10.1201/b17854

Bai, Y., & Bai, Q. (2019). 10—Subsea Risk and Reliability. In Y. Bai & Q. Bai (Eds.), *Subsea Engineering Handbook (Second Edition)* (pp. 239–261). Gulf Professional Publishing. https://doi.org/10.1016/B978-0-12-812622-6.00010-5

Barua, S., Gao, X., Pasman, H., & Mannan, M. S. (2016). Bayesian network based dynamic operational risk assessment. *Journal of Loss Prevention in the Process Industries*, *41*, 399–410. https://doi.org/10.1016/j.jlp.2015.11.024

Bobbio, A., Portinale, L., Minichino, M., & Ciancamerla, E. (2001). Improving the analysis of dependable systems by mapping fault trees into Bayesian networks. *Reliability Engineering & System Safety*, *71*(3), 249–260. https://doi.org/10.1016/S0951-8320(00)00077-6

Bourgoyne, A. T. (1991). Applied drilling engineering. Richardson, TX: Society of Petroleum Engineers.

BP. (2010, September 8). *Deepwater Horizon Accident Investigation Report*. https://www.sec.gov/Archives/edgar/data/313807/000119312510216268/dex993.htm

CCOHS. (n.d.). Risk Assessment: OSH Answers. Retrieved March 1, 2021, from https://www.ccohs.ca/oshanswers/hsprograms/risk_assessment.html

Chakrabarti, S., Halkyard, J., & Capanoglu, C. (2005). Chapter 1—Historical Development of Offshore Structures. In S. K. Chakrabarti (Ed.), *Handbook of Offshore Engineering* (pp. 1–38). Elsevier. https://doi.org/10.1016/B978-008044381-2.50004-7

Chandrasekaran, S. (2021). Chapter 1 - Marine risers: Introduction. In S. Chandrasekaran (Ed.), *Design of Marine Risers with Functionally Graded Materials* (pp. 1–23). Woodhead Publishing. https://doi.org/10.1016/B978-0-12-823537-9.00006-2

Chapman, R. E. (Ed.). (1983). Chapter 14 Abnormal Pressures. In *Developments in Petroleum Science* (Vol. 16, pp. 303–323). Elsevier. https://doi.org/10.1016/S0376-7361(08)70098-0

Cholteeva, Y. (2020, April 28). Deepwater exploration: What it takes to drill really really deep. https://www.offshore-technology.com/features/deepwater-exploration-what-it-takes-to-drill-really-really-deep/

Cordes, E., Jones, D., Amon, D., Bernardino, A., Brooke, S., Carney, R., DeLeo, D., Dunlop, K., Escobar-Briones, E., Gates, A., Genio, L., Gobin, J., Henry, L.-A., Herrera, S., Hoyt, S., Joye, S., Kark, S., C. Mestre, N., & Witte, U. (2016). Environmental Impacts of the Deep-Water Oil and Gas Industry: A Review to Guide Management Strategies. *Frontiers in Environmental Science*, *4*. https://doi.org/10.3389/fenvs.2016.00058

Crumpton, H. (2018). Chapter Eleven—Hydraulic Workover (Snubbing) Operation. In H. Crumpton (Ed.), *Well Control for Completions and Interventions* (pp. 567–632). Gulf Professional Publishing. https://doi.org/10.1016/B978-0-08-100196-7.00011-7

Crumpton, H. (2018). Chapter Thirteen—Subsea Completion and Intervention Riser Systems. In H. Crumpton (Ed.), *Well Control for Completions and Interventions* (pp. 681–721). Gulf Professional Publishing. https://doi.org/10.1016/B978-0-08-100196-7.00013-0

Earle, S. (2019). *Physical Geology—2nd Edition*. BCcampus. https://opentextbc.ca/physicalgeology2ed/

Eckle, P., & Burgherr, P. (2013). Bayesian Data Analysis of Severe Fatal Accident Risk in the Oil Chain. *Risk Analysis*, *33*(1), 146–160. https://doi.org/10.1111/j.1539-6924.2012.01848.x

Eklund, R. L., Knapp, L. C., Sandifer, P. A., & Colwell, R. C. (2019). Oil Spills and Human Health: Contributions of the Gulf of Mexico Research Initiative. *GeoHealth*, *3*(12), 391–406. https://doi.org/10.1029/2019GH000217

Enerijiofi, K. E. (2021). Chapter 19 - Bioremediation of environmental contaminants: A sustainable alternative to environmental management. In G. Saxena, V. Kumar, & M. P. Shah (Eds.), *Bioremediation for Environmental Sustainability* (pp. 461–480). Elsevier. https://doi.org/10.1016/B978-0-12-820524-2.00019-5

Dudek, E., Krzykowska-Piotrowska, K., & Siergiejczyk, M. (2020). Risk Management in (air) transport with exemplary risk analysis based on the tolerability matrix. *Transport Problems*, *15*, 143–156. https://doi.org/10.21307/tp-2020-027

Duvillard, P.-A., Ravanel, L., Schoeneich, P., Deline, P., Marcer, M., & Magnin, F. (2021). Qualitative risk assessment and strategies for infrastructure on permafrost in the French Alps. *Cold Regions Science and Technology*, *189*, 103311. https://doi.org/10.1016/j.coldregions.2021.103311

Fan, H., Deng, S., Ren, W., Duan, X., Cui, C., & Yang, J. (2017). A New Calculation Method of Dynamic Kill Fluid Density Variation during Deep Water Drilling. *Mathematical Problems in Engineering*, *2017*, e9642917. https://doi.org/10.1155/2017/9642917

Farrell, A., & Brandt, A. (2006). Risks of the Oil Transition. Environmental Research Letters - ENVIRON RES LETT, 1. https://doi.org/10.1088/1748-9326/1/1/014004

Fink, J. (Ed.). (2015). Chapter 1—Drilling muds. In *Petroleum Engineer's Guide to Oil Field Chemicals and Fluids (Second Edition)* (pp. 1–61). Gulf Professional Publishing. https://doi.org/10.1016/B978-0-12-803734-8.00001-1

Fraser, D., Lindley, R., Moore, D., & Vander Staak, M. (2014, October 27). *Early Kick Detection Methods and Technologies*. SPE Annual Technical Conference and Exhibition. https://doi.org/10.2118/170756-MS

Frink, P. (2006). Managed pressure drilling—What's in a name? *MANAGED PRESSURE DRILLING*, 3.

