DEVELOPING LEADING INDICATORS FRAMEWORK FOR PREDICTING KICKS AND PREVENTING BLOWOUTS

A Dissertation

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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May 2019

Major Subject: Chemical Engineering

ABSTRACT

Due to the operational complexities of drilling, completion and well intervention activities, it is often quite challenging to predict a potential blowout scenario timely and efficiently. In drilling operations, blowouts are usually preceded by kicks and predicting kicks early is crucial for regaining control of the well and preventing major incident. Kicks and blowouts happen due to failure of well control barriers and leading indicators could be very effective in identify vulnerabilities in such systems. For assessing integrity of well control barriers with appropriate sets of leading indicators, a robust framework was proposed and sets of probabilistic models were developed in this work. By following a systematic cause-based methodology proposed in this work, sets of leading indicators were identified for monitoring barrier performances while drilling, completion and well intervention activities. Analyses of Montara and Deepwater Horizon blowout incidents demonstrated applicability of leading indicators framework in revealing system weaknesses prior to major incidents. Using the real-time kick indicators, decision support algorithms were developed in this work which would help to understand a kick progression scenario and actions required to confirm a kick. Leading indicators-based probabilistic models were developed for evaluating the relative importance of different organizational and operational factors, and assessing their impacts on the key causal factors of well control barrier failure events. These models were constructed for hydrostatic head failure events which can be caused by abnormal pore pressure and swabbing, and cementing failure during drilling and completion activities. An integrated model for assessing well control failure events during wireline operations was also constructed. These models represent realistic scenario of barrier health and could be very useful for determining barrier failure probabilities from observed data. Addition to these, efficiencies of kick detection parameters to detect potential influxes and factors impacting their performances can also be assessed with the developed models. These functions enable informed decision-making for preventing kicks and blowouts while drilling or intervening a well, by providing real-time status of the well control system.

DEDICATION

To,

My loving wife Sadia Islam and our beloved son Arash Ekram

My dad EkramUllah Parvez and my mom Masuda Parvez

My mentor Dr. M. Sam Mannan

ACKNOWLEDGEMENTS

I would like to express my heartiest gratitude to my mentor and my advisor Dr. M. Sam Mannan. Dr. Mannan was the person who inspired me to pursue a career in process safety and work to make the industry safer. He taught me to be a better researcher, he motivated me to aim higher, he trained me how to face difficult challenges and gave me to tools to overcome those. I am grateful to him for giving me such a wonderful opportunity of joining his group. I am also greatly thankful to my current committee chair and my mentor Dr. M. Nazmul Karim for his constant help and guidance thorough out my PhD program. He motivated me to undertake the daunting challenge of doing a PhD and has been a great support since then. I truly appreciate Dr. Karim's and Dr. Mannan's tremendous effort towards my career and life.

I would also like to thank my co-advisor Dr. A. Rashid Hasan for his time and guidance to understand the technical issues of my research and helping me to solve them. Special thanks to my committee members Dr. James Holste and Dr. Mahmoud El-Halwagi for their constant support and guidance. I would love to express my gratitude toward my past team leader Dr. Ray Mentzer and current team leader Dr. Delphine Laboureur for their incomparable help in every steps of my graduate study. I also want to thank Dr. Jerome Schubert for sharing his expert opinion on drilling-related issues and Dr. Hans Pasman for his time to help me understand usage and applicability of Bayesian network. I would like to extend my thanks to Mr. Mike O'Connor, Captain James Pettigrew, the

members of MKOPSC steering committee and technical advisory committee, MKOPSC staff, and my research colleagues.

No word is enough to express my gratitude to my family. I am thankful to my father for believing in me more than I do in myself and for giving me courage and support, and my mother who made countless sacrifices to make me the person I am today. And finally, I am grateful to my wife for always being there for me and supporting me to achieve my goals. I could not make this happen without their help and motivation.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a dissertation committee consisting of Dr. M. Sam Mannan [past advisor], Dr. M. Nazmul Karim [current advisor], Dr. James Holste and Dr. Mahmoud El-Halwagi of the Artie McFerrin Department of Chemical Engineering and Dr. A. Rashid Hasan [co-advisor] of the Harold Vance Department of Petroleum Engineering.

The work conducted for the dissertation was completed by the student independently.

Funding Sources

This graduate study was supported and sponsored by the Mary Kay O’Connor Process Safety Center (MKOPSC), Texas A&M University, College Station, Texas.

NOMENCLATURE

API	American Petroleum Institute
BN	Bayesian Network
BSEE	Bureau of Safety and Environmental Enforcement
BOEM	Bureau of Ocean Energy Management
BOP	Blowout Preventer
ECD	Equivalent Circulating Density
EKD	Early Kick Detection
IChemE	Institution of Chemical Engineers
IOGP	International Oil and Gas Producers
MPD	Managed Pressure Drilling
OBD	Over Balanced Drilling
PCE	Pressure Control Equipment
PCCC	Pressure Containing anti-Corrosion Caps
SCSSV	Surface Controlled Sub-Surface Safety Valve
UBD	Under Balanced Drilling

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

1. INTRODUCTION*

Blowouts are considered to be the most notorious events in oil and gas industry which have caused hundreds of fatalities and injuries, millions of barrels of oil release to the environment and billions of dollars of property damage over the last few decades. As per US Bureau of Safety and Environmental Enforcement (BSEE) and US Bureau of Ocean Energy Management (BOEM) statistics, from 1980-2011 a total of 77 blowouts and 32 major well release events were reported from 31,574 drilled wells in US Gulf of Mexico (BOEM, 2014). The picture is almost similar in other parts of the world. Many catastrophic events resulted from uncontrolled well releases while drilling or other well operations. For instance, in recent times, the Deepwater Horizon blowout in the US Gulf of Mexico caused 11 fatalities (Marsh, 2014) and about 4.9 million barrels (U.S. Coast Guard, 2011) of oil spill in 2010 and the Montara blowout in Western Australia caused about 30,000 barrels (Koh, 2012) of crude oil spill in 2009. But incidents like Deepwater Horizon and Montara do not just happen due to a single failure, rather they usually result from a complex combination of deficiencies that coincide – technical or operational failure, inadequate safeguards or safety management systems, and human factors. Focus

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[*] Tamim, N., Laboureur, D. M., Mentzer, R. A., Hasan, A. R., & Mannan, M. S. (2017). A framework for developing leading indicators for offshore drillwell blowout incidents. *Process Safety and Environmental Protection*, *106*, 256-262. Copyright 2017 Institution of Chemical Engineers. Published by Elsevier B.V. Part of this section and figures are reprinted with permission from Elsevier Ltd.

[*] Tamim, N., Liu, R., Mannan, M.S. and Hasan, A.R. (2017). Understanding the physics of blowouts and their prevention approaches. Journal of Environmental Solutions for Oil, Gas, and Mining, 3(1), pp.1-18. Part of this section (Section 1.1.2) and figures are reprinted with permission from College Publishing.

on these factors can reveal any existing inconsistencies in the system that may initiate a blowout event.

This work is dedicated to studying the scope and methodology of developing leading indicators-based framework primarily for offshore drilling and well operations focusing on kicks and blowout incidents. Flow of uncontrolled well fluids into a wellbore and to the environment is called a blowout. As blowouts are low frequency-high consequence events, lagging indicators cannot offer a good measure because having a low past incident rate or low rate of gas kick events does not eliminate or help predict the chances of a future uncontrolled gas kick resulting in a blowout. Again, drilling is a complex multi-stakeholder process and organizational factors play a crucial role in risk management and acceptance which can only be taken into consideration with appropriate sets of leading indicators. Thus, it is utmost necessary to have comprehensive sets of leading indicators to constantly monitor the performances of well control systems while drilling or other well operations from both operational and organizational perspectives.

1.1. Thesis Organization

To understand kicks and blowout phenomenon and their prevention approaches, a comprehensive literature review was conducted which has been presented in Section 2. Current practices for developing and using leading indicators have also been analyzed and discussed in the same section. Based on the review presented in Section 2, a research roadmap was developed for solving the existing challenges of developing a robust program for predicting kicks and preventing blowouts by monitoring and managing well control barriers effectively. In Section 4, a working definition of leading indicators has been proposed with detailed categorization. Inspired from the aviation practices, a step-by-step cause-based approach was proposed and applied to identify potential sets of leading indicators for well control barrier elements. A comprehensive study of past blowout incidents has also been conducted to assess the applicability and usefulness of the proposed framework and the results have been included in Section 4. In the following section, leading indicators are further analyzed for their critical use in decision making and risk assessment purposes. With the real-time leading indicators, a couple of decision support algorithms were developed to demonstrate kick progression scenarios effectively. Major contributing causal factors for barrier failures and kick initiating events were identified by conducting fault-tree analysis for barrier failure events. Several Bayesian network models were developed correlating different categories of leading indicators for different well operations which have been presented and discussed in Section 5. Due to scarcity of leading indicators data, probability distributions for leading indicators were assumed based on incident findings and expert judgement. Section 6 contains a brief discussion on the major findings of this research work.

1.2. Major Contributions

Major contributions of this research work include but not limited to –

1. Developed a robust framework with clear definitions and categorization of leading indicators, that can be applied to any well operations including drilling, completion and well intervention.
2. Proposed a step-by-step caused-based methodology for identifying appropriate sets of leading indicators for monitoring health and performances of well control barrier system and identifying system weaknesses that need to be improved for preventing major well control events.
3. Identified comprehensive sets of leading indicators for drilling, completion and wireline operations that can be adopted by the industry. For drilling operations, primary focus was made on kick prediction and prevention, rather than blowout prevention. So, the program could identify problems in the system early enough when the risk is comparatively low and upsets are manageable.
4. Constructed probabilistic models to assess possibilities of encountering well control barrier failure events for drilling and completion activities, by integrating leading indicators information with real-time process observables. One of the major advantages of these models over the traditional risk assessment models is, the developed leading indicators-based probabilistic models can represent health and status of the well control programs/systems by using data obtained from the same system. Since this analysis is system-

specific, it can provide more realistic information on well control barrier failure probabilities.

5. One inherent advantage of Bayesian Network is its ability to perform both predictive and diagnostic analysis, which can be effectively utilized with the proposed models for designing effective well control program and constantly monitoring its performance.

1.3. Introduction to Well Operations and Well Control

1.3.1. Well Drilling and Completion

Wells are drilled for discovering petroleum reservoirs and producing oil and gas. When the purpose is to explore or discover potential reservoir, the drilling is called wildcat/exploration drilling. These are the first wells drilled with information from seismic surveys and nearby reservoirs (if available). If the result of wildcat drilling is promising, then appraisal wells can be drilled to obtain more information on the reservoir and its productivity. If considered economically viable, development wells are drilled for producing oil and gas from the reservoir/s. Seismic surveys and geologic studies are conducted prior to any drilling operations in order to obtain information on potential reservoirs and to determine the best possible location for drilling.

Drilling fluids or muds are integral part of well drilling process. They are added and circulated through the wellbore to facilitate drilling operations. While drilling a well, a constant flow of drilling fluid is maintained which has multiple critical functions including cuttings transport, cooling, support drillstring/casing weight and most importantly control subsurface pressure to prevent influxes from the reservoir. Based on mud component/phases drilling fluids can be divided into three major groups – water-based (WB) fluids, oil-based (OB) fluids and pneumatic fluids.

Based on the location of the reservoirs, wells can be drilled vertically or directionally. Drilling processes can further be categorized based on drilling pressure margin or applied bottom-hole/wellbore pressure –

1. Conventional: Overbalanced drilling
2. Unconventional: Managed pressure drilling (MPD), Underbalanced drilling (UBD)

Difference between conventional/overbalanced and unconventional/managed pressure drilling can be describe with the pressure profile presented in Figure 1. In conventional drilling, the wellbore/bottom-hole pressure are always kept significantly above the formation/pore pressure to reduce the possibilities of an influx. On the other hand, in unconventional drilling, the wellbore pressure is precisely controlled with a set of equipment and is kept very close to the formation pressure or sometimes even below the formation pressure. This helps to improve drilling efficiency, reduce cost and minimize probabilities of damaging the reservoir. Managed pressure drilling (MPD) is an example of unconventional drilling which is defined as "*an adaptive drilling method used to* *precisely control the annular pressure throughout a wellbore"*[1]. Applied backpressure or Constant Bottomhole Pressure (CBHP) MPD is one of the most common types of MPD system. In general, MPD system consists of Rotating Control Device (RCD) to provide a seal between the pipe and the annulus and a backpressure choke to pressurize the annular fluid. These set of equipment is considered to be a part of the well control primary barrier while drilling.

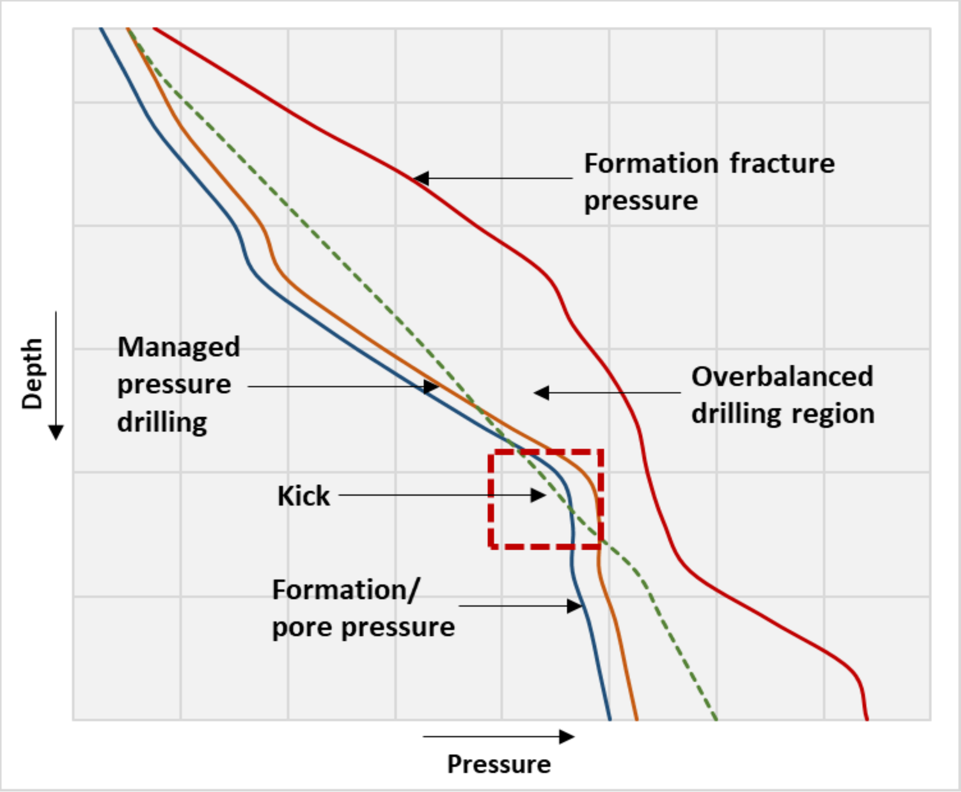

Figure 1 Pressure profile for overbalanced and managed pressure drilling

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[1] Schlumberger Oilfield Glossary. URL: https://www.glossary.oilfield.slb.com/en/Terms/m/managed_pressure_drilling.aspx

Well completion is the stage between well drilling and production operations. The purpose of well completion is to prepare a drilled well for production or injection. Typical steps of well completions include casing, cementing, perforating, gravel packing and installation of sub-surface valves and production trees. Completions can be divided into two groups – reservoir completion and upper completion. In reservoir completion, a connection is made with the reservoir and the well. And in upper completion the reservoir and well are connected to the surface facility.

1.3.2. Well Intervention/Workover

Well intervention or workover activities can be defined as well maintenance or surveillance operations that are performed on existing producing wells. The objectives include well stimulation to increase production, repair/modify downhole equipment, cleaning or collecting downhole information. Wireline/slickline, coiled tubing, hydraulic workover, snubbing are some examples of well intervention operations. A major difference between well drilling and intervention/workover is - in workover operations a pressurized producing zone is always present, where in drilling this zone is exposed for a short period of time. For this reason, well control planning is quite different in well workover operations when compared to drilling. This is discussed in detail in the next section. Well intervention operations require specific set of equipment and tools. Usually, a set of equipment are assembled and mounted on the top of the wellhead valve tree for intervening a well. For example, some major equipment that are used to facilitate wireline operations include stuffing box, lubricator, wireline, winch, grease injection system, hydraulic control pump and quick union.

1.3.3. Kicks and Blowouts

Flow of uncontrolled formation fluids (oil, gas, water or mixture) from a well is called a blowout. Kicks are precursors to blowout and flow of fluids from reservoirs to wellbore in presence of drilling fluid is called a kick. While drilling through a porous and permeable formations, if wellbore pressure drops below the pore pressure a kick or influx can happen (Figure 2).

Gas kicks behave differently in different types of drilling fluids based on their solubility. Solubility of hydrocarbon gases are very small in water-based drilling fluids compared to the oil-based drilling fluids. That makes a big difference in kick detection and well control planning. For oil-based drilling muds, if gas enters the wellbore, it mostly remains dissolved in drilling fluids due to high pressure. But with drilling fluid travelling upwards at a lower pressure zone, gas gradually starts to come out of the solution and starts expanding. This is a major challenge for early detection of gas kicks and thus it is very important to pick any weak signals or differential parameters to allow maximum time for kick handling.

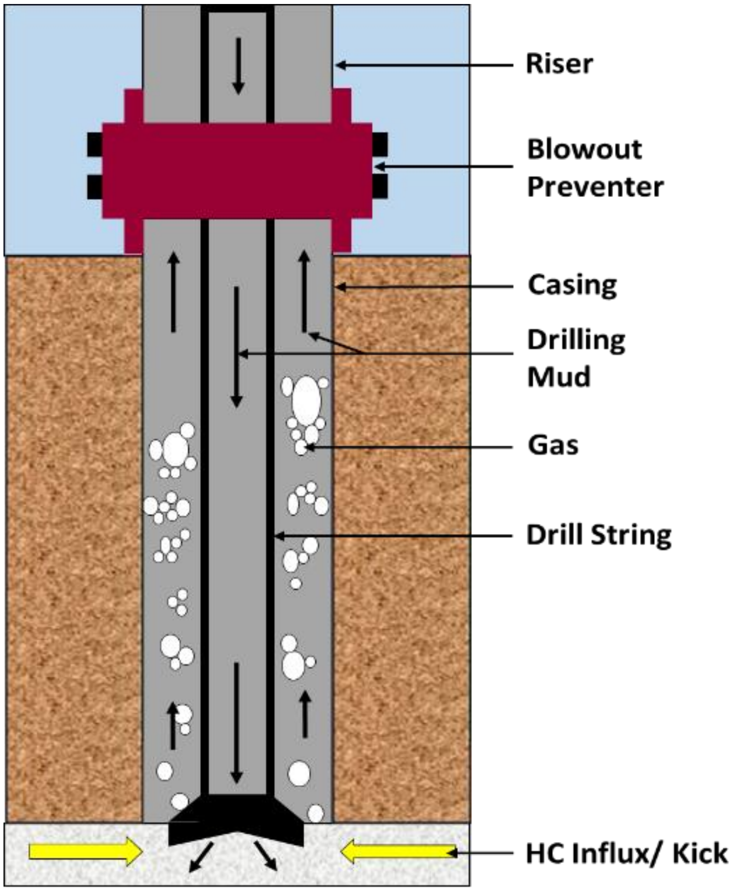

Figure 2 Gas kick while drilling

1.3.4. Well Control Barriers

To prevent uncontrolled influx of hydrocarbons, different ‘barriers’ are designed and used during different well activities (*e.g.*, drilling, tripping out, running casing, completion, workover). Barriers can be primarily divided into two categories – engineering/operational and organizational. For drilling or other well activities, different levels of barriers and actions to prevent blowouts can be represented with Figure 3.

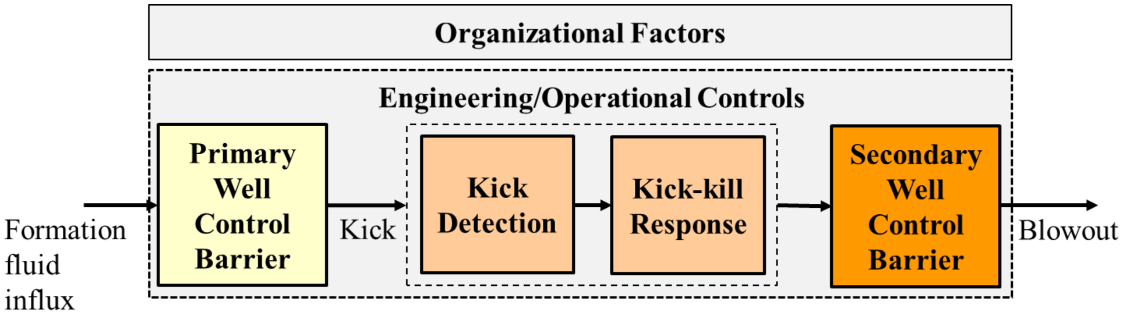

Figure 3 Well control barriers
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Organizational elements are the governing factors for engineering controls that are implemented to prevent blowouts. Key organizational factors include hazard analysis, risk assessment, barrier management systems, effective drilling practices and procedures, well control responses, training and competency, experience, effective management-of-change policies and procedures, robust audit and inspection programs. Well-designed risk indicators/safety metrics program can provide valuable information on overall organizational safety performances – which is one of objectives of this research study.

Different regulations, standards and literatures categorize and characterize barrier elements differently. As per the NORSOK standard (2004), well control barrier system includes primary and secondary well barriers, well barrier elements and/or common well barrier elements. The primary and secondary well barriers should be independent and available during all well activities and operations to ensure that no single failure of well barriers could lead to the uncontrolled wellbore fluid flow event. For conventional drilling, the primary barrier usually refers to the hydrostatic pressure provided by the drilling mud, and the secondary barrier could include a variety of equipment, such as the BOP, wellhead, casing, tubing, and drilling string safety valve. Barriers can also be categorized as dynamic barriers for drilling phase and static barriers for production phase (Holland, 1997). But regardless of different terminologies, it is established that during different well activities, at least two independent and tested well control barriers must be in place. NORSOK Standard (2004) requires two independent well barriers to be present during all well activities and operations. BSEE Well Control Rule (2015) also states the requirement of two independent and tested well control barriers prior to any well activities including BOP removal, negative pressure test, well interruption and others. In general, these two well barriers are termed as primary and secondary well control barriers. The drilling mud or hydrostatic head while drilling and the barrier closest to the reservoir (*i.e.*, Surface Controlled Sub-Surface Safety Valve (SCSSV)) for producing well are usually considered as primary well control barriers. BOP shear ram while drilling or servicing and any mechanical valve above SCSSV can serve as secondary well control barriers. Again, barrier elements can differ based on drilling technologies as well. For instance, in MPD, hydrostatic head may not always be greater that the formation pressure due to narrow mud pressure window and MPD pressure control equipment (PCE) serves as a barrier under those situations.

Failure in primary well control barrier may cause oil and gas influx into wellbore and kicks. The next step in blowout prevention is kick detection and kick killing operations, failures in that would require secondary barrier to be activated. Blowout may result if secondary barrier fails to cut the influx and seal the wellbore. Organizational factors govern the efficiency of each of the elements to prevent blowout. Potential primary and secondary well control barriers for different well activities have been briefly summarized in Table 1.

Table 1 Well control barriers for different phases of drilling and well activities

Well Control Barriers					
Engineering/Operational					**Organizational**
Drilling		*Testing/ Completion*	*Operations*	*Workover/ Servicing*	
Overbalanced / Traditional	*Managed Pressure Drilling*				
Primary Barriers					▪ Hazard Analysis ▪ Risk Assessment ▪ Training and Competency ▪ Inspection and Audit ▪ Drilling practices and procedure ▪ Barrier Management System ▪ Well Control Response ▪ Management of Change
▪ Hydrostatic head/ mud column	▪ Hydrostatic head/ mud column ▪ MPD Pressure Control Equipment	▪ Hydrostatic head/ mud column ▪ Cement ▪ Well test string/liner (for testing)	▪ Casing Cement ▪ Production packer ▪ Subsurface Safety Valve – SCSSV, Storm Choke	▪ Casing Cement ▪ Production packer ▪ Subsurface Safety Valve – SCSSV, Storm Choke ▪ Stuffing box/ Grease head	
Secondary Barriers					
▪ Cement ▪ Casing/ liner ▪ Blowout Preventer ▪ Plugs and packers	▪ Cement ▪ Casing/ liner ▪ Blowout Preventer ▪ Plugs and packers ▪ MPD Pressure Control Equipment	▪ Cement ▪ Casing/ liner ▪ Blowout Preventer ▪ Plugs and packers ▪ Wellhead	▪ Wellhead/ X-mass tree – Surface Safety Valves ▪ Casing/ liner ▪ Tubing hanger	▪ Wireline BOP ▪ Wellhead/ X-mass tree – Surface Safety Valves ▪ Casing/ liner ▪ Tubing hanger	

In majority of the drilling operations hydrostatic head is considered to be the primary well control barrier and failure of this causes kicks. Thus, it is very crucial to monitor integrity of this barrier as from here most of the well control issues start and many of them can lead to blowouts. This study focuses primarily on kick prediction and prevention so majority of the analysis is planned to be conducted for monitoring the integrity of primary well control barriers.

1.4. Introduction to Leading and Lagging Indicators

Different organization use process safety metrics or risk indicators to evaluate and benchmark their day to day safety performances. Historically, companies have been using lagging indicators, *i.e.*, the total recordable incident rate (TRIR), lost time incident rate (LTIR), number of fatalities or injuries in general, to monitor and track organizational safety performances. But these are mostly personal safety measures and provide very little or no picture at all on overall process safety performances. So, industry started to consider leading indicators which are proactive or predictive measures and offer a closer look into the operational and organizational safety culture. Necessity of having a workable set of process safety indicators came into discussion particularly after the Texas City refinery explosion in 2005 where the Baker panel report (Baker *et al.*, 2007) recommended to establish leading and lagging process safety indicators to help prevent such incidents. Offshore drilling and well activities (*e.g.*, workover, wireline jobs etc.), being very complex and high-risk operations, can similarly be benefitted from implementation of well-specified leading indicators for early prediction of potential upsets.

A well control event can be represented with the leading to lagging transitional arrow diagram presented in Figure 4. Originally, Wang *et al.* (2013) proposed a similar leading-lagging synthesis scale for general process industry, which was modified for describing drilling operations in this work.

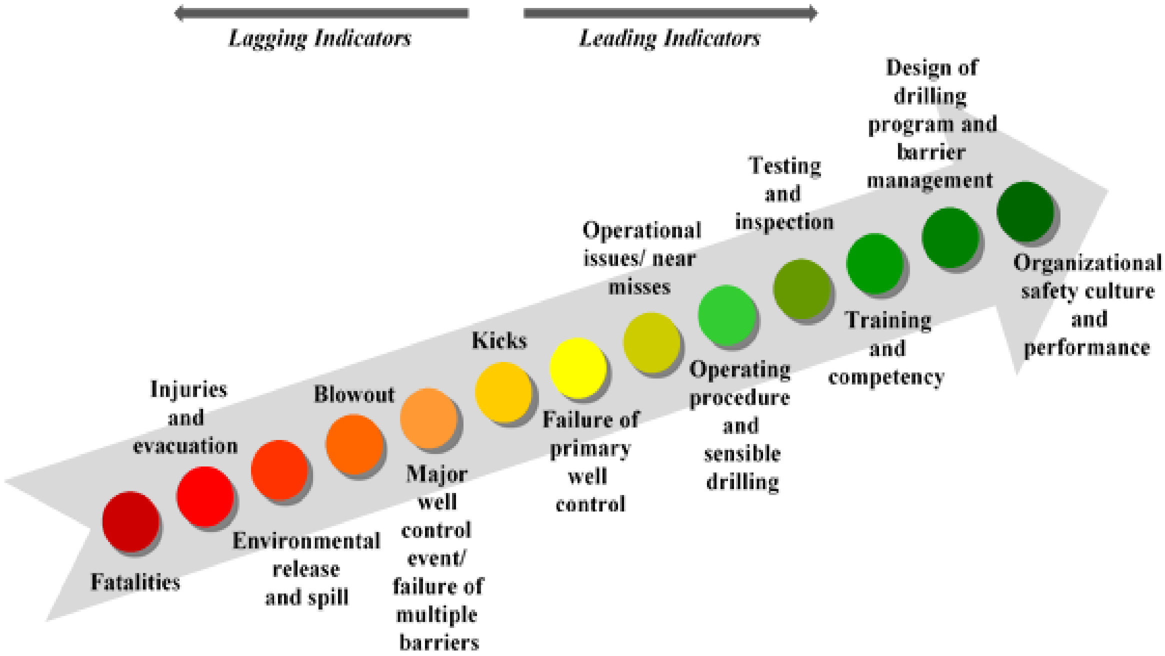

Figure 4 Transition from lagging to leading indicators in drilling
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For blowout incidents, fatalities/injuries/environmental releases are considered to be the most lagging events. On the other hand; training, barrier management, well design and overall organizational safety culture are amongst the most leading events. Events like kicks, failure of a primary barrier, or near-misses lie in a transition zone and they can be considered either as leading or lagging indicators based on the context.

2. LITERATURE REVIEW[**]

2.1. Well Control

As discussed in Section 1, well control is a process or system to keep flow of pressurized hydrocarbons within a safety envelope and operational control. Well control program is different for different phases of drilling and well operations. Hydrostatic head applied by the circulating drilling fluids, cementing and blowout preventer (BOP) are considered to be the major well control barriers to prevent unwanted hydrocarbon influxes. Early kick detection is also very critical for allowing maximum possible time to regain control of a flowing well and minimizing chances of major well control events. Many works have been done to improve barrier performances and kick detection capabilities which have been briefly discussed in this section.

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[*] Tamim, N., Laboureur, D. M., Mentzer, R. A., Hasan, A. R., & Mannan, M. S. (2017). A framework for developing leading indicators for offshore drillwell blowout incidents. *Process Safety and Environmental Protection*, *106*, 256-262. Copyright 2017 Institution of Chemical Engineers. Published by Elsevier B.V. Part of this section is reprinted with permission from Elsevier Ltd.

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2.1.1. Well Control Barriers

In conventional drilling, drilling fluid (mud) is considered as the primary well control barrier. The mud program is designed to maintain a hydrostatic head greater than the formation/pore pressure to prevent influxes but lower than the formation fracture pressure. Besides maintaining appropriate hydrostatic head, the functions of drilling fluid also include cutting transportation, cooling and lubricating the drill bit, maintaining wellbore stability, and fluid loss control. Therefore, designing a proper and efficient drilling fluid with safe density margin is very critical for drilling performances and well control activities. For underbalanced or managed pressure drilling, a combination of pressure and flow control equipment work together with drilling mud as primary well control barrier. For underbalanced condition the pressure control assembly comprises of sealing mechanism around drill pipe, choke manifold and non-return valves.

Cements can also serve as primary barrier in many circumstances (*e.g.*, well completion, testing, servicing, production phase). Cementing failure can cause severe well integrity issues and cements can fail due to several reasons which were identified and studied in various literature – formation damage/caving, casing centralization issue, inadequate placement, inadequate bonding or de-bonding of cements with casing and rocks, shrinkage, contamination, and mechanical/thermal stress (Teodoriu, *et al.*, 2013). Many studies have been performed to evaluate cement integrity in high pressure high temperature (HPHT) conditions using advanced imaging technologies, stress/strain analysis, and ultrasonic measurements. Still researchers are analyzing different aspects of cementing including development of new materials or additives, accurate placement techniques, bonding and sealing mechanisms, smart evaluation, and testing methodologies.

Blowout preventer (BOP) is considered to be the most crucial and critical secondary well control barrier. BOP consists of two major types of preventers – annular preventers and ram-type preventers. Annular preventers generally seal around objects, such as drill pipe, casing or well servicing tools; whereas ram-type preventers offer more diverse application. Pipe rams are designed to seal around a pipe, blind rams are used to seal an open hole and shear rams have cutting edges which can cut through the drill pipe and isolate the wellbore completely. Control module, choke manifold, choke lines, and accumulators are some other significant elements of blowout preventer system. BOP reliability is a major issue which drives the advancements in BOP control, operation and testing technologies. After the Deepwater Horizon blowout, many researchers have conducted work in the space of BOP performance and safety upgrades. Baugh *et al.* (2011) discussed some key BOP safety upgrades which are depth compensated accumulators, shearable drill collars, improved Remotely Operated Vehicle (ROV) dynamic positioning, constant tension reels and so forth. However comprehensive studies are required in many critical areas which include drill pipe shearing capacity, well compatibility, ROV capabilities, reliable equipment monitoring and piston positioning system, and smart control module.

2.1.2. Causes of Kicks

There are many factors which can cause bottomhole pressure to drop below the formation pressure and flow of formation fluids into the wellbore. Some of the major causes of kicks include –

- Abnormal pore pressure

  Drilling into an unanticipated abnormally pore pressure zone can lead to a kick. Abnormal pore pressure can be caused by different geographical issues including faulting and uplifting, salt formations, anticlinal structures or trapped pressures.

- Insufficient drilling fluid density

  This can cause reduction in hydrostatic head applied by the fluid column and well to go underbalance. Fluid density can be reduced intentionally (underbalanced drilling, fluid change), unintentionally (excessive dilution, heavy rains in the pits, temperature expansion) or due to operational error (miscalculation).

- Failure to keep hole full

  While tripping out of a hole, drilling fluid needs to be added to replace the drill pipes to prevent reduction in hydrostatic head. In case of failure to replace the displaced drill pipes, bottomhole pressure can drop below the formation pressure leading to a kick.

- Swabbing

  Swabbing refers to a piston effect in wellbore which can happen while tripping drill pipes out of the hole. If the drill pipe assembly is pulled too fast out of the hole and drilling fluids fail to fill it effectively, a void can be created downhole causing an influx from the reservoir.

- Lost circulation

  If hydrostatic pressure applied by the drilling fluid circulation exceeds the fracture pressure of an exposed formation while drilling, lost circulation can occur leading to a decrease in height of the fluid column. Failure to compensate the loss can result in kick.

- Cement failure

  Kicks can happen due to cement failure as well. Annular flow after primary cement job is a phenomenon which can happen due to improper placement/settling of cements. Cementing can fail and gas can migrate for different reasons, *e.g.*, cement contamination, shrinkage, inadequate placement, inadequate wait time.

2.1.3. Kick Detection

Kick detection is undoubtedly one of the most critical factors in blowout prevention. Typically, blowouts are preceded by kicks, so early kick detection allows more time to 'kill' a kick before it runs out of control. Traditionally, differential flow rate, pit volume, wellbore annulus pressure, mud pump stroke variation, drilling break, and mud properties have been used as some of the accepted kick indicators. But these parameters need an influx to trigger action and there could be false alarms as well. Based on the data accuracy and interpretation, and drillers' experience, the volume and position of kick can vary which largely impact the kick response and mitigation process. There are many challenges of using these conventional techniques for detecting kicks, for example –

- Inaccuracy or delay in kick detection due to gas solubility, fluid compressibility, wellbore elasticity or breathing, variable thermal conditions (BSEE, 2015)
- For offshore operations, vessel movement and wave motion can introduce additional difficulties

As per various investigation report, the Deepwater Horizon blowout incident demonstrated the shortcomings of conventional kick detection system as the kick, which eventually escalated to a blowout, went unnoticed for a certain period of time. Unfortunately kick detection technology has not made much progress compared to drilling technology, which constitutes a major well control threat. Many works are being done to develop advanced kick detection methodologies and researchers are continuously seeking for robust kick detection systems for different drilling processes. For example, one of the recent works suggested that, accuracy of the conventional kick detection methodology can be significantly improved by adding high accuracy mass flow meter, *e.g.*, Coriolis flow meter, in the outflow line (Fraser *et al.*, 2014). Mass flow measurements instead of volumetric flow can provide better calculation of pit gain. Johnson *et al.* (2014) discussed different aspects of kick detection and analyzed the use of conventional pit volume totalizer (PVT) system incorporating with advanced instrumentation to detect influx in managed pressure or deepwater drilling. In deepwater drilling risers can provide a very efficient platform to install pressure and temperature transmitting instruments.

Measurement while drilling (MWD) and Logging while drilling (LWD) systems are considered to be very useful tools for facing the challenges of early kick detection in unconventional wells and many researchers have developed methodologies using MWD/LWD techniques. National Energy Technology Laboratory proposed a technique of using MWD/LWD data signals with a series of filters and algorithms to monitor real-time borehole conditions (Tost *et al.*, 2016). MWD/LWD systems are consist of downhole electro-mechanical measurement tools which collect various bottomhole data (*e.g.*, pressure, temperature, flow, torque). These data can be transmitted to the surface facilities using various techniques, *e.g.*, acoustics, telemetry, ultrasonic sensors or wired drill pipe. Mud pulse telemetry is the most common data transmission tool but it has certain limitations including low data transmission rates, time lag and it requires a minimum fluid flow rate (BSEE, 2015). Use of intelligent/wired drill pipe is considered to be a potential solution to this problem, as it can transmit a large amount of data quickly to the surface facility while drilling. This technology has successfully been deployed in many rigs and it is believed that by using this technology the kick detection time can be reduced to less than half (Vajargah *et al.*, 2013).

Use of managed pressure drilling (MPD) technique can significantly improve accuracy of kick detection and efficiency of kick control. Managed pressure drilling is a closed-loop, pressurized process which offers great benefits of detecting small influxes in the system. By using advanced equipment and flow measurements, kicks can be detected very early and circulated out by increasing backpressure and/or adjusting pump flow rate [Vajargah *et al.*, 2015]. Field performances has also suggested MPD to be capable of eliminating wellbore ballooning and breathing (Fraser *et al.*, 2014). One of the biggest advantages of using MPD technique is its ability to detect small influxes in oil-based drilling fluids (Santos *et al.*, 2007), which is a big challenge for conventional drilling process. But deployment of MPD techniques can be expensive and many of the existing rigs and drilling systems are not capable of accommodating MPD technology.

Another big challenge in kick detection is detecting kicks while making connections. Mud pumps are turned off during adding a drill pipe and bottomhole pressure in the wellbore is decreased due to loss of the frictional part of the total equivalent circulating density (ECD) of drilling mud. This may cause well to kick, but the transient nature of connection related back-flow from the well can complicate kick detection process. To overcome this challenge machine learning tools was used to develop fingerprints of expected flow behavior for providing information on abnormal situations or kicks (Tarr *et al.*, 2016). Kick detection while pulling out of hole is another challenging task and these are heavily reliant on driller's experience and situational judgment.

Researchers have applied some other novel technologies to improve kick detection timing and efficiency. Bang *et al.* (1994) developed an acoustic gas kick detection system with wellhead sonar which is independent of mud circulation. They reported successful kick detection with an experiment in water and water-based drilling fluid. Later, Taherian *et al.* (2013) also proposed a kick detection method using an acoustic transducer. Another interesting method was proposed by DiFoggio *et al.* (2014) who used reflectors on the outside of bottomhole assembly to detect influx using a transducer assembly. Doria *et al.* (1997) studied the challenges of kick detection in floating drilling rig due to heavy motion and proposed a new approach for accurate mud flow measurement to detect influx.

Despite all these efforts and development, implementation of many of these technologies have still remained a big challenge due to many factors including cost, lack of adaptability, capabilities of drilling system and induced complexities.

2.1.4. Kick Control

Once a kick is detected and confirmed it is essential to shut-in the well promptly. Shut-in procedure depends on the operation being performed while taking the kick, *e.g.*, drilling, tripping, running a casing. There are two common procedure for shutting a well after receiving a kick while drilling – 'hard' shut-in and 'soft' shut-in. In the hard shut-in, the annular preventers of blowout preventer (BOP) stack are closed immediately after the mud pumps are shut down. On the other hand, in soft shut-in, the choke is operated before closing the annular preventers. For shallow kicks, instead of complete shut-in diverter system can be used to divert the flow away from the rig.

After shutting the well, proper kill method needs to be implemented to kill/control the kick. Some type of constant bottom hole pressure method is usually used to control a kick, where heavier drilling fluid is pumped into the well to circulate the formation fluid out of the system. There are different types of well control methodologies, *e.g.*, wait and weight method, driller's method, reverse circulation. In managed pressure drilling, bottomhole pressure can be quickly adjusted/increased to an overbalanced condition by making necessary adjustments to choke.

2.1.5. Well Intervention – Differences and Challenges

Well control and blowout prevention approaches are different in well drilling and intervention operations. Blowout risk is significant in workover due to many factors, in fact, more deepwater well blowouts occurred in the past during well workover than during development drilling phase (Holland, 1997). Two major issue that makes the well intervention/workover operations critical are –

- In well workover operations, pressurized producing zone is exposed and available for flow nearly 100% of the time, where in drilling the producing zone is exposed for a short period of time

- The conditions of casing and other sub-surface equipment can deteriorate over time which can be a big issue for well workover operations

Rike *et al.* (1990) identified sixteen key differences between well drilling and workover operations and suggested for having a robust well control program for well workover operations different than drilling well control program to prevent blowouts. Some of the key differences are discussed here –

- In drilling, mud filter cake makes a very effective seal against formation to prevent influx/losses. Since solids-free fluids are used during workover similar seals doesn't form and there can be continuous losses into the formation.
- During no circulation or when the pumps are stopped, any influxes/gas travel toward the surface much quicker in most of the workover fluids than drilling mud.
- The formation fracture pressure could be considerably less during well intervention/workover operations than that experienced during drilling operations due to reservoir depletion.
- Trip tanks can provide indication of kicks for drilling mud systems, but they are less reliable for solids-free workover fluids due to constant presence of producing zone and casing open at the surface.