Furfari, S. (2016). Energy efficiency of engines and appliances for transport on land, water, and in air. *Ambio*, *45*(Suppl 1), 63–68. https://doi.org/10.1007/s13280-015-0734-9

Gad, S. C. (2005). Kerosene. In P. Wexler (Ed.), *Encyclopedia of Toxicology (Second Edition)* (pp. 664–665). Elsevier. https://doi.org/10.1016/B0-12-369400-0/00549-4

Gilbert, D. (2015, April 19). Oil Rigs' Biggest Risk: Human Error. *Wall Street Journal*. https://www.wsj.com/articles/rig-safety-five-years-after-gulf-spill-1429475868

Grayson, B., & Gans, A. H. (2012, March). Closed loop circulating systems enhance well control and efficiency with precise wellbore monitoring and management capabilities. In *SPE/IADC Managed Pressure Drilling and Underbalanced Operations Conference and Exhibition*. OnePetro.

Haghshenas, A., Paknejad, A. S., Rehm, B., Consultant, D., & Schubert, J. (2008). CHAPTER ONE - The Why and Basic Principles of Managed Well-Bore Pressure. In B. Rehm, J. Schubert, A. Haghshenas, A. S. Paknejad, & J. Hughes (Eds.), Managed Pressure Drilling (pp. 1–38). Gulf Publishing Company. https://doi.org/10.1016/B978-1-933762-24-1.50007-3

Holand, P. (1996). *Offshore Blowouts, Causes and Trends*. https://www.osti.gov/etdeweb/biblio/481374

Hsieh, L. (2013, March 18). Improving well control calls for continuous evaluation of barriers. Drilling Contractor. https://www.drillingcontractor.org/improving-well-control-calls-for-continuous-evaluation-of-barriers-21463

Hsu, W.-K., Tseng, C.-P., Chiang, W.-L., & Chen, C.-W. (2012). Risk and uncertainty analysis in the planning stages of a risk decision-making process. Natural Hazards, 61(3), 1355–1365. https://doi.org/10.1007/s11069-011-0032-1

Huo, F., Li, A., Zhao, X., Ren, W., Dong, H., & Yang, J. (2021). Novel lithology identification method for drilling cuttings under PDC bit condition. *Journal of Petroleum Science and Engineering*, *205*, 108898. https://doi.org/10.1016/j.petrol.2021.108898

Hustrulid, W. Andrew (2020, January 21). *Prospecting*. *Encyclopedia Britannica*. https://www.britannica.com/technology/prospecting-mining

IEA. (2016). *International Energy Outlook 2016*. 290.

Ibrahim, A. A., Sheikh, R., & Rachid, G. (2016, November 7). *HSE Governance Concerns and Challenges in a Potential Oil and Gas Producer*. Abu Dhabi International Petroleum Exhibition & Conference. https://doi.org/10.2118/183128-MS

Islam, M. R., & Hossain, M. E. (2021). Chapter 2—State-of-the-art of drilling. In M. R. Islam & M. E. Hossain (Eds.), *Drilling Engineering* (pp. 17–178). Gulf

Professional Publishing. https://doi.org/10.1016/B978-0-12-820193-0.00002-2

John, S., & F, M. (2016, May 2). *Macondo and Bardolino: Two Case Studies of the Human Factors of Kick Detection Prior to a Blowout*. Offshore Technology Conference. https://doi.org/10.4043/26906-MS

Khakzad, N., Khakzad, S., & Khan, F. (2014). Probabilistic risk assessment of major accidents: Application to offshore blowouts in the Gulf of Mexico. *Natural Hazards*, *74*(3), 1759–1771. https://doi.org/10.1007/s11069-014-1271-8

Khakzad, N., Khan, F., & Amyotte, P. (2013). Dynamic Safety analysis of process systems by mapping bow-tie into Bayesian network. *Process Safety and Environmental Protection*, *91*, 46–53. https://doi.org/10.1016/j.psep.2012.01.005

Khakzad, N., Khan, F., & Amyotte, P. (2013). Quantitative risk analysis of offshore drilling operations: A Bayesian approach. Safety Science, 57, 108–117. https://doi.org/10.1016/j.ssci.2013.01.022

Khakzad, N., Khan, F., & Paltrinieri, N. (2014). On the application of near accident data to risk analysis of major accidents. *Reliability Engineering & System Safety*, *126*, 116–125. https://doi.org/10.1016/j.ress.2014.01.015

Khan, F., Abimbola, M., & Hashemi, S. J. (2018). *Blowout Risk in Drilling and Production. Encyclopedia of Maritime and Offshore Engineering, 1–19.* doi:10.1002/9781118476406.emoe356

Kleijunas, J. T., Burdsall, H. H., Denitto, G. A., Eglitis, A., Haugen, D. A., Haverty, M., & Micales, J. A. (2006). Pest risk assessment of the importation into the United States of unprocessed Pinus logs and chips from Australia.

Kloeden, P. E., Platen, E., & Schurz, H. (1994). Background on Probability and Statistics. In P. E. Kloeden, E. Platen, & H. Schurz (Eds.), *Numerical Solution of SDE Through Computer Experiments* (pp. 1–61). Springer. https://doi.org/10.1007/978-3-642-57913-4_1

Kroh, K., & Conathan, M. (2012, April 19). *The Lasting Impact of Deepwater Horizon*. Center for American Progress. https://www.americanprogress.org/issues/green/news/2012/04/19/11409/the-lasting-impact-of-deepwater-horizon/

Lage, A. C. V. M., Nakagawa, E. Y., & Cordovil, A. G. D. P. (1994, April 27). *Well Control Procedures in Deep Water*. SPE Latin America/Caribbean Petroleum Engineering Conference. https://doi.org/10.2118/26952-MS

Lynch, W. (2021, February 19). *Fault tree analysis (FTA)—Secret weapon for root cause analysis*. Medium. https://warren2lynch.medium.com/fault-tree-analysis-fta-secret-weapon-for-root-cause-analysis-5f7a1f458d02

Ma, Z. (2011). Uncertainty Analysis in Reservoir Characterization and Management. *AAPG Memoir 96*, *96*, 1–15.

Malika, M., Khochmane, L., Bouzaouit, A., & Bennis, O. (2017). Transformation of fault tree into Bayesian Network Methodology for Fault Diagnosis. *Mechanics*, *23*(6), 891–899. https://doi.org/10.5755/j01.mech.23.6.17281

Mawejje, J., & Bategeka, L. (2013, December). *Accelerating growth and maintaining intergenerational equity using oil resources in Uganda*. Library of Congress, Washington, D.C. 20540 USA. https://www.loc.gov/item/2019352344/

Mishra, T. (2019, October 21). *Blowout preventer's (BOP) and its importance in environmental safety*. https://www.trenchlesspedia.com/blowout-preventers-bop-and-its-importance-in-environmental-safety/2/4512

Mitchell, R. L., Miska, S. Z., & Aadnoy, B. S. (2011). *Fundamentals of drilling engineering*. Society of Petroleum Engineers.