If detected early, controlling a kick during well workover is generally less complicated when compared to drilling kicks. But if not planned carefully, some of these factors can make kick control and blowout prevention challenging in well workover operations. Low hydrostatic head, snubbing equipment failure, cement failure, kelly valve failure, wireline lubricator failure and BOP failure were found to be the major causes of blowouts in well intervention/workover operations.

2.2. Development and Application of Leading and Lagging Indicators

2.2.1. Recommended Practices and Guidelines

Several organization including the UK Health and Safety Executive (UK HSE), the American Petroleum Institute (API), the International Oil and Gas Producers (IOGP) and the Institution of Chemical Engineers (IChemE) published guidelines on developing process safety indicators for different organizations – upstream, downstream or general hazard organizations. In 2006, UK HSE published a Step-by-Step Guideline to Develop Process Safety Indicators for Major Hazard Industries (UK HSE, 2006). UK HSE defines leading indicators as active monitoring systems for operational and organizational controls placed to prevent any unwanted situation and lagging indicators as reactive measures which are the desired outcome the risk control system is designed to deliver. In this guideline the concept of dual assurance was introduced where leading and lagging indicators perform in combination in a structured and systematic way of defining each critical risk control factor.

The Centre for Chemical Process Safety (CCPS) published a guideline book on development and use of process safety metrics (CCPS, 2010) where safety metrics are defined as some observable measures and categorized into leading, lagging and near-miss metrics. Later, in 2010, ANSI/API Recommended Practice 754: Process Safety Performance Indicators for the Refining and Petrochemical Industries (API, 2010) was published. The four-tier approach of safety performance indicators was introduced with Tier 1 being the most lagging and Tier 4 being the most leading aspects of events.

Until this point, the guidelines mostly focused on downstream operations, but in 2011 IOGP published a report (456) on Recommended Practice on Key Performance Indicators (IOGP, 2011) focusing on upstream operations. The proposed framework was built based on API RP-754 and guidelines published by UK HES, CCPS and OECD (Organization for Economic Co-operation and Development). IOGP recommends using API's four-tier approach, but also provides guidance to support upstream operations and activities. Later in 2015, IChemE published a guidance document (IChemE, 2015) on leading process safety metrics for industries with hazardous activities. They developed comprehensive guidelines on selecting and tracking process safety lead metrics for six pre-classified organizational function areas, which are, knowledge and competence, engineering and design, systems and procedures, assurance, human factors and culture. Very recently, in 2016, IOGP published another report (556) (IOGP, 2016) on Process Safety – Leading key performance indicators as a supplement to report 456. This report emphasizes on API Tier-3 and Tier-4 process safety key performance indicators and includes discussion on the concepts of barrier management and monitoring using dual-assurance approach which was initially proposed by UK HSE.

All these recommended practices and guidelines are very useful in developing a safety indicators program for process plants but these are partly applicable to onshore and offshore drilling and other well operations. Some of the shortcomings in applying the existing guidelines to drilling scenarios include – primary focus on production related losses in most of the guidelines (Wilkinson, 2012), emphasis on consequence-based approach rather than cause-based approach and use of process operations focused language and concepts in general (Wilkinson, 2012).

2.2.2. Notable Works related to Drilling Operations

Few analytical works have been carried out to develop leading indicators to predict and prevent blowout incidents. One of the major works is the Trends in Risk Level in the Petroleum Activity (RNNP) project which analyzed and discussed major hazard indicators primarily for production installations. Vinnem *et al.* (2006) and Vinnem *et al.* (2010) discussed various aspects of RNNP works – identification and data collection for defined situations of hazard and incident (DSHA/DFU), development of risk model and finally development of incident and barrier indicators. Almost similar to IOGP classification, the barrier elements were classified in two categories – technical systems and human and organizational factors. This study also outlined some critical questions regarding indicator validity, for example, which are the critical elements for evaluating barrier health, is the indicators really valid for the major incidents, does the indicator actually measure what needs to be measured *etc*. The whole study was conducted based on barrier test data of only two installations while it was suggested that more extensive studies are required for assessing major incident risk for drilling operations with considering all the possible precursor events scenarios and associated barriers.

Skogdalen *et al.* (2011) suggested extension of indicators developed in the RNNP project for monitoring and evaluating safety in drilling operations. Few significant areas were identified, such as well planning, well incident, well response, status of safety critical equipment, and others, and for some areas a set of indicators were proposed for consideration. For example, low mud weight, annular losses, and swabbing can serve as incident indicators, while time lapse between incident and response, evaluation of well response action, *etc*. can serve as indicators for the area of operator well response. Oien *et al.* (2012) and Skogdalen *et al.* (2011) discussed the scope of safety indicators to prevent catastrophic blowout incidents using the Deepwater Horizon incident as a test case. The issue of cement failure, misinterpretation of negative pressure test result, delay in kick detection and subsequent well control actions and finally failure of blowout preventer (BOP) – all these were deep rooted into organizational and operational practices which could be tracked by leading risk indicators.

2.2.3. Approach of a High Reliability Organization

Despite having a completely different type of business and activities, the drilling industry has some similarities with the aviation industry in terms of major hazard and risk undertaking and mode of operations. Both industries need more focus on leading indicators as major incidents are rare but the consequences are large, and in both cases several stakeholders are involved to achieve a common goal. The latter is of great importance in drilling operations because less focus is given in the consistent interaction between different parties on a rig and this particular element came into discussion after almost every major incident.

The similarities between aviation and drilling industries regarding multi-stakeholder involvement is represented in Figure 5:

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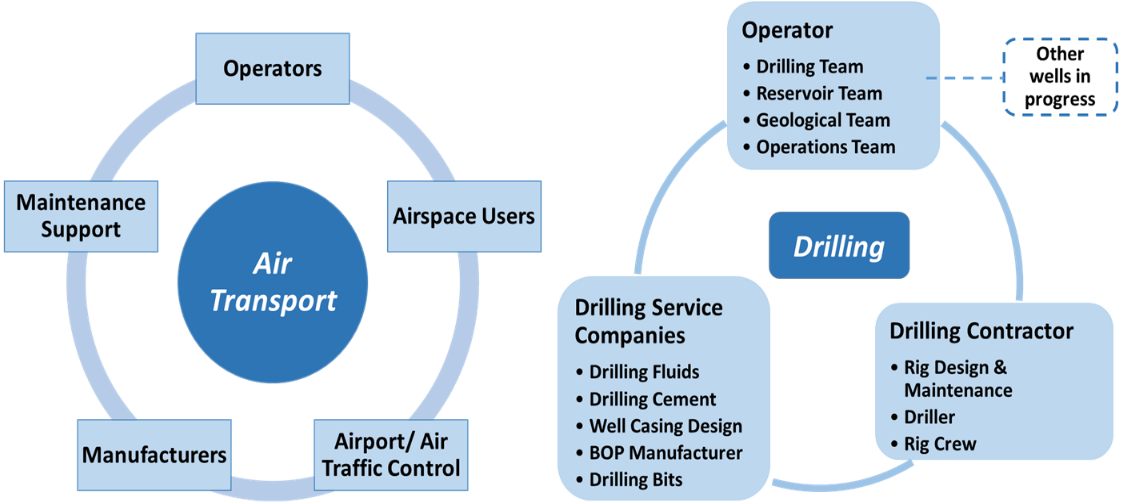

Figure 5 Multi-stakeholder involvement in aviation and drilling
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The Aviation Safety and Certification of new Operations and Systems (ASCOS) framework for developing safety performance indicators for aviation systems (Roelen *et al.*, 2014) defined indicators for four levels – technology, human, organizational and system of organizations. Where system of organizations represents the interaction and harmony among individual organizations needed to ensure safe and reliable operations.

To design and develop indicators for tracking the synchronization among the stakeholders in terms of operational performance and safety is certainly an interesting and useful concept. These indicators would allow one to monitor the interaction between different parties, *i.e.,* operators, drilling contractors and manufacturers, on a drilling rig and ensure no compromise in safety performances at organizational interfaces. They identified major causal factors which may lead to catastrophic incidents and developed indicators to track and monitor different operational and organizational factors influencing the causal elements. Aviation industry focuses more on minimizing causes and implement learnings from near-miss events to prevent major incidents.

2.3. Blowout Risk Assessment using Bayesian Network

Bayesian network (BN) is a popular probabilistic method that has been widely used for safety and risk assessment of various complex systems over the past few years. It can represent probabilistic relationships among a set of variables and allows both predictive and diagnostic analysis. One of the biggest advantages of Bayesian network is its ability to handle complexity and uncertainty. This tool is gaining popularity for assessing safety and risk of drilling operations for its flexibility and wider applications. Khan *et al.* (2017) analyzed application of different methodologies for blowout risk assessment and identified Bayesian network as one of the strongest tools as they offer following advantages –

- Capability of incorporating new information/evidence and update the prior beliefs/probabilities
- Capability to handle uncertainty, incomplete datasets, multistate variables, and complex causal relationships

Bayesian approach was used for real-time problem detection while drilling a well (Hargreaves *et al.*, 2001). This approach was found to be useful for dealing with noisy drilling data, and avoiding false alarms by modeling kick and non-kick events. Khakzad *et al.* (2013) used bow-tie and Bayesian network methods to perform quantitative risk analysis for offshore drilling operations. The research indicated the flexibility of BN tool as it can consider common cause failures and conditional probabilities and perform probability updating. Bayesian network method has also been used for assessing blowout scenarios for managed pressure drilling (MPD) and underbalanced drilling (UBD) (Abimbola *et al.*, 2015). Bow-tie models were developed for each type of drilling cases and mapped into Bayesian networks for conducting risk analysis using failure data from literature. Similar analysis was performed for casing and cementing operations of a well (Abimbola *et al.*, 2016). In another work, blowout flowcharts were converted into Bayesian networks to predict failure scenarios and potential consequences for MPD and UBD techniques (Bhandari *et al.*, 2015). Earlier, Cai *et al.* (2013) proposed a five-steps methodology for translating flowcharts into Bayesian network. Five categories of influencing factors; human, hardware, software, mechanical, and hydraulic; were modeled using Bayesian networks to assess probability of failure on demand of subsea blowout preventer. Most of the works used historical failure data obtained from various data sources for estimating failure probabilities and consequences of loss of well control events.

3. RESEARCH OBJECTIVES

3.1. Gaps and Challenges

1. As discussed in the earlier Section (2.1.2), many works have been done to detect kicks early. Kick detection efficiency has improved over the time with technological advancements. But effective implementation of many of these technologies have been a big challenge due to several factors including cost, complexity and lack of adaptability of the existing drilling systems. So, kick detection process has still remained somewhat elementary for many of the drilling operations around the world. They rely on some conventional kick indicators which has proven to be ineffective in many of the past blowout incidents (*e.g.*, Deepwater horizon blowout). But kick is not the initiating events for blowouts, they occur due to some failure of the primary barrier system. Which is preceded by some other events or leading indicators that can provide valuable information on the health and integrity of the total well control system. These indicators are mostly related to operational discipline, job planning, preparation, design and organizational safety culture. Even for the most advanced drilling rigs using a state-of-the-art kick detection technology, the accuracy and efficiency of the technology largely depend on influencing operational and organizational factors, *e.g.*, maintenance, inspection, training and competency of the personnel. These factors indicate the reliability or vulnerability of the total kick detection and well

control system. Since blowout is a low frequency high consequence event, extensive focus is required on developing leading indicators to predict and prevent undesirable events. So, along with focusing on advanced kick detection and control technologies, a comprehensive leading indicators framework is required specific to drilling and other well operations for monitoring barrier performances and successfully predicting potential upsets or kicks. But the oil and gas industry are currently using a set of “accepted” indicators for development of a safety program whereas it is believed that to prevent a catastrophic event, a more exhaustive and detailed approach is required.

2. Many of the blowout incidents, *e.g.*, Montara in 2009 and Deepwater Horizon in 2010 showed that, there were early indications of potential abnormalities both from organizational and operational perspectives. The lagging indicator data showed good safety records prior to the incidents but didn’t reveal the vulnerabilities within the safety system. Actual risk for both of the cases was pretty high due to impaired barrier conditions. Such faults could be identified with an extensive leading indicators program and it is believed that the consequences of such blowouts could have been lessened or minimized with appropriate focus on safety performance indicators or leading indicators.

3. The recommended practices and guidelines discussed in section 2.2.1 are very useful in developing a safety indicators program for general process industries, but

these are partly applicable to well drilling operations. Some of the shortcomings in applying the existing guidelines to well drilling scenarios include (Wilkinson, 2012) –

- Most of the guidelines primarily focused on production related losses
- Majority of the emphasis was made on consequence-based approach rather than cause-based approach
- Use of process operations focused language and concepts in general

Due to major differences between general process operations and well drilling or intervention operations, it is essential to have a robust guideline and framework for developing leading indicators program specific to well drilling and intervention operations.

4. Since well control performance is heavily governed by technical, operational and organizational factors, it is essential to consider all of these factors together in integrated models for assessing blowout risk. Some good works have been done to assess risks of blowouts or major well control events, but very little emphasis has been made on developing predictive models using leading indicators information which could demonstrate a more realistic scenario. Leading indicators can provide early information on chances of encountering an event that can cause barrier/s to fail. They can identify weak points in a system that need to be improved for avoiding such failures. This information can be collected from job planning, preparation and execution phases. So, if integrated in probabilistic models, they

can provide valuable information on potential failure of well control barriers specific to a certain job. But the major challenge in achieving this, is to combine these diverse set of data in same models and translate the information into probabilistic values.

3.2. Research Roadmap

Based on the gaps and challenges discussed in the earlier section following research objectives have been identified –

1. Development of a general framework for identifying sets of leading indicators to predict kicks and blowouts
    a. Define and categorize leading indicators
    b. Propose a systematic methodology for identifying sets leading indicators and identify categorized sets of leading indicators for drilling, completion and workover activities
    c. Perform case studies to assess the applicability of the proposed framework
2. Construct leading indicators-based decision support algorithms and predictive models
    a. Construct decision support algorithms using real-time indicators
    b. Develop predictive models correlating different levels of leading indicators to evaluate probabilities of primary barrier failure

3.2.1. Leading Indicators Framework

A general framework is required for well operations which can be applied regardless of operational phases, *e.g.*, drilling, completion, production, surveillance and workover. Leading indicators need to be defined clearly and categorized appropriately based on the circumstances and the nature of information they may provide. The recommended practices and guidelines published by UK HSE, API, IOGP and IChemE discussed in section 2.2.1, are excellent sources for understanding the characteristics of leading indicators and their application.

Once defined and categorized, a step-by-step guide is required for identifying appropriate sets of leading indicators. Aviation industry has a practice of analyzing potential failure causes and initiating events to identify critical issues that need to be monitored. This could be a viable practice for well operations as well, because the first step of preventing blowout events is to making sure that the barrier functions are not being compromised. The next task is to take the proposed methodology and develop sets of leading indicators for different barrier systems during drilling, completion and well workover/intervention operations.

The proposed framework also needs to be assessed for their applicability. To accomplish that, past blowout incidents can be analyzed from a perspective of the proposed leading indicators framework. This study should provide information on whether the proposed framework could be useful for identifying suitable leading indicators that could have provided early information on potential upsets.

3.2.2. Algorithms and Predictive Models

As drilling, completion and workovers are complex processes, only having discrete sets of leading indicators may not be sufficient for preventing well control events. They need to be integrated together for providing realistic information of the well control system and potential events. For example, kicks can be identified by carefully observing changes in certain process parameters. If algorithms are developed combining these parameters with necessary actions and further observations to confirm kick, that can be very useful for identifying kicks timely and efficiently using information obtained from the process observables.

But for evaluating potential barrier failure scenario, a more holistic approach is needed. Probabilities of barrier failure or kick initiating events can be assessed by correlating organizational, operational and real-time indicators. Bayesian network is believed to be an appropriate tool for handling these diverse set of information by translating these to some probability functions.

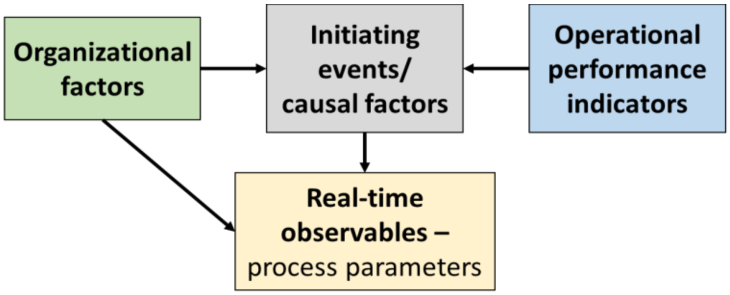

Figure 6 Assessing probability of barrier failure events

As indicated in Figure 6, probability of a kick initiating event can be determined by analyzing influencing organizational factors and operational performance indicators. Kicks can be detected by observing changes of certain process parameters. But whether the changes could be effectively detected or not, that depends on how the kick detection system is designed and managed. These issues are governed by relevant organizational factors and safety culture. This correlation is very critical because it could identify vulnerabilities in a kick detection system along with probabilities of barrier failure and kick events. For assessing well control performance, different sets of algorithms and probabilistic models were developed and discussed in Section 5.

4. DEVELOPING LEADING INDICATORS FRAMEWORK[**]

4.1. Definition and Categorization

Even though various definitions of leading indicators have been adopted in different guidelines, the basic notion is the same – they are proactive measures. The following key characteristics were outlined by analyzing the definitions provided in various sources, *e.g.*, API, UK HSE, IOGP and IChemE. Leading indicators –

- are considered to be a predictive set of parameters/course of actions,
- should deliver early information on barrier performance,
- must be measurable and recognizable, and
- should indicate and benchmark operational and organizational performances.

Based on these features and considering complexities of onshore and offshore well operations following definition has been proposed:

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[*] Tamim, N., Laboureur, D. M., Mentzer, R. A., Hasan, A. R., & Mannan, M. S. (2017). A framework for developing leading indicators for offshore drillwell blowout incidents. *Process Safety and Environmental Protection*, *106*, 256-262. Copyright 2017 Institution of Chemical Engineers. Published by Elsevier B.V. Part of this section and figures are reprinted with permission from Elsevier Ltd.

[*] Tamim, N., Laboureur, D. M., Hasan, A. R., & Mannan, M. S. (2019). Developing leading indicators-based decision support algorithms and probabilistic models using Bayesian network to predict kicks while drilling. *Process Safety and Environmental Protection, 121, 239-246*. Copyright 2018 Institution of Chemical Engineers. Published by Elsevier B.V. Part of this section and figures are reprinted with permission from Elsevier Ltd.

“A leading indicator provides early observable signs of threat from any event which may compromise the safety of a process, personnel or the environment, by progression to an undesirable state or value”.

It should be noted that leading indicators is a general term and based on the characteristics function and application, different industries use different terminologies - process safety leading indicators or lead metrics, leading risk indicators, leading performance indicators *etc*. Ultimately, they represent to a safety performance scenario or operational risk level.

For drilling, completion or well intervention activities, leading indicators can primarily be categorized into two different groups as shown in the Figure 7 – real-time indicators/process observables and indicators based on operational and organizational performance. Traditionally, the latter are considered as leading indicators in general and it has three different categories – operational, human and organizational, and system of organization. The category ‘system of organization’ is adopted from the aviation industry practice as discussed in the earlier section. The organizational factors mostly cover design, planning, preparations and competency issues where the operational factors include combination of preparations and execution part.

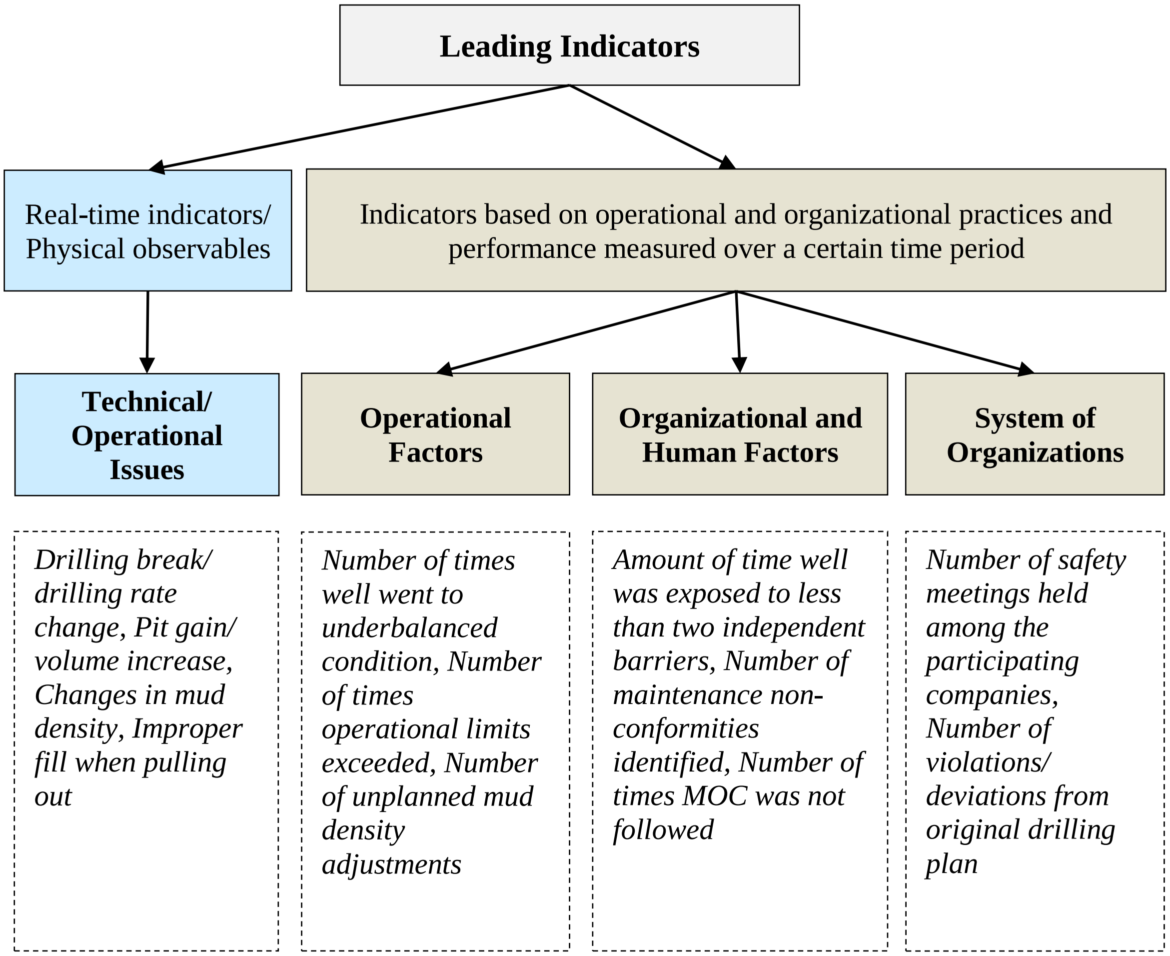

Figure 7 Categorization of leading indicators

4.2. Step-by-Step Process for Developing Sets of Leading Indicators

Based on the definition and categorization proposed in Section 4.1, a systematic cause-based approach was proposed for establishing comprehensive sets of leading indicators which can be represented with Figure 8:

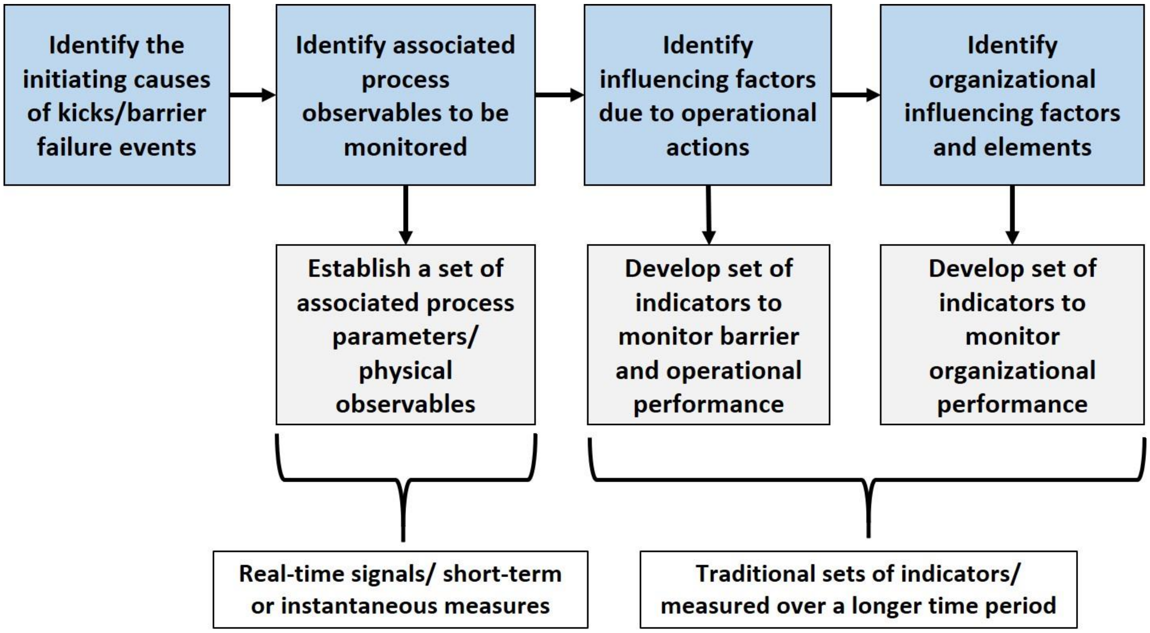

Figure 8 Flow diagram for identifying sets of leading indicators
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Different sets of indicators can be identified by analyzing operational scenarios that could lead to major events. At the beginning, indicators can be developed upon studying possible initiating causes/events (technical or operational issues). Then subsequent analysis can be performed to correlate the technical or operational failures with operational performance and eventually underlying organizational factors can be identified which are responsible for the incident. For each of the categories, appropriate sets of indicators can be established to track the elements affecting the safety and integrity of the total system. Initiating events and causal factors can be identified by conducting fault-tree analysis and from past incident data. This framework can be adopted for any operations or systems. In this study, this is applied to well drilling, completion and intervention activities.

4.2.1. Sets of Leading Indicators for Drilling and Completion Phases

To better understand the causes of blowouts and related barriers, a bow-tie diagram was constructed (Figure 9). This diagram summarizes how kick is initiated and escalated to a blowout event. Failure of hydrostatic head (or Pressure Control Equipment for managed pressure drilling) and/or cement can initiate kicks. Kicks can be further escalated to major well control events with failure of other well control elements, *e.g.*, plugs and packers, casing/liner. Blowout preventer (BOP) and/or valve arrangements are used to kill the kicks and regain control of the well. Failure of this secondary set of barriers can cause catastrophic blowout. Major failure causes of primary barriers have been represented in the clouds and physical observables for kick detection have also been included in this modified bow-tie diagram.

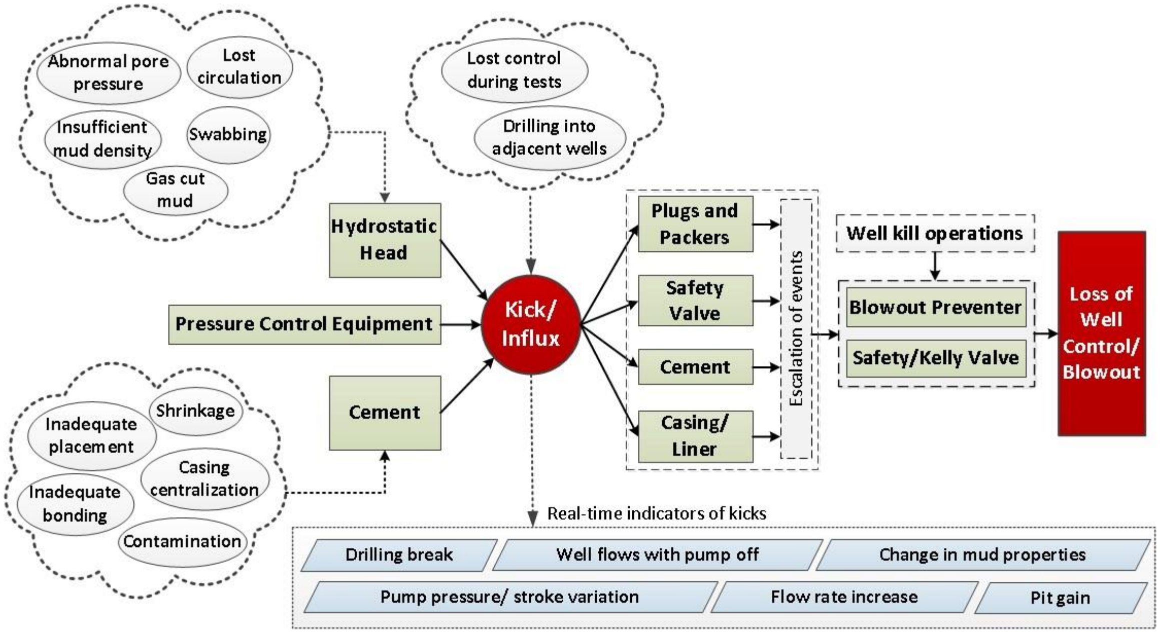

Figure 9 Bow-tie diagram

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Hydrostatic head is considered to be the primary barrier for majority of well drilling and completion operations. Many of the catastrophic blowouts in the past were initiated from low hydrostatic head events. A fault-tree analysis (Figure 10) was performed to identify the major causes of this crucial barrier failure.

By following the steps described in the earlier section, sets of leading indicators are developed for drilling and completion phases. Each of the failure causes were carefully analyzed to understand their impacts on process observables that can serve as real-time indicators for kicks and blowouts. Operational issues and complexities that can arise due to these failures were also assessed thoroughly. Finally, the underlying organizational factors that could lead to such failures and escalate well control issues were identified. The operational issues and organizational factors were then converted to appropriate leading indicators which can be evaluated for assessing performance of hydrostatic head barrier. The combined list of indicators is presented in Table 2.

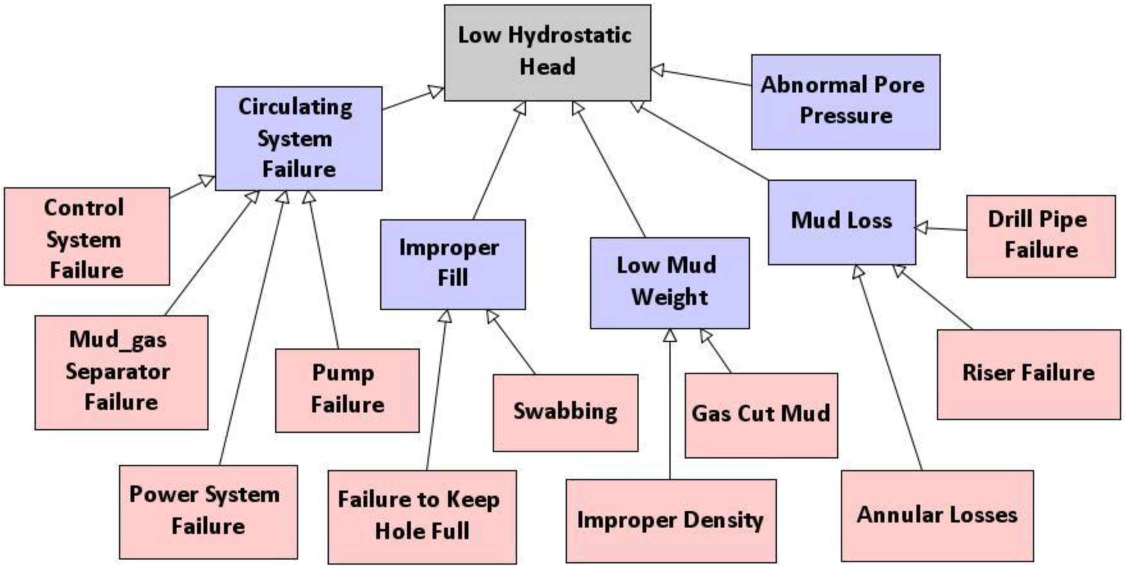

Figure 10 Fault tree analysis for hydrostatic head barrier failure

Different aspects of organizational factors were considered in this study. Two events need to occur for a barrier to fail and kick to happen – presence of an initiating cause and failure to detect any abnormal conditions. For example, abnormal pore pressure is one of the major causes of hydrostatic head failure during drilling. Availability of accurate information (from seismic survey, offset well data) while planning of drilling operation is very crucial to avoid such events. Again, maintenance practices, inspection process, drilling procedures and competency of personnel are some other critical factors that could indicate vulnerability and resiliency of the system.

Table 2 List of leading indicators for monitoring primary barrier (hydrostatic head) performance. Reprinted with permission from Elsevier Ltd. Copyright 2018.

Event	Low hydrostatic head
Initiating Causes	Abnormal pore pressure, Swabbing, Improper fill, Mud loss, Low mud weight, Circulating system failure
Barrier Element	Hydrostatic head/Mud column
Stage of Operations	Drilling/ Completion
Real-time Observables	▪ Drilling break/increase in rate of penetration ▪ Pit gain ▪ Flow differential ▪ Changes in pump pressure ▪ Changes in mud density ▪ Trip tank volume differential ▪ Change in D-exponent[†]
Indicators based on Operational Issues	▪ Number of times operational limits exceeded ▪ Number of unplanned mud density adjustments ▪ Number of unplanned pump flow rate adjustments ▪ Number of times well went to underbalanced condition ▪ Number of times separator high/low level alarm activated ▪ Number of times mud pressure drops within 5% of pore pressure ▪ Number of times mud pressure rises within 5% of fracture pressure ▪ Number of unplanned stoppages of drilling operations

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[†] D-exponent is an extrapolation of drilling parameters that estimate pressure gradient

Table 2 List of leading indicators for monitoring primary barrier (hydrostatic head) performance (continued)

Indicators based on Organizational Factors	▪ Geo hazards survey ▪ Availability of offset well data ▪ Resemblance with offset well conditions ▪ Geo hazards contingency plans ▪ Learning from prior events – repetitive incidents/near-misses ▪ Experience in current position ▪ Competency profile and training program evaluation ▪ Meantime between mud density measurements ▪ Arrangements for mud tank volume monitoring ▪ Arrangements for mud property measurement ▪ Overdue maintenance/function test items ▪ Number of maintenance non-conformities identified ▪ Number of work order generated for corrective maintenance ▪ Overdue audit/incident investigation action items ▪ Number of failures or defects found during routine inspection ▪ Overdue hazard analysis action items ▪ Number of times MOC process is exempt or not followed ▪ Number of plan changes without formal risk assessment ▪ Number of violations/deviations from original drilling plan ▪ Number of safety critical activities performed without procedure
Indicators based on System of Organization	▪ Number of safety meetings held among different parties ▪ Inadequate assessment of contractor training and competency ▪ Common agreement on proposed drilling and well design plans and subsequent adjustments ▪ Inadequate engagement with contractors for critical decision-making

Another set of indicators represent job preparations for not only preventing the influxes, but also detecting them timely and efficiently. On the other hand, indicators based on operational issues are the events that indicate overall operational discipline and complexities that could arise from the presence/occurrence any of the initiating causes of barrier failure.

Cement is another very crucial barrier for preventing influxes from the reservoir. Depending on the operational phase or the job being performed, cement can act as both primary or secondary barrier. Abimbola *et al.* (2016) conducted a comprehensive assessment on cementing operations and their potential failure causes. Based on that work, a fault-tree analysis (Figure 11) was performed to identify failure causes of cements. Influxes due to cement failure may occur due to poor cement job and failure to evaluate integrity of the cement. Formation fracture while placing cement may also initiate kicks.

By following the methodology proposed in the earlier section, sets of leading indicators were identified to monitor cement performance as a well control barrier. Proposed sets of leading indicators have been presented in Table 3. The real-time observables and relevant organizational factors for influxes due to cementing failure are same as hydrostatic head barrier failure events, and thus omitted from this list.

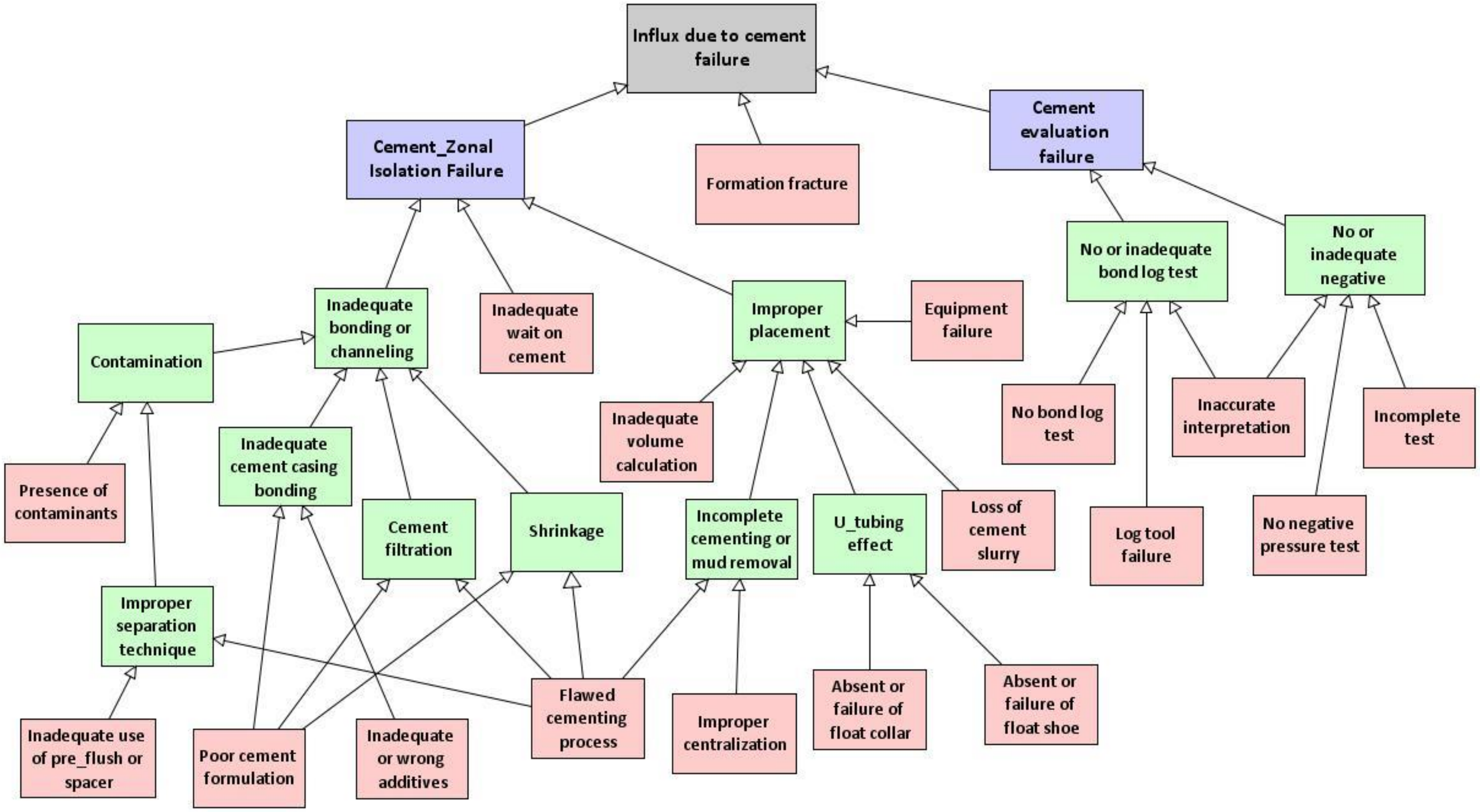

Figure 11 Fault tree analysis for cement failure

Table 3 List of leading indicators for monitoring cementing performance

Event	Influx due to cement failure
Indicators based on Operational Issues	▪ Full return of mud ▪ Increase in annular pressure ▪ Pipe stand-off ratio ▪ Plug landing/setting time
Indicators based on Organizational Factors	▪ Extent of pre-job testing ▪ Inadequate cement slurry testing ▪ Simulation of cementing ▪ Availability of reservoir data ▪ Absence of a critical equipment ▪ Inadequate cement slurry formulation ▪ Lack of formation evaluation ▪ Experience in current position ▪ Training and competency profile ▪ Quality of cement bond log ▪ Quality of negative pressure test ▪ Experience in test data interpretation

4.2.2. Sets of Leading Indicators for Well Intervention Operations

As discussed in Section 1 and 2, there are different types of well intervention operations including workover, wireline/slickline, coiled tubing and snubbing jobs. Most of the leading indicators discussed in Section 4.2.1 are applicable to well workover operations as well. The barrier arrangement in wireline and slickline operations are slightly different from what have been discussed in this section.

In wireline or slickline operations, stuffing box and/or pressurized grease head work as primary barrier elements. The stuffing box generally contains rubber packing which is tightened to seal around the cable/wire. Pressurized grease may also be used to prevent hydrocarbon leakage depending on the operations. Hydrocarbon release may also initiate due to lubricator failure. Wellhead tree valves are used as secondary barriers to prevent any well control events. Depending on the phase of operations or type of emergency wireline BOP may also be used to control the well. A well control event may occur due to failure of primary and/or secondary set of barriers or lubricator failure. Initiating causes of major well control events during wireline/slickline operations can be represented with the fault-tree diagram in Figure 12.