Mori, J., Chester, F. M., Eguchi, N., & Toczko, S. (2012). *Integrated Ocean Drilling Program Expedition 343 Scientific Prospectus*. Integrated Ocean Drilling Program. https://doi.org/10.2204/iodp.sp.343.2012

Nadjafi, M., Farsi, M., & Jabbari Khamnei, H. (2016). Reliability analysis of multi-state emergency detection system using simulation approach based on fuzzy failure rate. *International Journal of System Assurance Engineering and Management*, *8*. https://doi.org/10.1007/s13198-016-0563-7

National Academy of Engineering & National Research Council. (2012). *Macondo Well Deepwater Horizon Blowout: Lessons for Improving Offshore Drilling Safety*. The National Academies Press. https://doi.org/10.17226/13273

Ng, F. (2007). *Risk assessment, kick modelling mitigate well control risk events in complex operations*. 4.

Nwankwo, C. D., Arewa, A. O., Theophilus, S. C., & Esenowo, V. N. (2021). Analysis of accidents caused by human factors in the oil and gas industry using the HFACS-OGI framework. *International Journal of Occupational Safety and Ergonomics*, *0*(0), 1–13. https://doi.org/10.1080/10803548.2021.1916238

Obesogenicity. (n.d.) *Segen's Medical Dictionary*. (2011). Retrieved June 26 2021 from https://medical-dictionary.thefreedictionary.com/obesogenicity

O'Neill, M., Summers, E., & Collins (Firm : Bishopbriggs, S. (2015). *Collins English dictionary*.

OREDA: Offshore reliability data handbook. (2002). Høvik, Norway: OREDA Participants.

OSHA. (n.d.). *Oil and Gas Extraction—Overview | Occupational Safety and Health Administration*. Retrieved May 4, 2021, from https://www.osha.gov/oil-and-gas-extraction

Pal, I., & Ghosh, T. (2018). *Natural Hazards Management in Asia*. https://doi.org/10.4135/9789353280604

Rathnayaka, S., Khan, F., & Amayotte, P. (2013). Accident modeling and risk assessment framework for safety critical decision-making: application to deepwater drilling operation. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of risk and reliability, 227(1), 86-105.

Rausand, M., & Hoyland, A. (2003, December). *System Reliability Theory: Models, Statistical Methods, and Applications, 2nd Edition | Wiley*. Wiley.Com. https://www.wiley.com/en-us/System+Reliability+Theory%3A+Models%2C+Statistical+Methods%2C+and+Applications%2C+2nd+Edition-p-9780471471332

Raza, M. A., Salehi, S., Ghazal, S., Ybarra, V. T., Mehdi Naqvi, S. A., Cokely, E. T., & Teodoriu, C. (2019). Situational awareness measurement in a simulation-based training framework for offshore well control operations. *Journal of Loss Prevention in the Process Industries*, *62*, 103921. https://doi.org/10.1016/j.jlp.2019.103921

Razavi, S., & Gupta, H. V. (2015). What do we mean by sensitivity analysis? The need for comprehensive characterization of "global" sensitivity in Earth and Environmental systems models. *Water Resources Research*, *51*(5), 3070–3092. https://doi.org/10.1002/2014WR016527

Refsdal, A., Solhaug, B., & Stølen, K. (2015). Risk Evaluation. In *SpringerBriefs in Computer Science* (pp. 91–96). https://doi.org/10.1007/978-3-319-23570-7_9

Rocha, L. A. S., Junqueira, P., & Roque, J. L. (2003, May 5). Overcoming Deep and Ultra Deepwater Drilling Challenges. Offshore Technology Conference. https://doi.org/10.4043/15233-MS

Rosenfeld, P. E., & Feng, L. G. H. (2011). 5—The Petroleum Industry. In P. E. Rosenfeld & L. G. H. Feng (Eds.), *Risks of Hazardous Wastes* (pp. 57–71). William Andrew Publishing. https://doi.org/10.1016/B978-1-4377-7842-7.00005-2

Rr. (2008). In *Cambridge School Dictionary* (Cambridge Schools Dictionary, pp. 607-653). Cambridge: Cambridge University Press. doi:10.1017/CBO9780511667183.021

Saha, S. K. (2010). *Impact Assessment of Environmental consequences on a blowout at Chhatak-2 (Tengratila) Gas Field, Bangladesh*.

Shoar, S., Zarandi, H., & Nasirzadeh, F. (2019). Quantitative assessment of risks on construction projects using fault tree analysis with hybrid uncertainties. Construction Innovation. https://doi.org/10.1108/CI-07-2018-0057

Silvianita, S., Khamidi, Dr. M. F., & Kurian, V. J. (2011). Critical review of a risk assessment method and its applications. 2011 International Conference on Financial Management and Economics, 83–87.

Singh, B. (2019, June 8). Offshore Well Drilling: A General Overview. *Marine Insight*. https://www.marineinsight.com/offshore/offshore-well-drilling-a-general-overview/

Sklet, S. (2006). *Safety Barriers on Oil and Gas Platforms. Means to Prevent Hydrocarbon Releases*.

Speight, J. G. (2020). Chapter 12—Petrochemicals. In J. G. Speight (Ed.), *Handbook of Industrial Hydrocarbon Processes (Second Edition)* (pp. 511–552). Gulf Professional Publishing. https://doi.org/10.1016/B978-0-12-809923-0.00012-6

St. John, M. F. "Macondo and Bardolino: Two Case Studies of the Human Factors of Kick Detection Prior to a Blowout." Paper presented at the Offshore Technology Conference, Houston, Texas, USA, May 2016. doi: https://doi.org/10.4043/26906-MS

Tabassum, A., Sabatini, R., & Gardi, A. (2019). *Probabilistic Safety Assessment for UAS Separation Assurance and Collision Avoidance Systems*. *6*, 19. https://doi.org/10.3390/aerospace6020019

Tauxe, R. V., & Besser, J. M. (2014). Public Health Measures: Surveillance of Foodborne Diseases. In Y. Motarjemi (Ed.), Encyclopedia of Food Safety (pp. 77–88). Academic Press. https://doi.org/10.1016/B978-0-12-378612-8.00328-0

Tom, R. (2012). *Integrated Operations in the Oil and Gas Industry: Sustainability and Capability Development: Sustainability and Capability Development*. IGI Global.

Torstad, E. (2010). Closed loop systems reduce the probability of loss of well control. *DNV presentation*, *September*, *30*.