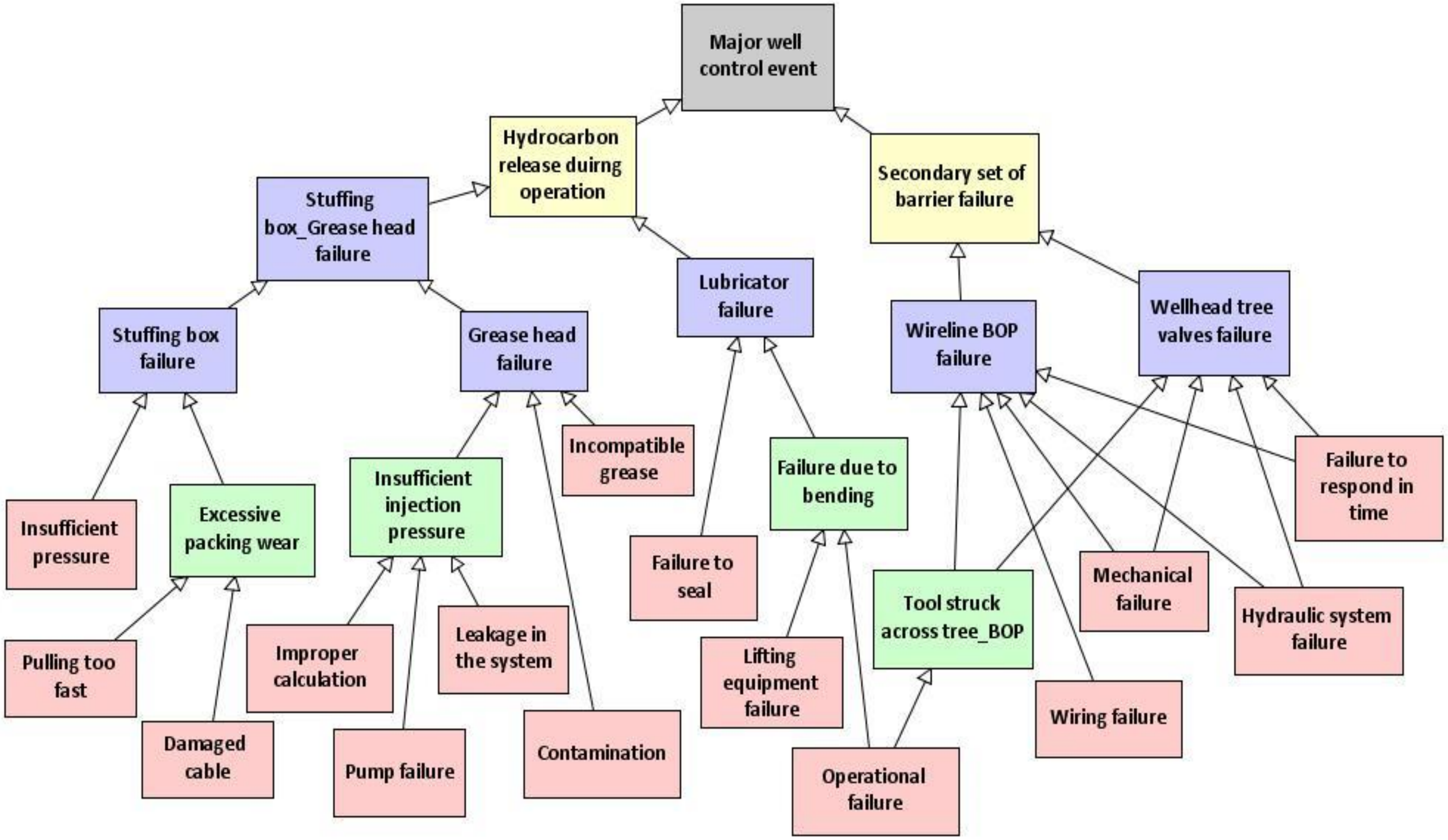

Figure 12 Fault tree analysis of well control events while wireline operations

Potential operational issues and underlying organizational factors for the initiating causes of well control barrier failures while conducting wireline operations were analyzed. Major organizational factors include – inadequate planning and job safety assessment, design failure, lack of competency, inadequate inspection and maintenance, inadequate function and pressure testing. Operating outside planned operational envelope, procedural violations, number of on-job complications, *e.g.*, tool stuck, are examples of operational issues that may cause an incident to initiate. These factors were converted into quantifiable indicators that could indicate organizational and operational performances and shortcomings. Integrity of well control barrier system while conducting wireline operations can be assessed by carefully evaluating the indicators. A list of potential leading indicators for assessing wireline operations has been presented in Table 4. Grease-head/stuffing box, lubricator, wireline BOP and wellhead tree valves were considered as major well control barriers in this analysis.

Table 4 List of leading indicators for monitoring barrier performance during wireline operations

Event	Uncontrolled hydrocarbon release
Barrier Elements	Grease-head/stuffing box, lubricator, wireline BOP, wellhead tree valves
Indicators based on Operational Issues	▪ Operating outside planned envelope ▪ Need for frequent packing/pressure adjustments ▪ Number of tool stuck issues ▪ Length difference between tool and BOP/tree assembly
Indicators based on Organizational Factors	▪ On job experience ▪ Training and competency profile ▪ Overdue maintenance items ▪ Ratio of corrective maintenance over preventive maintenance ▪ Number of bypassed inspection items ▪ Extent of pre-job inspection ▪ Number of overdue function test items ▪ Number of failures during function tests ▪ Number of expired pressure test certification ▪ Number of overdue valve integrity tests ▪ Performing grease quality check ▪ Change of plan without review

4.3. Case Studies

Two blowout incidents have been studied to assess whether leading indicators could have provided early warnings about blowouts or not. Several organizational and operational issues were identified for both of the incidents which could be revealed by appropriate sets of leading indicators. The blowout incidents analyzed were Montara and Macondo/Deepwater Horizon.

4.3.1. Montara Blowout [2009]

H1 well of the Montara Wellhead Platform in the Timor Sea, Australia, kicked and uncontrolled hydrocarbon started to flow on August 21, 2009 (Borthwick, 2010). The report of the Montara Commission of Inquiry (Borthwick, 2010) revealed a series of operational and organizational issues and failures that led to this disaster. On March 2009, operations on the well were temporarily suspended with barriers – cemented casing shoe, pressure containing anti-corrosion caps (PCCC) and overbalanced well fluid. The integrity of each of these barriers was compromised and the well control system failed to prevent influx of hydrocarbons into the wellbore and eventually to the environment. A leading risk indicator program could have predicted ongoing disorders and vulnerabilities of the well control system. A pressure test was conducted after installation of the cemented casing shoe. Volume and pressure data showed some discrepancies which indicated possible leakage through the float valves. Two anti-corrosion caps (PCCC) were planned to be installed instead of cement plugs, where PCCC is not a recognized well control barrier. Even, one of the anti-corrosion caps (PCCC) were not been installed which caused corrosion in the casing thread and complicated the completion operations. A proper risk assessment program could have identified the incompatibility of PCCCs as a well control barrier, and an effective inspection and audit program could have revealed the issue of non-installation of the PCCC. Again, the density of casing fluid was not sufficient to balance the formation pressure and the absence of a long-term barrier monitoring program allowed the incident to develop.

The barrier scenario and progression of events can be represented with Figure 13:

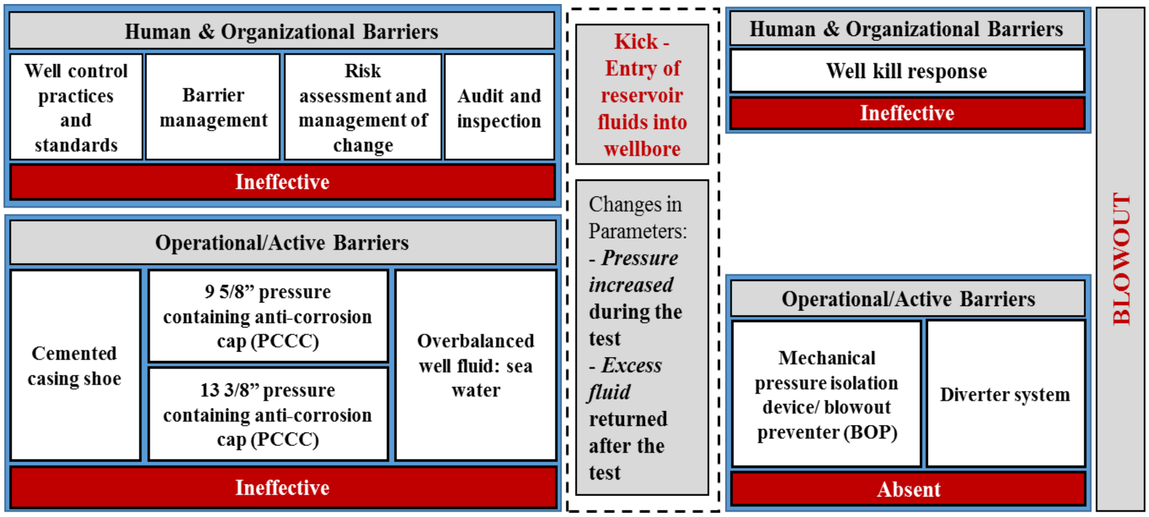

Figure 13 Barrier diagram for Montara blowout
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As per the report (Borthwick, 2010), there were several early signs of potential well control event which had not been considered or investigated. Again, several operational and organizational factors indicated lack of integrity of the well control and barrier management system. This incident was analyzed from the perspective of the leading indicators framework discussed in earlier section. And, relevant real-time indicators and leading operational and organizational factors for this incident have been presented in Table 5. This clearly shows the critical necessity of shifting focus towards leading indicators to successfully predict and prevent catastrophic incidents.

Table 5 List of Potential Leading Indicators for Montara Incident
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Real-time Indicators	Operational Factors	Organizational Factors	System of Organization
▪ Differential flow volume - Pumped 9.25 bbl of fluids; 16.5 bbl returned ▪ Changes in annular pressure – Pressure increased after initial test	▪ Non-installation of one of the pressure containing valves (PCCC) 13 3/8” PCCC ▪ Insufficient density of overbalance well fluid	▪ Absence of BOP, diverter system or any independent secondary barrier ▪ Change of plan without formal risk assessment; lack of compliance with MOC system ▪ Improper well barrier management system and risk assessment - Installation of PCCC instead of cement plug ▪ Lack inspection of compliance audit and system	▪ Lack of understanding between the operator and the contractors on drilling safety, integrity and individual responsibilities

4.3.2. Deepwater Horizon Blowout [2010]

Deepwater Horizon blowout is considered to be one of the most catastrophic incidents in recent history. This incident led to 11 fatalities, 17 injuries and severe environmental damage (Counsel, C., 2011). Failure in cementing caused hydrocarbons to enter the wellbore and misinterpretation of pressure test results allowed further escalation. The blowout preventer (BOP) failed to prevent the influx from escalating to the blowout event. The attempt to completely seal the well by the blind shear ram was not successful due to the off-centered drill pipe. This incident points out the need for establishing better approaches to manage hazards, minimize risks and uncertainties associated with deepwater drilling activities. Relevant real-time indicators and leading operational and organizational factors for this event have been presented in Table 6.

Table 6 List of Potential leading Indicators for Deepwater Horizon Blowout. Reprinted with permission from Elsevier Ltd. Copyright 2018.

Real-time Indicators	Operational Factors	Organizational Factors	System of Organization
▪ Changes in process parameters - increase in drillpipe pressure and decrease in riser mud level, during negative pressure test	▪ Deviations and abnormalities - Higher pressure required to activate float valves - failure of float assembly - Unsteady drillpipe pressure throughout the negative pressure test ▪ Inconsistent BOP test and inspection results	▪ Safety critical activities performed without formal procedure – negative pressure test ▪ Change of well plan without formal risk assessment – no cement bond log, less centralizers used than originally planned for, no bottom up circulation ▪ Lack of compliance with MOC process ▪ Inadequate instructions and well control procedure ▪ Simultaneous operations in mud tank system – couldn't notice pit gain	▪ Lack of supervision and engagement with contractors ▪ Inadequate assessment of contractor training and competency

4.4. Discussion

A general framework for identifying and developing sets of leading indicators have been proposed and discussed in this section. The framework was primarily developed for well operations. But the proposed cause-based methodology has given the framework such adaptability and robustness that it can be applied effectively to any processes or operations. Drilling, completion and well intervention operations were assessed thoroughly for developing suitable sets of indicators by following the proposed systematic approach.

For drilling and completion activities, only primary barriers were analyzed since the principal focus of this study was on kick prevention. Due to the complex nature of drilling and completion activities, hydrostatic head and cementing barriers were assessed individually. Among different types of well intervention activities, wireline operations were analyzed due to its differences in well control barrier system compared to other well operations. Detailed analysis was performed to identify key causal factors for failure of the critical barriers while drilling, completion and well intervention operations. Each of the key causal factors were carefully analyzed to develop sets of leading indicators by following the step-by-step methodology proposed in this work. It should be noted that, the proposed set of indicators is not uniform; rather a mixture of percentage, numbers and observations due to their nature of use and application. This may not be a concrete list and some of the indicators may not apply for certain cases where some additional indicators can be added based on the operational circumstances.

Proposed leading indicators can be defined and expressed differently based on their features. But for each of the indicators certain criteria needs to be set to identify acceptable and unacceptable region. For example, indicators can be expressed in terms of their vigor or performance level – low, medium and high. One of the major benefits of using performance state/level for denoting leading indicators is, any observation or percentage can be easily transferred into different states or levels based on industry best practices or expectations.

Indicators which are directly measurable with numbers or convertible to percentages can be easily represented by performance states, *e.g.*, number of overdue maintenance items. If no maintenance is overdue the observation of this indicator is 'low' which represents best possible performance. 'Medium' and 'high' states of overdue maintenance can also be defined based on criticality and expectations. But for the indicators based on observation or scenario assessment, clear criterion needs to set for each of the performance states. For example, one of the leading indicators for determining efficiency of kick detection system during drilling can be - arrangements for mud properties measurements. This item cannot be measured directly with numbers. This indicator can have different components which can be defined as represented in Table 7. Other indicators can be defined and represented in similar manner for uniformity.

It should be noted that, this table is just an example of how the leading indicators can be defined and expressed with different performance states, and does not represent industry practices.

Table 7 Example for defining leading indicators with performance states

Arrangements for Mud Properties Measurements	**Reliability/Performance**		
	High	**Medium**	**Low**
Mean-time between mud density measurement	<10 min	10-30 min	>30 min
Mean-time between gas content measurement	<10 min	10-30 min	>30 min
Stand-by equipment for property measurements	1 or more	None, but have contingencies	None
Simultaneous activities impacting mud property measurement	None	Yes, but no immediate impact	Yes

*The numbers presented in this table are for demonstration purposes only, and do not represent industry practices.

To demonstrate importance of leading indicators and assess the applicability of the proposed framework, a couple of case studies were performed. For Montara blowout, inadequate job planning, change in drilling plan without proper risk assessment and inadequate inspection were found to be the underlying organizational issues that contributed towards the incident. Non-installation of one of the critical pressure control equipment and insufficient density of the overbalance fluid were some of the key operational failures. Again, drilling contractors did not have proper communication and understanding with the owner and other service providers on changing well design and drilling plans. All these factors could have identified with proper sets of leading indicators as discussed in Section 4.3.1.

Similarly, for Deepwater Horizon blowout incident, multiple operational and organizational issues had existed before the blowout. For example, cement failure was believed to be the initiating event for the kick which was escalated to a catastrophic blowout event after a series of additional failures. Less centralizers were used than originally planned for a cementing job which was considered to be critical given the casing arrangements. This change in plan was not assessed thoroughly. Addition to this, the cement slurry formation was found to be poor and unstable, which could not provide proper isolation. Cement bond log was not run to save time, which could have identified potential issues with the cementing job. And, negative pressure test results were not properly interpreted and the test itself was performed without formal procedure. Finally, the temporary abandonment procedure was finalized at the last minute without proper risk assessment, which caused the well to go underbalance with insufficient well control barriers. The rig personnel failed to detect the kick early as they could not notice the pit gain due to simultaneous operations at the pit tank. All these factors were deeply rooted into organizational safety culture and proper sets of leading indicators could have identified the weaknesses in the well control system caused by the series of changes in drilling and testing plans. Again, complications during cement placing and changes in process paraments including drill pipe pressure further indicated towards a potential failure which were also overlooked.

A carefully developed leading indicators program could have provided a holistic picture of the well control program and barrier health for both of the incidents. These analyses clearly show the critical necessity of shifting focus towards leading indicators for successfully predicting and preventing catastrophic incidents.

5. DECISION SUPPORT ALGORITHMS AND PREDICTIVE MODELS[*]

5.1. Decision Support Algorithms

As identified in Table 2, several real-time indicators or process parameters can be tracked for predicting and detecting kicks while drilling. Some of these are considered to be primary indicators (*e.g.*, pit gain, flow differential) which provide confirm signs of kicks. And some are secondary indicators (*e.g.*, rate of change in penetration, changes in pump pressure) which may not always indicate a confirmed kick scenario but provide early warnings of something abnormal. To relate these indicators with a kick scenario several algorithms are constructed – which can aid effective decision-making during drilling operations.

The algorithm in Figure 14 was constructed for drilling process where abnormal pore pressure is considered to be a major contributor of risk.

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[*] Tamim, N., Laboureur, D. M., Hasan, A. R., & Mannan, M. S. (2019). Developing leading indicators-based decision support algorithms and probabilistic models using Bayesian network to predict kicks while drilling. *Process Safety and Environmental Protection, 121, 239-246*. Copyright 2018 Institution of Chemical Engineers. Published by Elsevier B.V. Part of this section and figures are reprinted with permission from Elsevier Ltd.

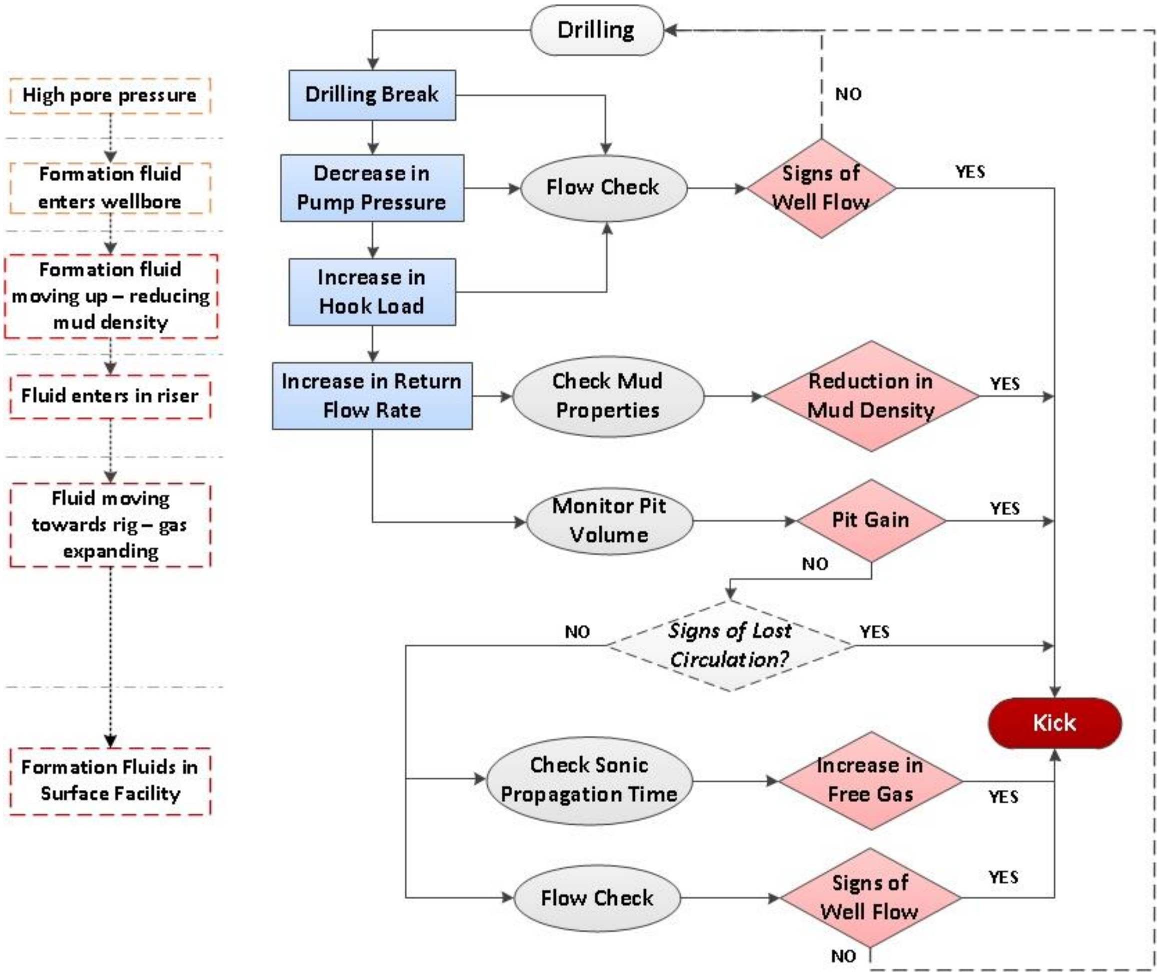

Figure 14 Kick detection algorithm for drilling
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This algorithm shows the sequence of warning signs and indicators if the drilling process hits an abnormal pressure zone and formation fluid starts to come into the wellbore. The left side of the flow diagram represents the increasing intensity of the kick with time. It is obvious that the earlier the kick is detected from the real-time observables the lesser the kick intensity would be. For example, in case of a gas kick, 'pit gain' means the formation fluid has already reached closer to the surface facility as dissolved gas has started to come out of the drilling mud. But for oil/water (incompressible fluids) kick pit gain might be observed at an earlier phase when oil/water enters the wellbore and starts displacing the mud.

Similar algorithm is developed for tripping out operations. Tripping out generally refers to pulling the drillstring out of the drilled hole. Swabbing is the major risk contributor for this phase and Figure 15 represents the sequence of events for a swabbing scenario.

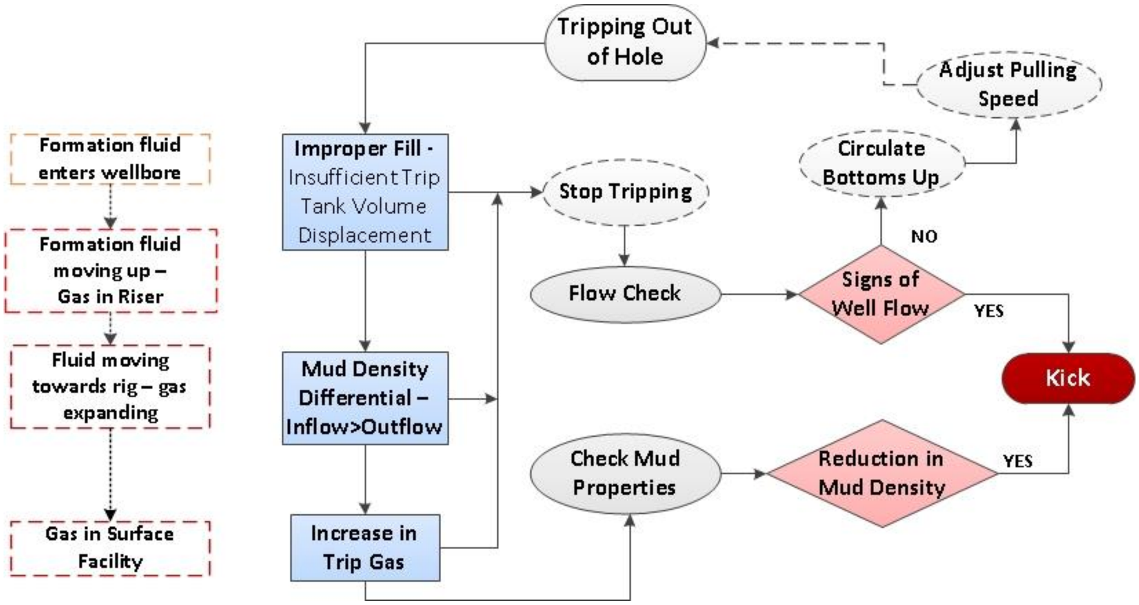

Figure 15 Kick detection algorithm for tripping operations
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Improper fill would be the first indication of a developing kick scenario and ‘flow check’ is a common practice to check for kicks. The earlier the trip tank volume differential is identified the better and that would allow some extra time to handle the kick.

5.2. Predictive Models

Comprehensive predictive models were developed correlating different levels of leading indicators to evaluate probabilities of kick initiating events or primary barrier failure. As discussed in Section 4, fault tree analysis was performed to identify the key causal factors for well control barrier failures. A Bayesian network (BN) tool was used to construct the models. Agenarisk, a software for constructing Bayesian network and modeling risk and uncertainty, was used to construct leading indicators-based probabilistic models for assessing –

- Occurrence probabilities of causal elements (abnormal pore pressure and swabbing for hydrostatic head failure)
- Failure probability of a barrier (cementing)
- Probability of major well control event (for wireline operations)

These models allow both predictive (cause to effect) and diagnostic (effect to cause) reasoning. Bayesian network models can make optimum predictions by combining different types of information including system specific data, expert judgement and generic information. Due to unavailability of leading indicators data for drilling operations, probability distributions of the indicator elements were assumed in this study, based on the learnings from past incidents, literature review and expert judgement. The methodology for constructing leading indicators-based probabilistic models can be represented with the flow-chart in Figure 16.

In this study, indicators and the final events (barrier failure or causal factors for barrier failure) were denoted with ranked nodes. Ranked nodes enable using non-uniform indicators together in a same platform for comprehensive assessment. The states of the discrete variables (*e.g.*, indicators) can be represented on ordinal scales using the ranked nodes. The ordinal scales can then be mapped into bounded numerical scale. For example, all the ranked nodes can be defined with a unit interval of [0-1] scale. If three-point scale or three performance states (low, medium and high) are used the width for each state would be 1/3 - which were used in this study. Thus, the associated intervals for different states can be expressed as –

Low: [0 – 0.333]
Medium: [0.333 – 0.666]
High: [0.666 – 1]

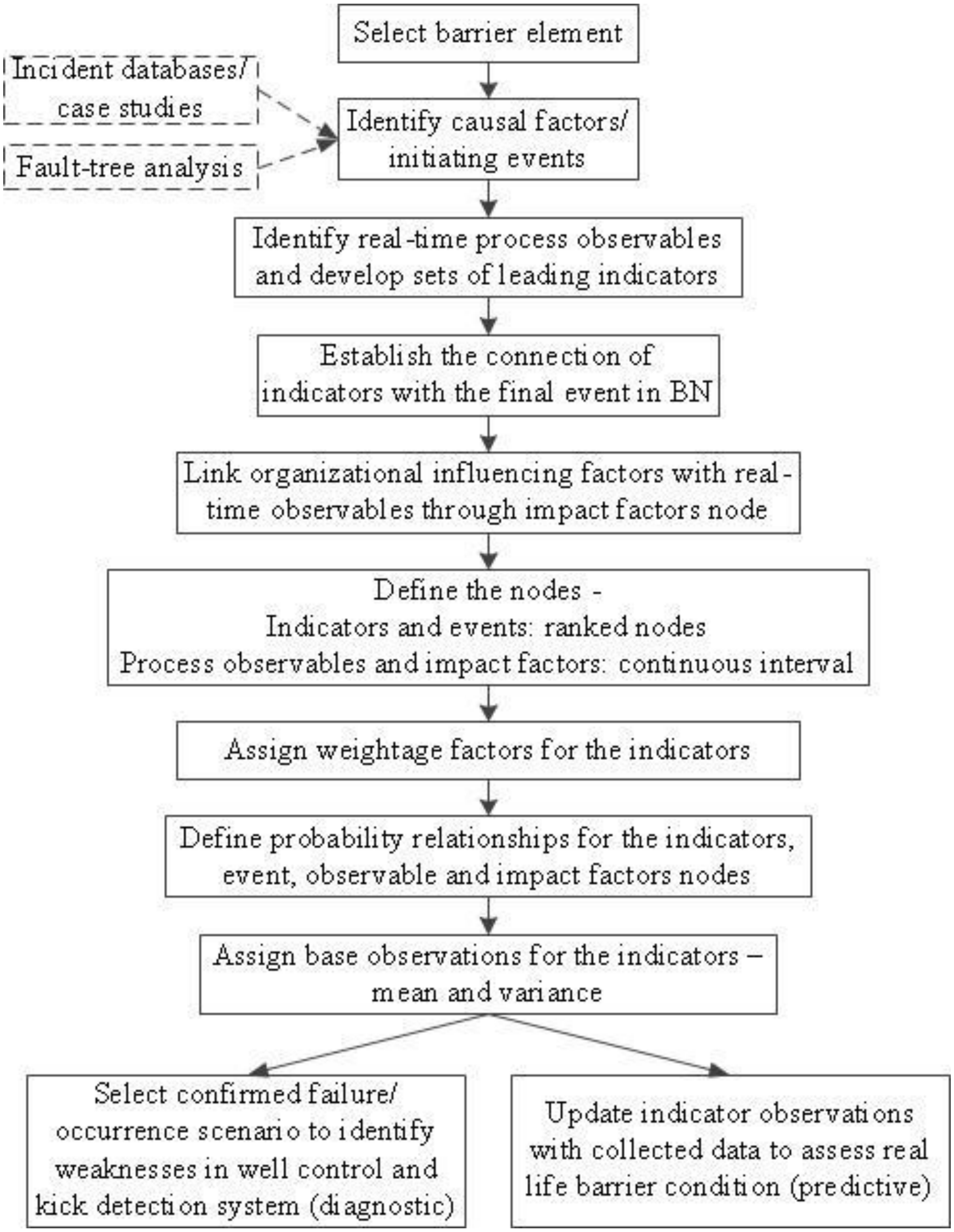

Figure 16 Flow chart for constructing probabilistic models using BN

In the software interface, that was used in this study, the labeled states were displayed rather than the numeric one, but the numerical values were used to calculate the associated probabilities and generating node probability tables (NPT).

For example, operational performance (B) while conventional drilling can be evaluated with two indicators – number of unplanned mud density adjustments (A1) and number of times mud pressure/bottomhole pressure falls within 5% of the formation pressure (A2) as represented in Figure 17:

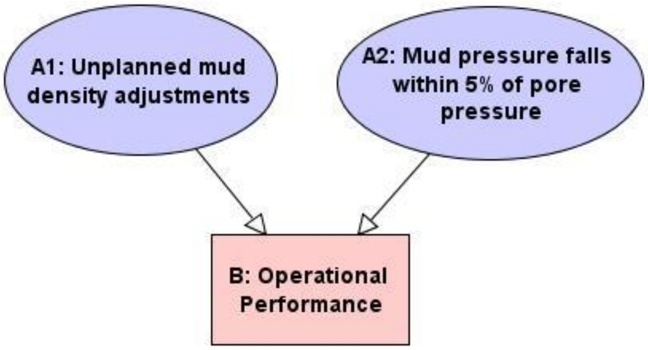

Figure 17 Example of using indicators in Bayesian network

These nodes can be denoted with truncated normal (TNormal) distributions, which have finite end points. So, the indicator nodes can be defined as –

TNormal (μ, σ^2, 0, 1); where, μ = mean and σ^2 = variance

To measure the contributions of the parent nodes (indicators) on the child nodes (indicators/events), a weighted sum model was used, which can be represented as –

P(B|A) = TNormal [$\frac{\sum_{i=1}^{n} WiAi}{\sum_{i=1}^{n} Wi}$, σ_A^2, 0, 1]; where, W_i is weightage factor

To construct the base models, probability distributions (mean and variance) for each of the parent nodes were assigned along with appropriate weightage factors for better correlation. The assigned values have been shown in Table 8 –

Table 8 Example of assigned base values to leading indicators

Factor	Indicators	Weightage factor	Mean	Variance
Operational Issues	Number of unplanned mud density adjustments	1	0.15	0.01
	Number of times mud pressure drops within 5% of formation pressure	2	0.2	0.01

The probability distributions for 'low', 'medium' or 'high' operational performance, P(B|A), for this scenario has been shown in Figure 18:

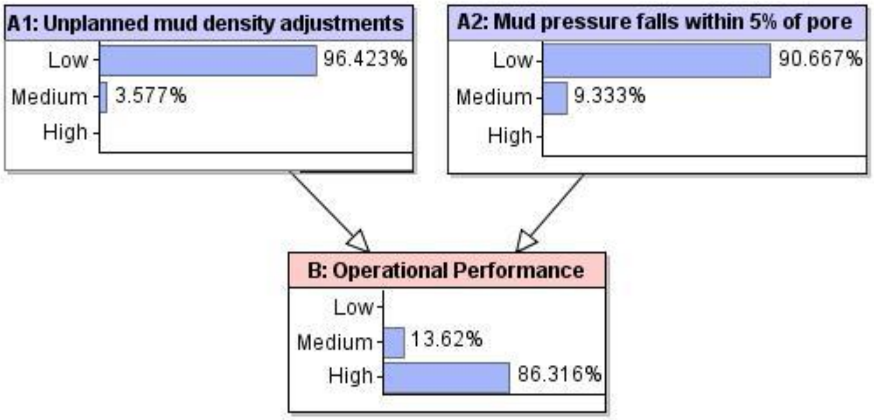

Figure 18 Example for assessing operational performance using leading indicators

Same principles were applied in the large models to denote the indicator nodes. In this study, informed assumptions were made to assign the variances of both the parent and child nodes. The variances of the child nodes can also be estimated by taking the inverse sum of the weightage factors –

$$\sigma_A^2 = \frac{1}{\sum_{i=1}^{n} Wi}$$

To reduce model "washing out" affect, which can be caused due to deep hierarchical ranked nodes, indicators were grouped into smaller segments/factors and then the combined effect was modeled in this study.

For denoting the process observables, continuous interval type nodes were used. Event nodes (barrier failure or causal factor) were converted to continuous interval to connect with these observable nodes. Also, to correlate the process observable nodes with relevant performance indicators, intermediate nodes were used which were defined as 'impact factors'. For example, these correlations can be represented by Figure 19.

If kick occurs due to abnormal pore pressure, return mud flow would increase as the downhole mud would be displaced by the influx (for water-based mud system). Whether the flow difference would be timely detected or not that depends on the arrangement and accuracy of flow measurement devices and driller's experience. Mud flow can also be impacted due to lost circulation, which could further impact kick detection efficiency. For better estimation, mud flow differential was denoted with continuous interval and thus the correlated nodes had to be converted into continuous interval as well.

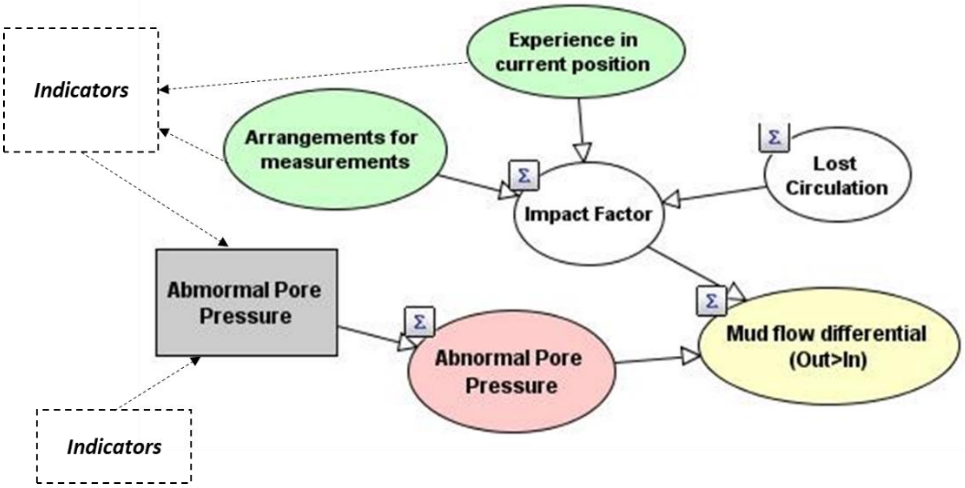

Figure 19 Example of integrating process observables with leading indicators

For continuous interval type nodes, the cumulative density function of a variable X, with probability distribution function *f*(X), can be represented as –

F(X) = $\int_{-\infty}^{x} f(t)dt$ and, $\int_{-\infty}^{\infty} f(t)dt$ = 1

And, for the range of values of X can be defined as [m, n], the probability that X lies in this range can be expressed as –

P $(m \leq X \leq n)$ = F(X) = $\int_{-\infty}^{x} f(t)dt$

In this study, normal distributions were used to denote probabilities of the changes in the process observables due to occurrence of kick initiating events/barrier failure causal factors. For some of the models, ranked nodes of the final elements were converted to Boolean nodes to represent probabilistic occurrences or failure values.

5.2.1. Drilling and Completion

As discussed in Section 4, hydrostatic head is considered to be the primary barrier for majority of the drilling operations. A fault-tree analysis (Figure 20) was performed to assess the failure probability of hydrostatic head and to identify major contributors for failure of this crucial barrier. Abnormal pore pressure and swabbing were found to be the major contributors for low hydrostatic head.

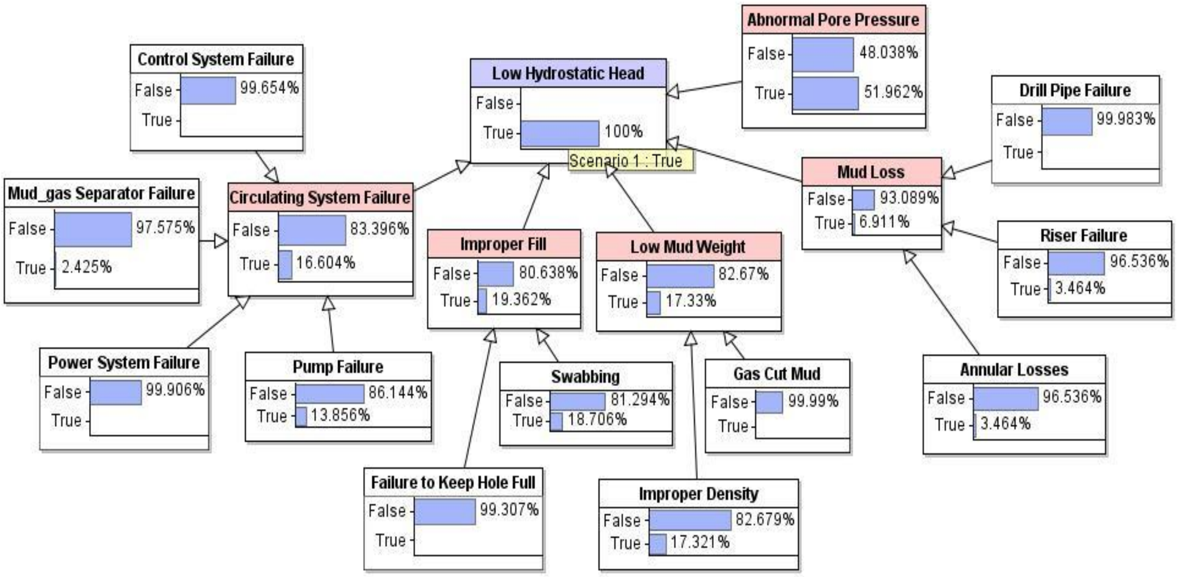

Figure 20 Fault-tree analysis for low hydrostatic head event
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It should be noted that, the failure probabilities of initiating/parent events were collected from various data sources (Khakzad *et al.*, 2013, Bhandari *et al.*, 2015, Rathnayaka *et al.*, 2013 and Abimbola *et al.*, 2014), where different drilling scenarios were taken into consideration (*e.g.,* deepwater, shallow water, different reservoir conditions, type of drilling). So, there are certain uncertainties involved with the calculated values.

Since abnormal pore pressure and swabbing are the major contributors for low hydrostatic head or mud column failure, these two causal factors were further studied with proposed sets of leading indicators. Suitable sets of leading indicators for evaluating barrier failure due to abnormal pore pressure event were identified from Table 2 in section 4.2.1. The leading indicators model developed to assess the occurrence probability of the event of abnormal pore pressure has been shown in Figure 21. In this model, two different types of leading indicators, organizational factors and operational performance issues, were integrated to determine the probability of encountering an abnormal pore pressure scenario. Organizational factors mostly reflect drilling preparations, planning, inspection, maintenance and competency information, whereas, operational factors reflect real-time execution scenarios.