Velez, P. K., Liles, C. O., & Satterlee, K. (1995, May 1). An Overview of API RP 75 and RP 14J. Offshore Technology Conference. https://doi.org/10.4043/7732-MS

Vinnem, J. E., Hestad, J. A., Kvaløy, J. T., & Skogdalen, J. E. (2010). Analysis of root causes of major hazard precursors (hydrocarbon leaks) in the Norwegian offshore petroleum industry. *Reliability Engineering & System Safety*, *95*(11), 1142–1153. https://doi.org/10.1016/j.ress.2010.06.020

Walsh, M. (2020, February 20). Develop a “Probabilistic” Approach to Managing Uncertainty. Harvard Business Review. https://hbr.org/2020/02/develop-a-probabilistic-approach-to-managing-uncertainty

Whittaker, A. (1985). Swab and Surge. In A. Whittaker (Ed.), *Theory and Applications of Drilling Fluid Hydraulics* (pp. 111–118). Springer Netherlands. https://doi.org/10.1007/978-94-009-5303-1_8

Yoe, C. (2016). Principles of Risk Analysis: Decision Making Under Uncertainty. In Principles of Risk Analysis: Decision Making Under Uncertainty (p. 552). https://doi.org/10.1201/9780429021121

Zhu, H., Wang, S., Li, Z., Yan, X., Song, Z., & Gong, P. (2019). A new high-precision timely monitoring and metering system for early kick and loss. *Natural Gas Industry B*, *6*(4), 394–398. https://doi.org/10.1016/j.ngib.2019.01.015

APPENDICES

A. Failure description and probabilities of FTA elements

Data in this study are mainly obtained from three different resources. These are, (1) Khakzad et al., (2013), Abimbola et al., (2014), and Abimbola et al., (2016). Some these data are already presented in a detailed fault trees, so data in the following tables may represent an evaluated part of the fault trees.

Table 9.1: Kick occurrence probabilities (Khakzad et al.,2013)[28]

Basic Event	**Probability [-]**	**Description**
K_01	5.40E-02	Surge
K_02	5.40E-02	Swab
K_03	3.00E-05	Gas pocket/shallow gas
K_04	1.50E-01	Abnormal pressured zone
K_05	2.00E-03	Inadequate hole fill-up
K_06	1.00E-02	Annular losses
K_07	1.00E-02	Riser rupture
K_08	2.00E-04	Failure in density measurement equipment
K_09	7.00E-03	Gas-cut mud
K_10	3.00E-02	Operator failure in mixing right density
K_11	2.50E-03	Temperature effects
K_12	2.06E-02	Circulation system Failure

[28] Khakzad et al. (2013) extracts probability data from (OREDA, 2002), which provides statistical failure rates on a 10^6 (a million) service hour basis, and (Bercha, 1978), which we could not access it.

Table 9.2: Kick detection (Khakzad et al.,2013)

Basic Event	Probability [-]	Description
KD 01	1.40E-04	Failure of tank level indicator (float system)
KD 02	1.00E-01	Failure to notice tank level changes
KD 03	1.10E-04	Failure of flowmeter
KD 04	5.00E-03	Failure to notice flowmeter
KD 05	1.65E-02	Failure of pressure gage
KD 06	1.00E-01	Failure to notice pressure change
KD 07	2.00E-04	Failure of displacement sensor
KD 08	5.00E-02	Failure to notice change in penetration rate
KD 09	2.00E-04	Failure of gas detector
KD 10	5.00E-02	Failure of operator to notice gas
KD 11	2.00E-04	Failure of density meter (column-type)
KD 12	5.00E-03	Failure to notice density changes
KD 13	2.00E-04	Failure of resistivity sensor
KD 14	5.00E-03	Failure to notice conductivity changes

Table 9.3: Casing failure probabilities (Abimbola et al.,2016)[29]

Basic Event	Probability[-]	Description
CSG 01	5.40E-02	Swab
CSG 02	5.40E-02	Surge
CSG 03	1.10E-03	MPD system failure
CSG 04	3.97E-02	Casing collapse
CSG 05	1.14E-01	Wellhead failure
CSG 06	3.97E-02	Casing Coupling
CSG 07	1.00E-03	Logging tool failure (casing inspection log)
CSG 08	1.00E-02	Inaccurate interpretation of log
CSG 09	2.50E-02	Pressure tests failure
CSG 10	1.00E-02	Inaccurate interpretation of test results

[29] Abimbola et al. (2016) extracts probability data from (Torstad, 2010, Grayson and Gans, 2012, Khakzad et al., 2013, Abimbola et al., 2014, Rathnayaka et al., 2013).

Table 9.4: Cement failure probabilities (Abimbola et al.,2016)

Basic Event	Probability [-]	Description
C 01	2.00E-02	Poor slurry formulation
C 02	3.60E-06	Inadequate mud cake removal
C 03	2.00E-01	Formation fluid (contaminating cement slurry)
C 04	1.00E-01	Drilling mud (contaminating cement slurry)
C 05	3.30E-02	Inadequate use of pre-flush/spacer
C 06	2.00E-02	Poor slurry formulation
C 07	1.50E-02	Operator error
C 08	1.00E-02	Insufficient cement slurry volume
C 09	1.00E-04	Wrong/no placement of wiper plugs
C 10	6.25E-06	U-tubing effect
C 11	1.65E-07	Slurry loss
C 12	1.10E-02	Temperature log failure
C 13	1.60E-02	Inadequate mud removal
C 14	6.66E-03	Filtration Loss
C 15	4.00E-02	Pumping system failure
C 16	1.50E-02	Operator error
C 17	1.10E-03	MPD system failure
C 18	1.21E-04	Evaluation Log Failure
C 19	2.50E-02	Pressure tests failure
C 20	1.00E-02	Inaccurate interpretation pressure test

Table 9.5: Circulation system failure probabilities (Abimbola et al.,2014)[30]

Basic Event	Probability [-]	Description
Circ_01	1.00E-03	Pump control failure
Circ_02	1.85E-05	Pump Failure
Circ_03	2.50E-07	Power Failure
Circ_04	1.30E-04	ESD valve failure
Circ_05	3.60E-04	Choke/kill lines
Circ_06	1.30E-04	non-return valve failure
Circ_07	2.20E-04	Failsafe valves
Circ_08	4.51E-03	Choke manifold
Circ_09	5.00E-04	Drill pipe
Circ_10	1.00E-03	float shoe
Circ_11	5.10E-04	Riser
Circ_12	1.40E-04	Failure of tank level indicator
Circ_13	2.00E-04	Pump stroke
Circ_14	1.10E-04	Failure of flowmeter/Mud flow indicator
Circ_15	1.00E-05	Wellhead connector
Circ_16	1.00E-05	Wellhead housing damage
Circ_17	8.43E-03	Casing
Circ_18	3.91E-03	Cementing

[30] Abimbola et al. (2014) extracts probability data from (Bercha, 1978, Khakzad et al., 2013, OREDA, 2002)

Table 9.6: Blowout preventor failure probabilities (Abimbola et al.,2014)

Basic Event	Probability [-]	Description
B_01	4.00E-05	Rotating control device (RCD)
B_02	3.65E-03	Diverter
B_03	4.30E-03	Snubbing
B_04	2.60E-04	Lower annular preventer
B_05	2.50E-05	Lower pipe ram
B_06	2.50E-05	Middle pipe ram
B_07	2.50E-05	Upper/Variable pipe ram
B_08	1.00E-05	Blind shear ram
B_09	1.00E-06	Casing shear ram
B_10	2.60E-04	Upper annular preventer
B_11	1.00E-05	Upper flexible joint
B_12	1.00E-05	Lower flexible joint
B_13	1.00E-05	LMRP connector
B_14	2.00E-03	Operator error
B_15	1.00E-10	Accumulator unit
B_16	6.35E-04	Control system

B. Bayesian Network Models

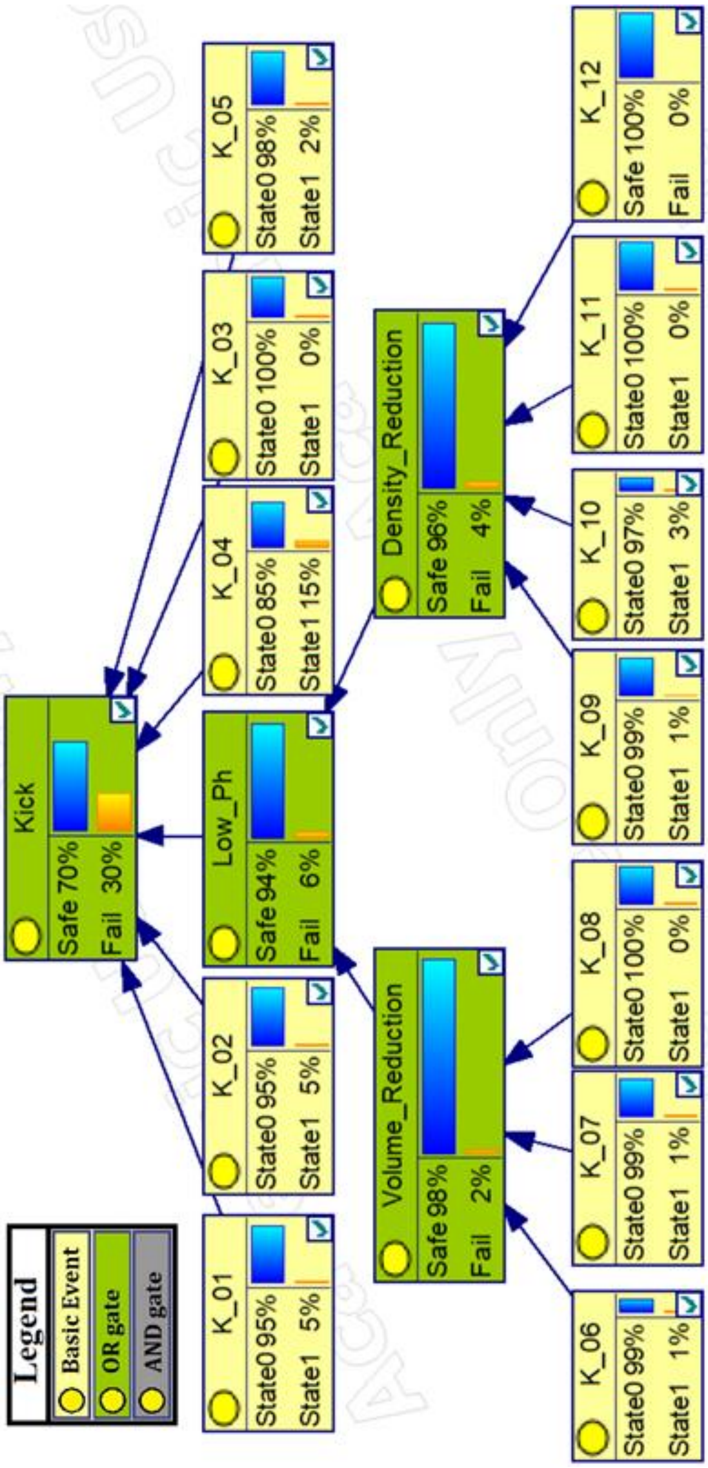


Figure 9.1: BN showing kick initiation probability

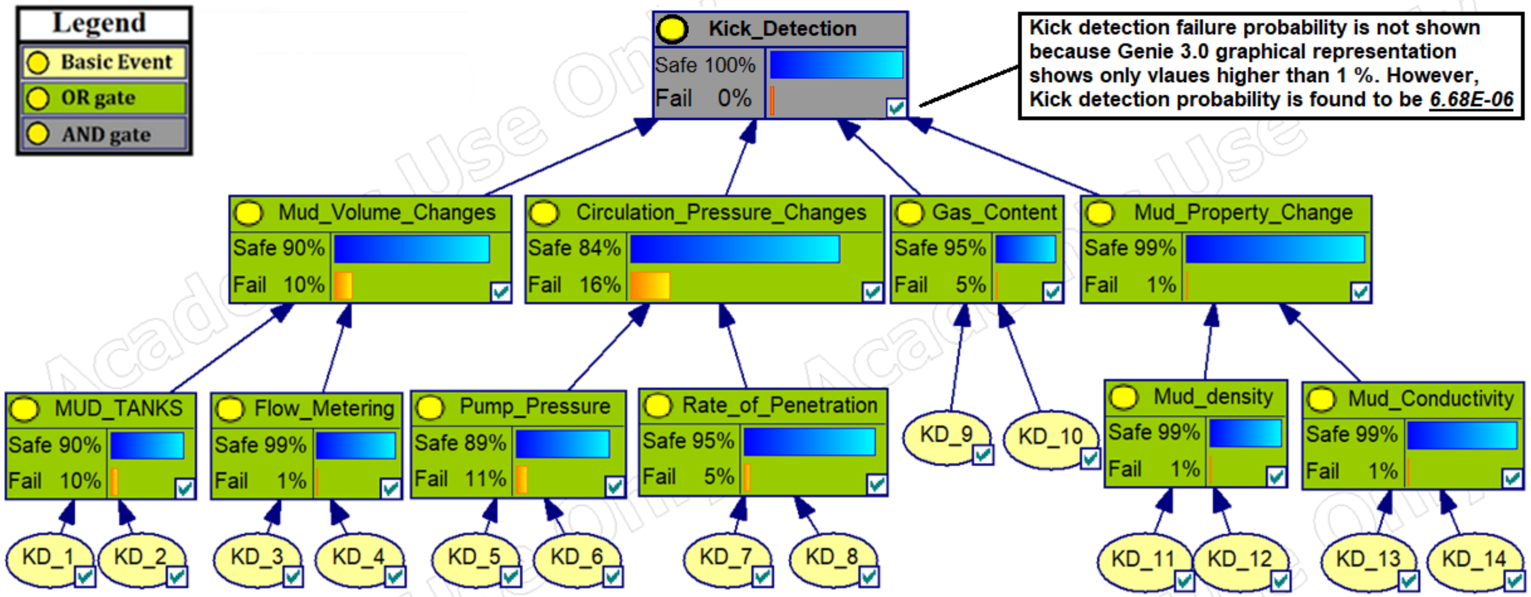


Figure 9.2: BN showing default failure probability of kick detection system