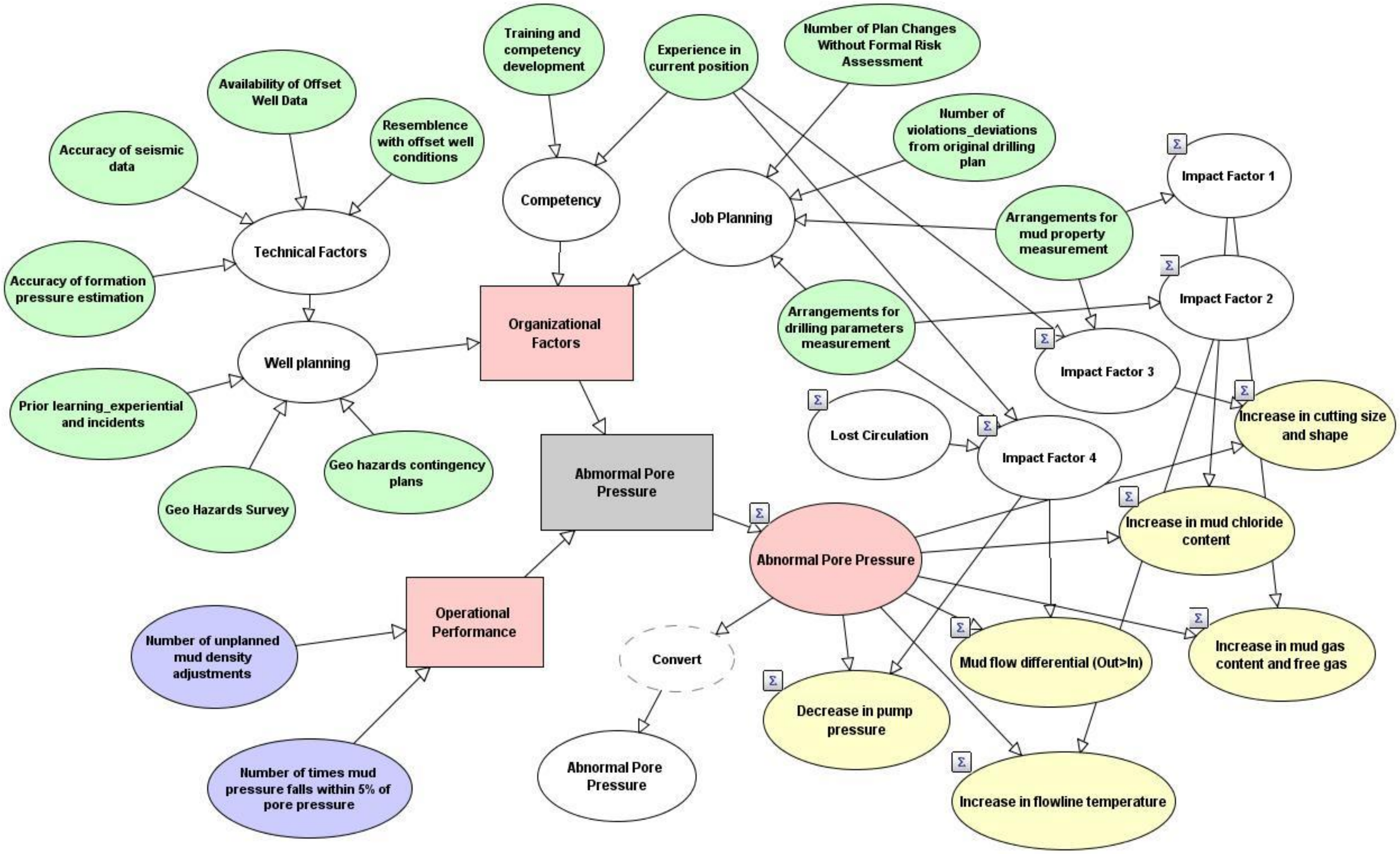

Figure 21 Leading indicators model – Loss of hydrostatic head due to abnormal pore pressure

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If drilling hits an abnormal pore pressure zone and influx happens due to underbalanced conditions, it would trigger some changes in the process observables. These observables can serve as real-time indicators for kick identification. The probability distributions for observing changes in real-time parameters when a kick is developing due to abnormal pore pressure were also incorporated in this model. These parameters are function of both abnormal pore pressure event and some impact factors (*e.g.*, presence/accuracy of measurement devices) which are largely influenced by the organizational safety culture.

Similar assessment was conducted for well swabbing event which can cause influxes while tripping out of the hole (Figure 22). Design of drillstring and bit, job planning, job preparations and competency are the key organizational factors that influence probability of swabbing a well while pulling out of the hole. Since, this is a no circulation condition, detecting a kick can be particularly challenging. Monitoring trip tank volume can be a reliable indicator only if the mud in tank is not used for any other purposes.

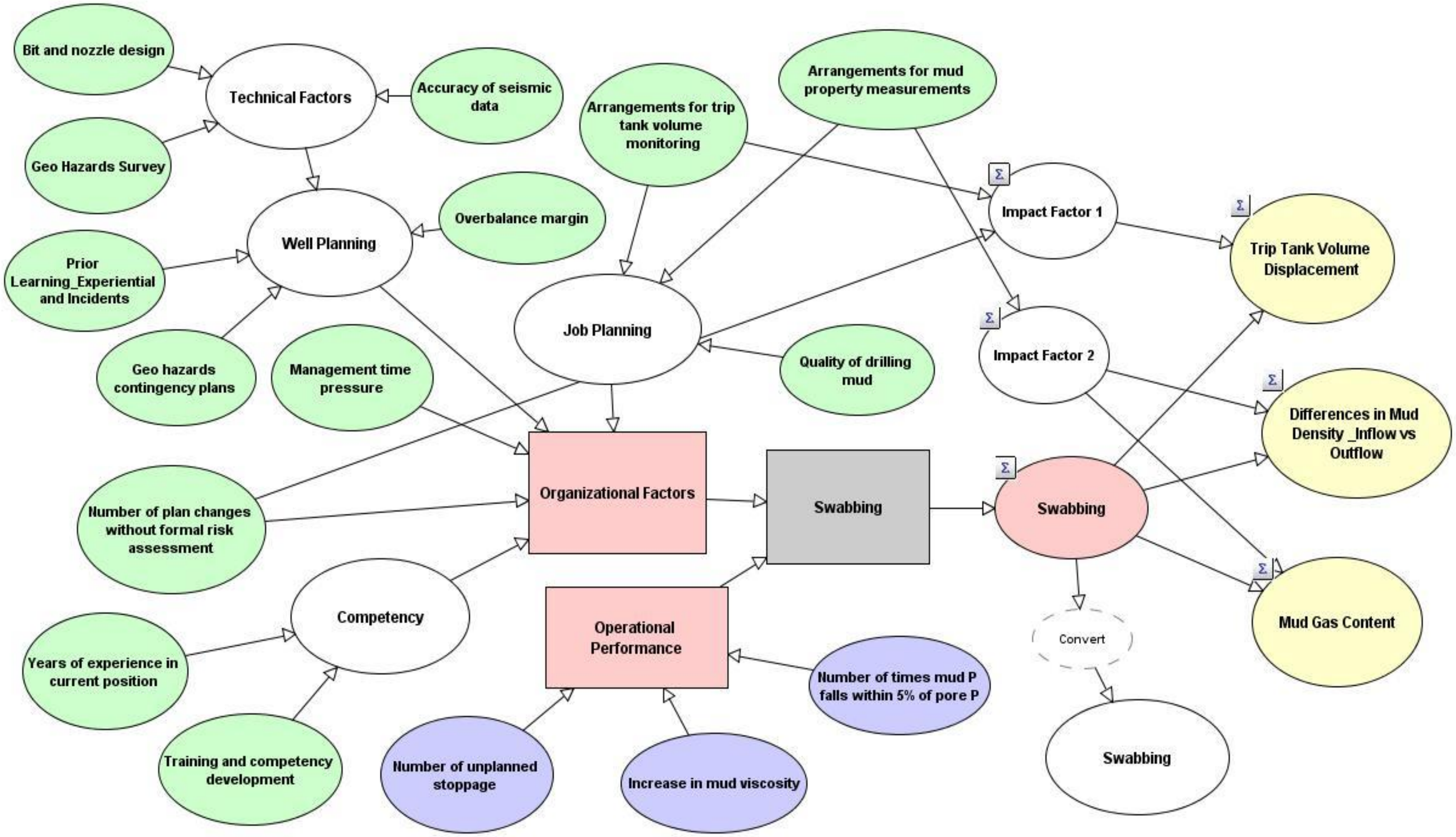

Figure 22 Leading indicators model- Loss of hydrostatic head due to swabbing
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Cement has multiple functions including creating zonal isolation by sealing off the annular space to prevent movement of well fluids, support the casing and closing off abandoned portion of the well. The process of cementing is complex and requires careful planning and preparation, precise execution and thorough evaluation. As discussed in Section 4, cement failure can be grouped into two categories – failure to achieve proper isolation and failure to evaluate cement integrity. Pre-job testing, preparation, job design and competency of personnel are crucial factors in achieving effective zonal isolation. Proper use of critical equipment including centralizer, float collar, float shoe and spacer are essential for success of cementing operation. Return of displaced mud, plug setting time, pipe stand-off ratio and change in annular pressure during cementing operation could indicate potential issues in cement placement. Cement evaluation is very critical as it cannot be inspected directly. Thus, conducting appropriate test, such as, cement bond log and negative pressure test, and carefully evaluate the test results are very important for preventing well control events due to cement failure. All these factors were considered while developing sets of leading indicators and constructing probabilistic models to assess cement failure probability. The Bayesian network model has been presented in Figure 23. As discussed earlier, the leading indicators were converted into probability distributions to construct the model. Observations can be entered in terms of low, medium or high based on accepted definitions to evaluate integrity of cementing as well control barrier.

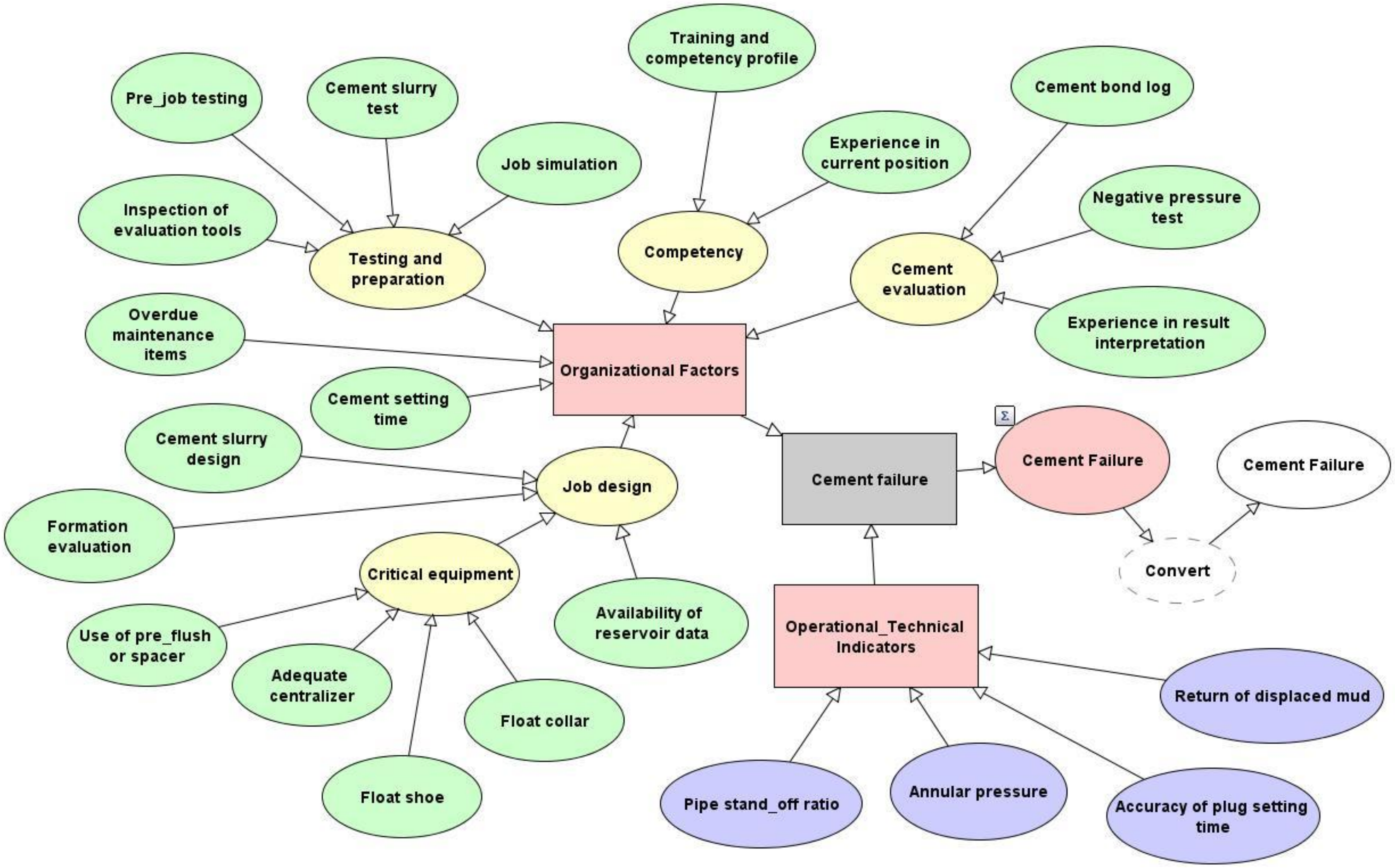

Figure 23 Leading indicators model- Cementing failure

5.2.2. Well Intervention – Wireline operations

Wireline/slickline operations are conducted on producing wells and the barrier arrangements are quite different compared to drilling and completion activities. Wireline blowouts do not necessarily precede by kicks, failure of wireline equipment may initiate a well control event which can be escalated to a blowout by failure of tree valves and/or wireline BOP equipment. Release of hydrocarbon to atmosphere is the major real-time indicator for potential barrier failure issues, thus, focusing on leading indicators to evaluate and monitor barrier performance is very important in wireline operations.

Unlike drilling and completion, for wireline operations all the potential barriers were incorporated together in a single model to assess probability of a major well control event. The Bayesian network model has been presented in Figure 24. Mechanical failure of pressure/well control equipment, procedural deviation and human factors in well control response are some of the major causes of well control events. Thus, organizational performance indicators related to maintenance, function testing, pressure testing, inspection and competency profile were proposed and used in the probabilistic model. On the other hand, operational complexities (*e.g.*, tool stuck issues), need for frequent adjustments of packing or pump pressure and overall operational discipline can also indicate possibilities of well control issues. All these indicators can assess integrity of individual barriers and overall probability of a major well control event during wireline operations.

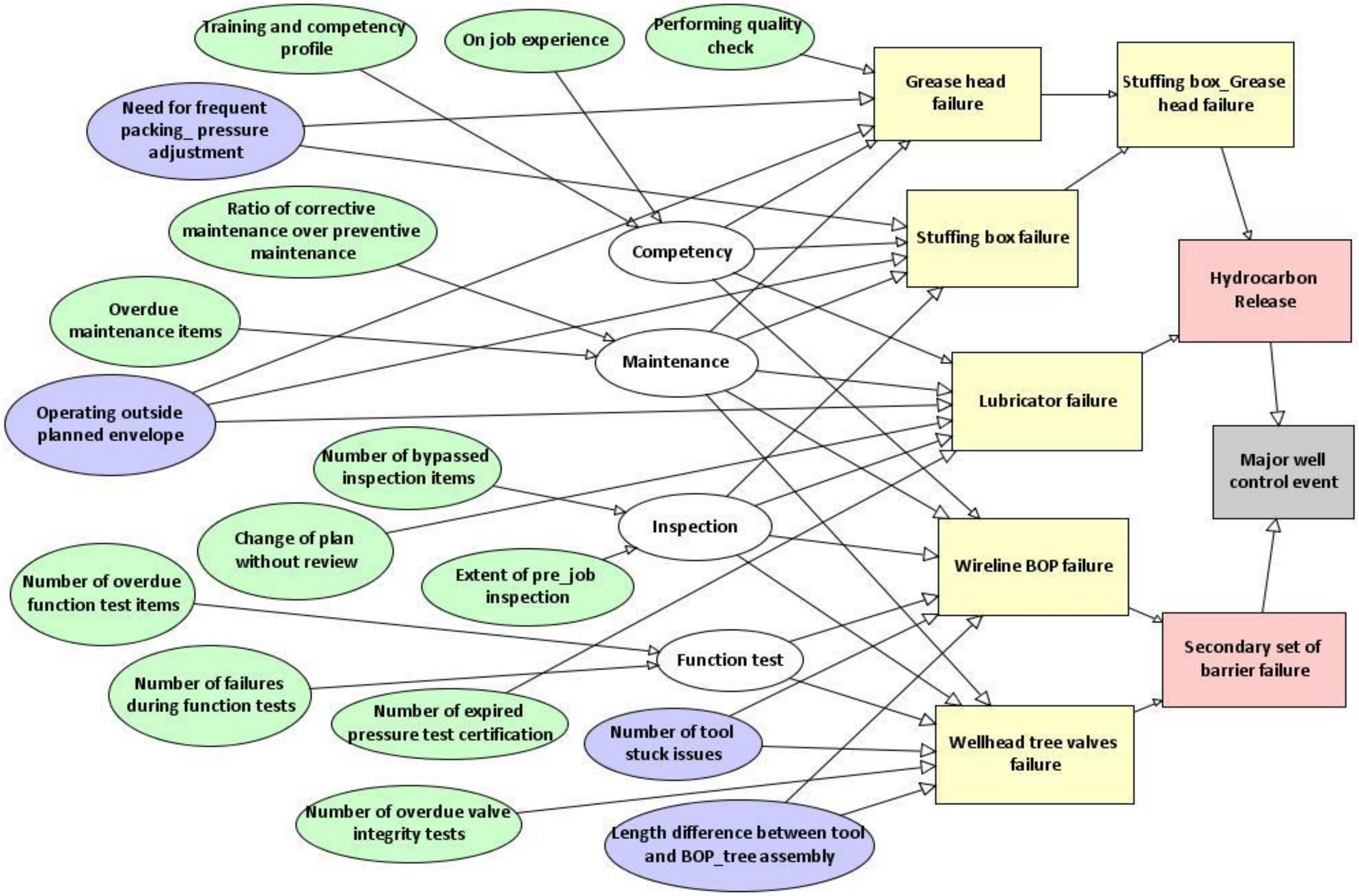

Figure 24 Leading indicators model- well control event during wireline operations

5.3. Discussion

The leading indicators-based Bayesian network models that were constructed have multiple functions –

1. With available leading indicators data, the probabilities of kick initiating events or barrier failures can be estimated
2. Role of influencing organizational/operational factors for confirmed kick or barrier failure scenario can be estimated (diagnostic assessment), this could be helpful for identifying weaknesses and vulnerabilities in a system
3. The efficiencies of different kick detection parameters can be assessed for a confirmed kick scenario and performance influencing factors for these parameters can also be identified and improved for effective kick detection

For example, Figure 25 shows the distribution of leading indicators based on operational issues and organizational factors, and efficiencies of relevant process observables to indicate abnormalities during kicks caused by abnormal pore pressure (pore pressure>wellbore pressure). For the mock dataset, the level of efficiencies of different real-time indicators (*e.g.*, mud flow differential, increase in pump pressure, mud gas content) were found to be ranged from 70-80% due to limitations in system design, planning and preparations. Which could mean that, there might be a 20-30% chance that low hydrostatic head due to abnormal pore pressure will not be detected in the early phase of kick development. So, the factors that affect proactive measurement process can be identified with this diagnostic analysis. In this case, arrangements for mud flow and mud properties measurement are crucial for detecting influxes timely and efficiently. Again, job planning and competency were found to be the most critical organizational factors for preventing hydrostatic head failure. So, indicators related to these factors could play a big role in predicting potential failure.

Similar assessment was conducted for well swabbing events which has been presented in Figure 26. During pulling out, adequate amount of mud needs to be pumped into the wellbore to fill back the volume previously occupied by the drilling assembly. If pulling out faster than mud pumping/filling rate, bottomhole pressure may drop below the formation pressure causing influx. Thus, trip tank volume serves as a very crucial indicator which can show whether adequate mud has been added to the system or not. Also, influx from reservoir may replace mud in the wellbore causing an increase in the trip tank volume. To accurately assess these events, it is important to use accurate flow and volume measurement techniques. Proper job planning is also very crucial not only for preventing swabbing events but also to make sure that the trip tank volume is not impacted by any other jobs apart from the pulling out operations. For confirmed kick scenario due to swabbing, the efficiencies of real-time time indicators were found to be in the range of 65-70% (Figure 26).