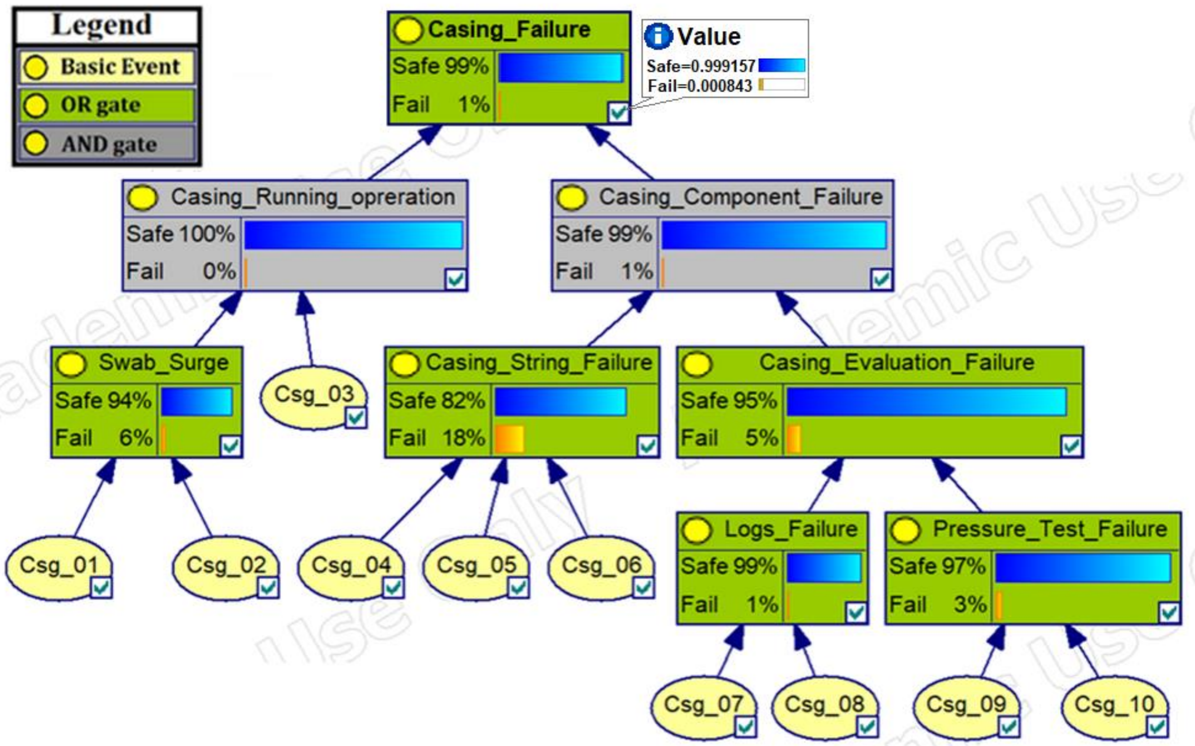


Figure 9.3: BN showing default failure probability of casing

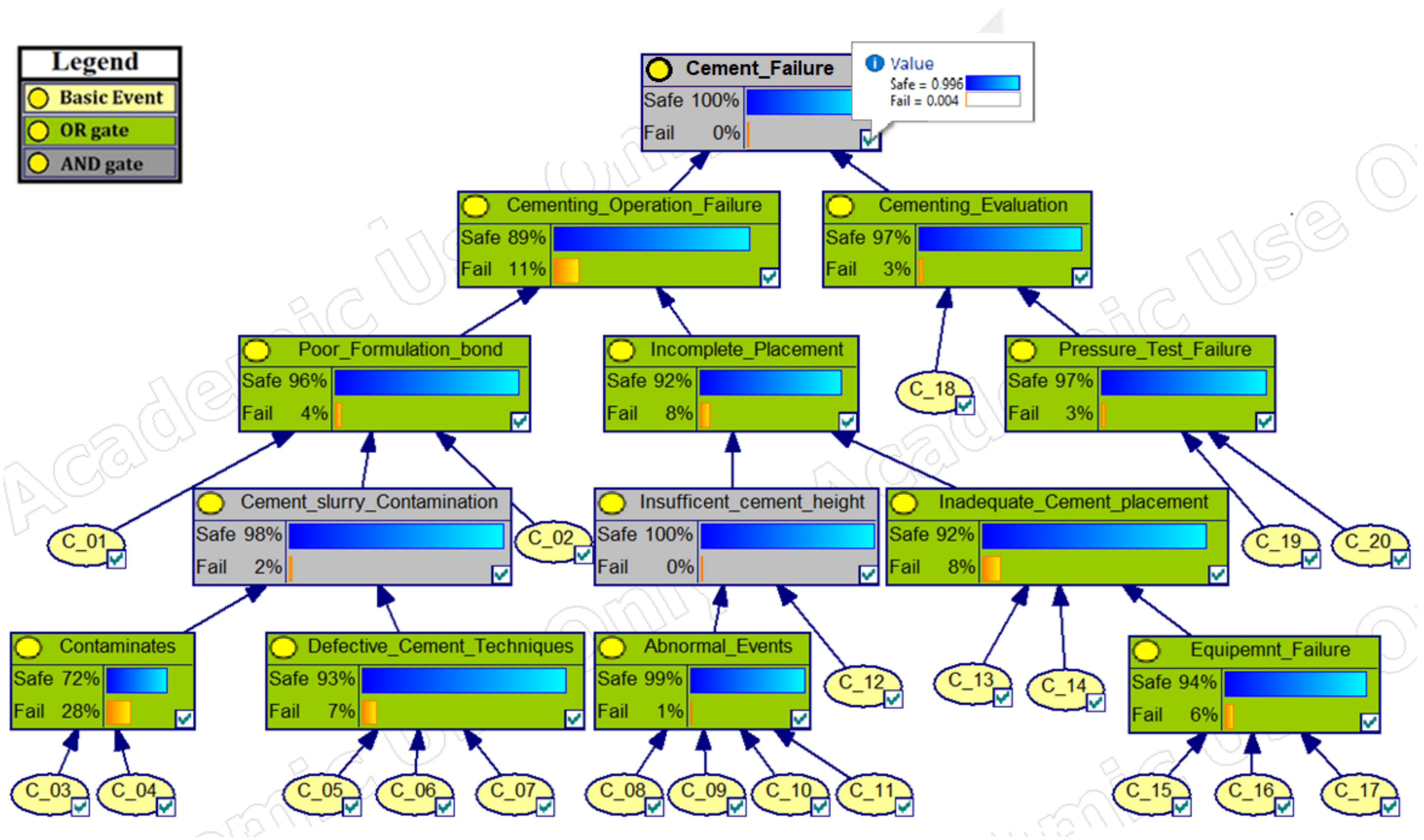


Figure 9.4: BN showing default failure probability of cement operation

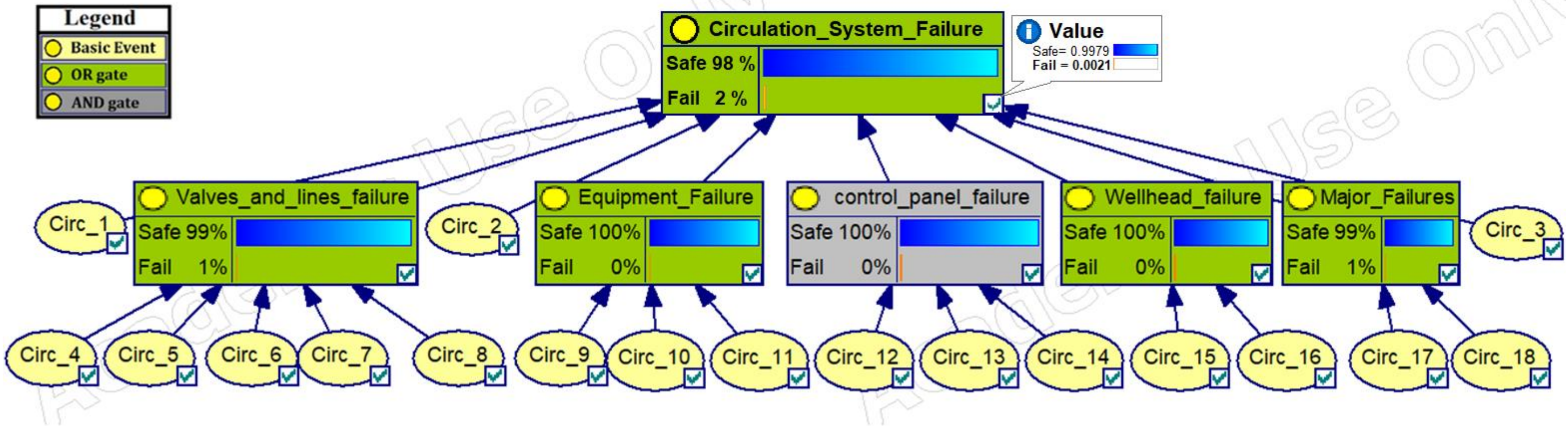


Figure 9.5: BN showing default failure probability of circulation system

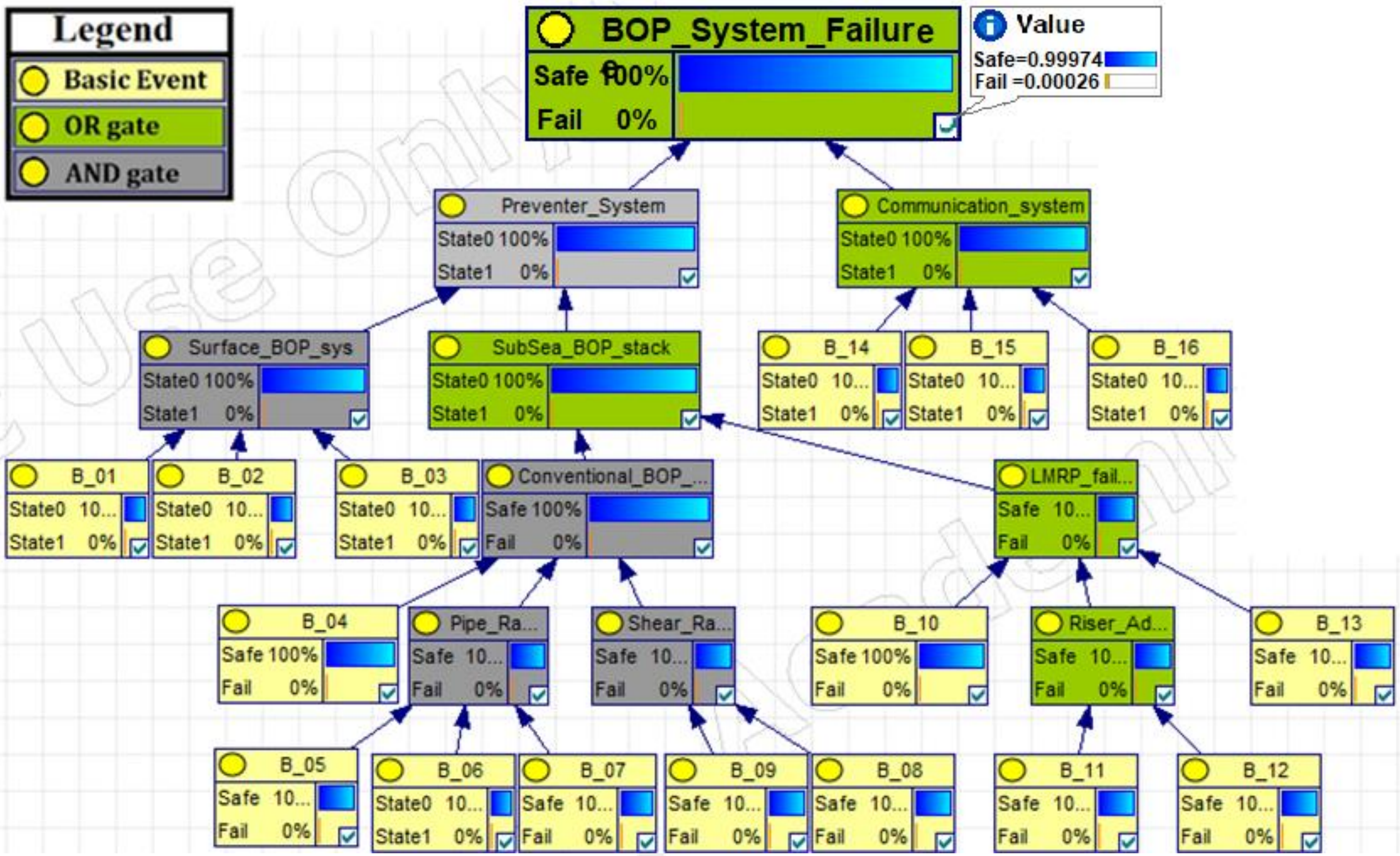
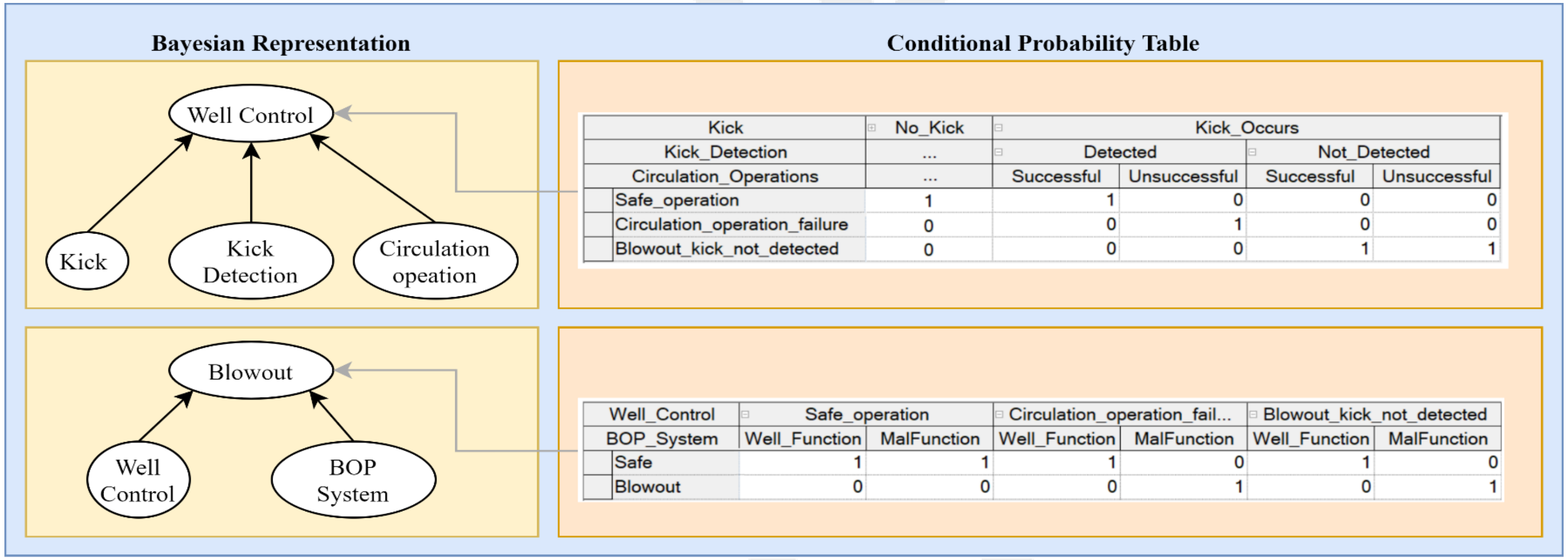


Figure 9.6: BN showing default failure probability of BOP system



Kick	No_Kick	Kick_Occurs			
Kick_Detection	...	Detected		Not_Detected	
Circulation_Operations	...	Successful	Unsuccessful	Successful	Unsuccessful
Safe_operation	1	1	0	0	0
Circulation_operation_failure	0	0	1	0	0
Blowout_kick_not_detected	0	0	0	1	1

Well_Control	Safe_operation		Circulation_operation_fail...		Blowout_kick_not_detected	
BOP_System	Well_Function	MalFunction	Well_Function	MalFunction	Well_Function	MalFunction
Safe	1	1	1	0	1	0
Blowout	0	0	0	1	0	1

Figure 9.7: MSG mapping to Bayesian Network

C. Importance Measures

Birnbaum Importance is the probability that system is in a state where a particular component is critical (if fails, the system will fail). Calculated as in Eq 9.1.

$$\mathrm{BI} = \mathrm{P(TE|P(BEi)} = 1) - \mathrm{P(TE|P(BEi)} = 0) \qquad \text{Eq 9.1}$$

Where,

BI=P(TE|P(BEi)=1): the probability of top event given that BEi is failing

BI=P(TE|P(BEi)=0): the probability of top event given that BEi is safe

Criticality Importance is probability Basic event ‘i’ has occurred and is critical to the system failure. Calculated as in Eq 9.1.

$$\mathrm{CI} = \frac{\mathrm{BI}}{P(BEi)} \qquad \text{Eq 9.2}$$

Where, P(BEi): probability of the components of analysis interest (BEi) failure

C.1 Ranking issue in DI calculations

The Diagnostic importance is ranking the elements according to their failure probability. When probabilities are extremely large such as (C3=0.1 and C4=0.2), compared to the rest, which have a failure probability less than 0.01, DI may rank elements incorrectly due to the nature of AND and OR gates. In Table 9.7, we compare CI, DI, and RRW for the data in section 8.1.4 (cement fault tree).

Table 9.7: Comparison of CI, DI, and RRW illustrating DI ranking issue

CI		***DI***		***RRW***	
C 03	9.66E-02	**C 04**	**0.139**	C 03	1.107
C 16	1.21E-01	C 13	0.143	C 16	1.137
C 13	1.29E-01	C 01	0.178	C 13	1.148
C 01	1.62E-01	**C 03**	**0.277**	C 01	1.193

C.2 Ranking issue of BI in Blowout calculations

The BI ranks the most contributing elements to blowout based on the systems contribution, i.e., the BOP system is ranked as most contributor with its element to show that BOP failure can lead to a direct blowout, circulation system as the second most contributor, kick detection system as the third, and kick as the last.

Table 9.8: BI ranking issue

Element	BI [-]	Element	BI [-]
B 14	6.168254E-03	KD 02	7.734337E-04
B 16	6.159829E-03	KD 06	7.734313E-04
Circ 17	7.800036E-04	KD 14	7.734306E-04
Circ 08	7.769313E-04	KD 12	7.734306E-04
Circ 18	7.764637E-04	KD 08	7.734292E-04
Circ 01	7.742015E-04	KD 05	7.734279E-04
Circ 10	7.742015E-04	K 04	4.466042E-05
Circ 11	7.738220E-04	K 01	4.012851E-05
Circ 09	7.738142E-04	K 02	4.012426E-05
Circ 05	7.737059E-04	K 10	3.913565E-05
Circ 07	7.735975E-04	K 12	3.875913E-05
KD 10	7.734340E-04		