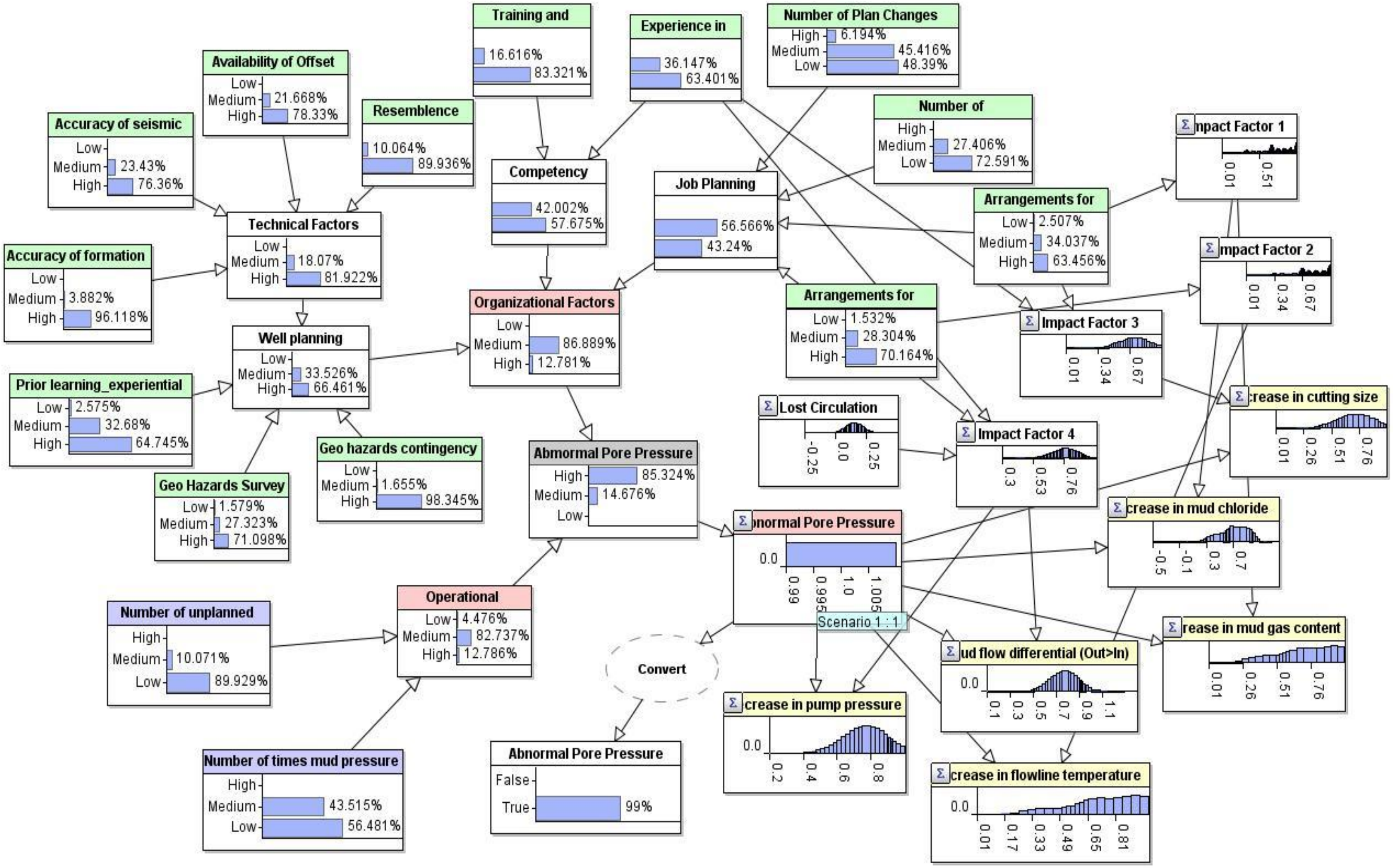

Figure 25 Leading indicators model – Loss of hydrostatic head due to abnormal pore pressure (confirmed scenario)
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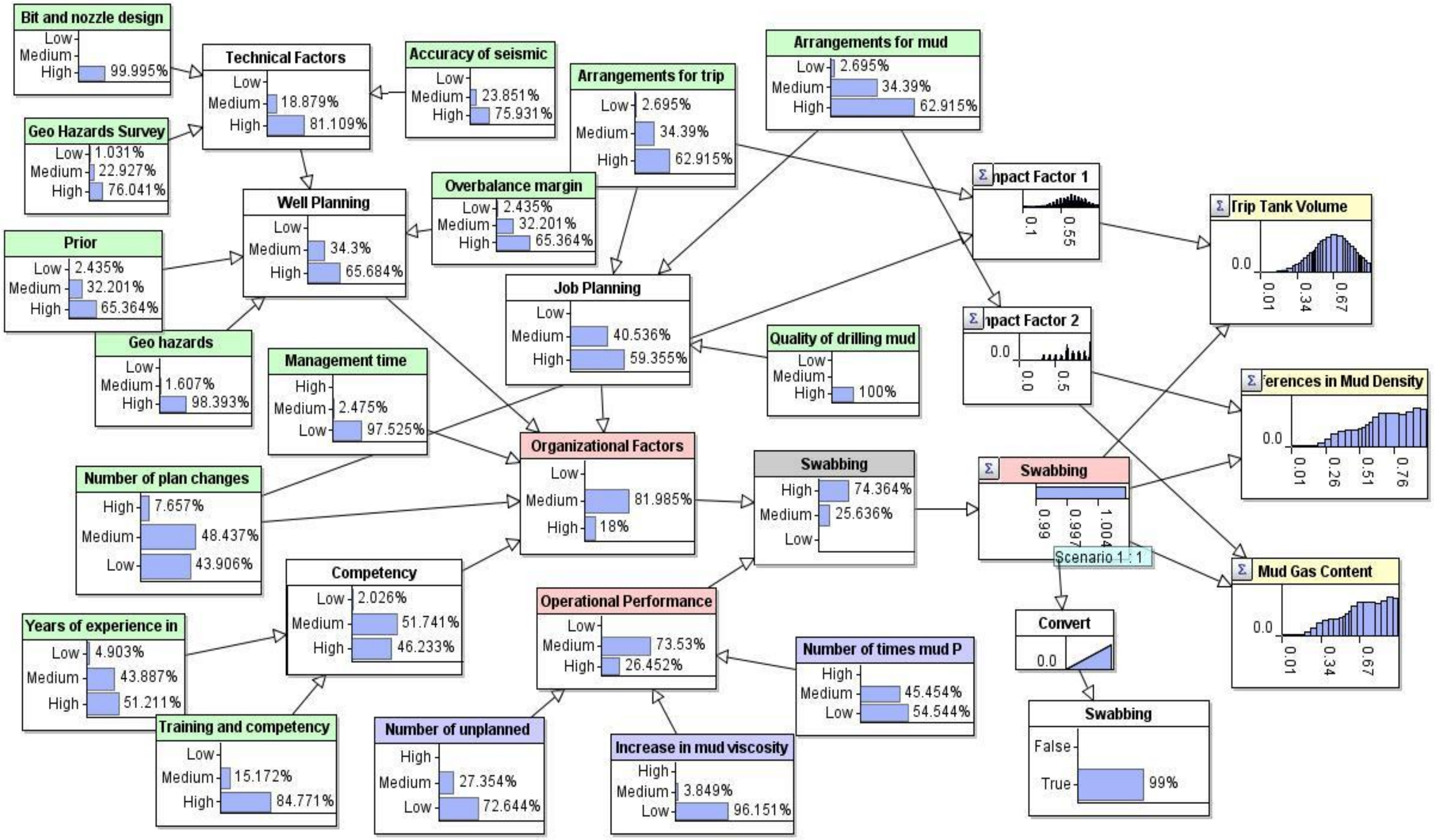

Figure 26 Leading indicators model- Loss of hydrostatic head due to swabbing (confirmed scenario)
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For assessing integrity of cement as a well control barrier, probability distributions for leading indicators were assigned to the Bayesian network model discussed in Section 5.2.1. Appropriate observations can be made to the leading indicators nodes for determining possibilities of well control events due to cement failure. One possible scenario has been presented in Figure 27 to discuss predictive application of the model. In this hypothetical case, the cement bond log test was assumed to be inadequate (node state set as ‘low’) and the annular pressure observed to be high (node state set as ‘high’). These observations could potentially indicate improper cement placement in the annulus and the probability of cement failure was found to be about 35%. If performance states of some other leading indicators also fall into unacceptable region, for example, ‘low’ for use of adequate centralizer and ‘low’ experience in current position and result interpretation, the failure probability of cement would significantly increase (Figure 28). For this case the failure mechanism can be explained as follows –

use of inadequate centralizer → ***low pipe stand-off ratio*** → *presence of mud channels in annulus* → *improper cement placement* → *failure to achieve zonal isolation* → ***failure to detect due to inadequate cement evaluation (cement bond log)*** → *removal of hydrostatic head* → *influx through annulus* → ***annular pressure increases***

Similarly, other potential failure mechanisms can be analyzed with the developed leading indicators-based models.

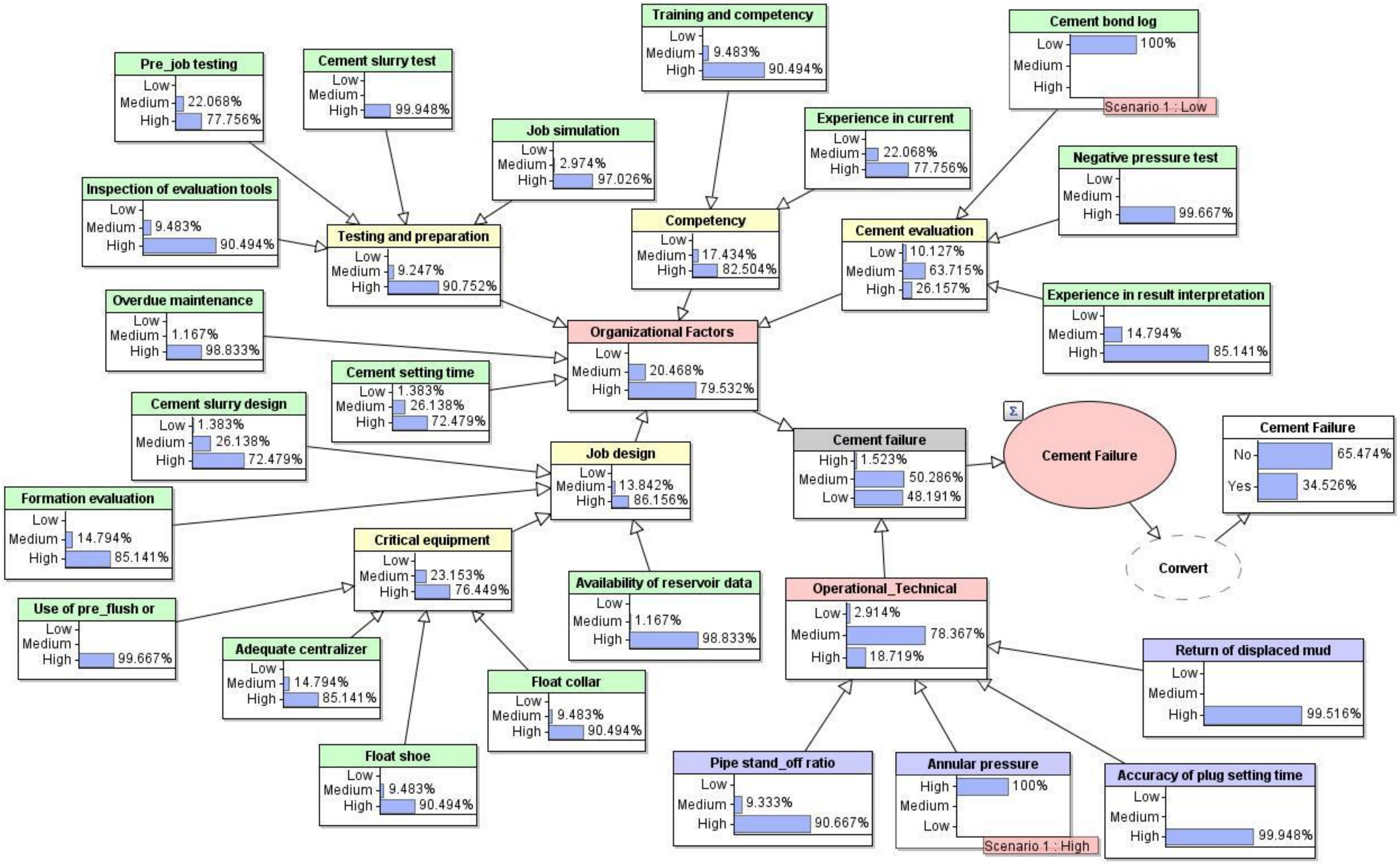

Figure 27 Leading indicators model- cementing failure (observation 1)

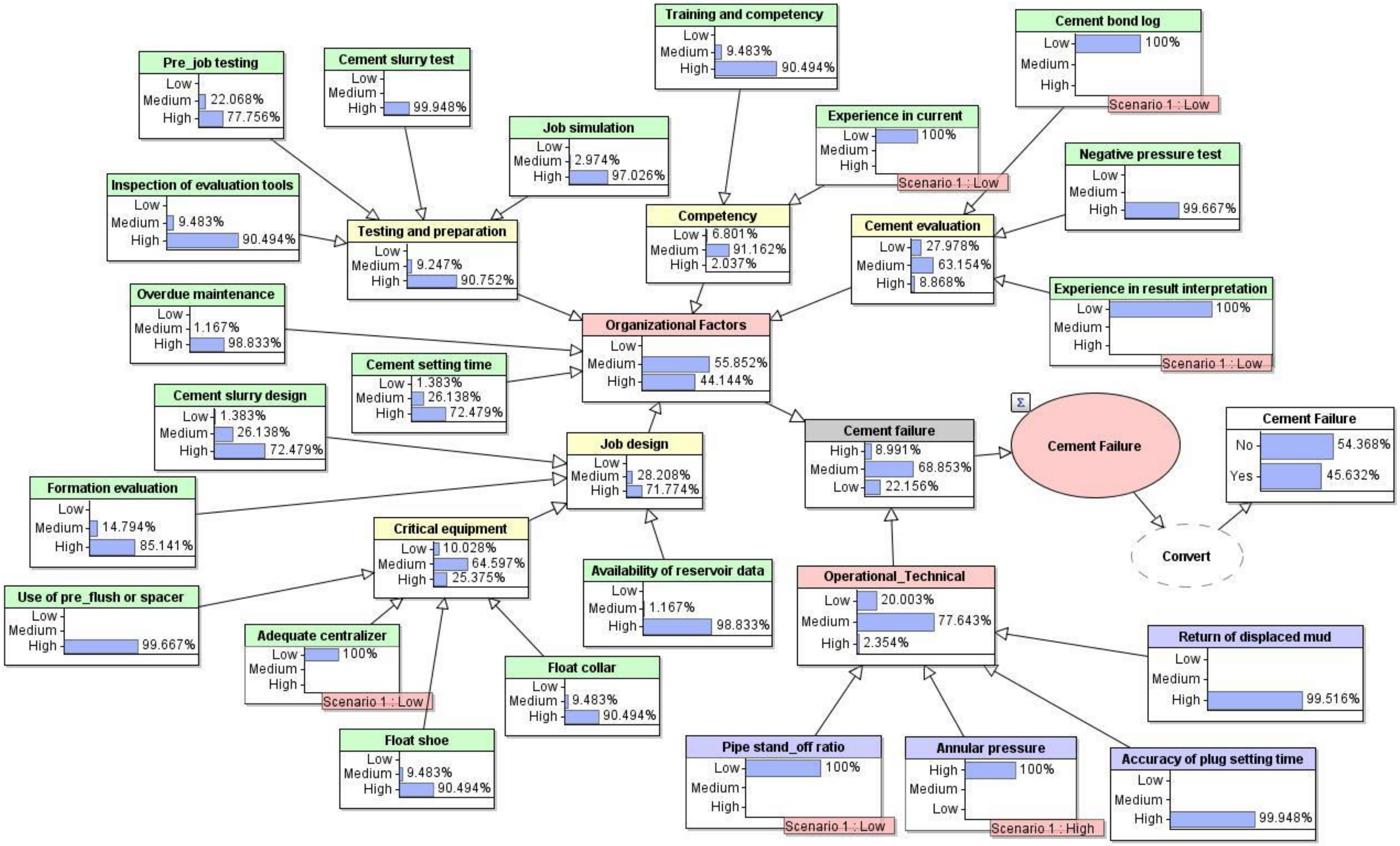

Figure 28 Leading indicators model- cementing failure (observation 2)

Both diagnostic and predictive functions of the developed models were tested in this study. Diagnostic reasoning was performed for confirmed kick scenario while drilling and completion. This analysis proved that, the weaknesses and vulnerabilities of a well control system can be identified with integrated leading indicators-based probabilistic models. Major events can be avoided if these weaknesses are identified and fixed in time.

Predictive reasoning was performed for cementing operations. Two hypothetical cases were analyzed to observe responses of the developed model. For a same failure mechanism, four or more leading indicators in unacceptable range indicate higher probability of cementing failure when compared to a case with two leading indicators in unacceptable range. This was an expected outcome, which proves the applicability of these models in predicting abnormal conditions.

Sensitivity analysis can also be performed for the developed models to assess the impacts of some selected indicators on target nodes (causal factor/barrier failure). A tornado graph representing the sensitivity of a target variable (abnormal pore pressure) to some selected variables (leading indicators) has been shown in Figure 29. For example, the indicator which has highest impact on the pore pressure to be in the ‘low’ state is ‘number of times mud pressure falls within 5% of pore pressure’. This can change the probability of abnormal pore pressure to be low from 30.6%-83%. These impact results can change if the models are updated with probability observations from real data.

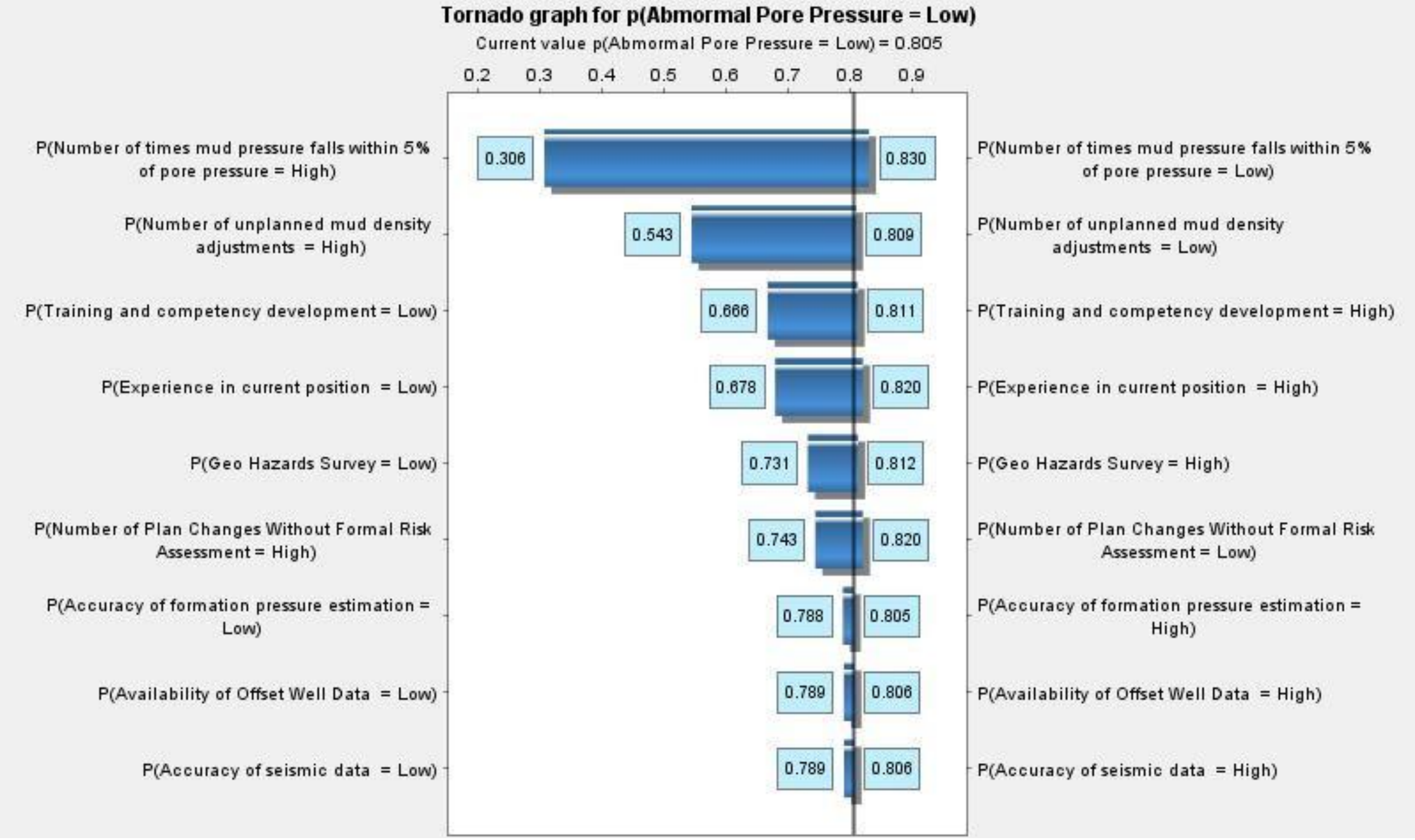

Figure 29 Tornado graph for sensitivity of abnormal pore pressure

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

The primary objectives of this research study were to develop a robust framework for identifying leading indicators for oil and gas well drilling, completion and intervention operations, and to construct probabilistic models using leading indicators data for assessing well control barrier failure events. Key results and findings of this study can be summarized as follows:

1. A general framework for identifying and developing sets of leading indicators were proposed with clear definition and categorization of leading indicators. Leading indicators have been primarily categorized into two groups – real-time observables and indicators based on operational/organizational performances. A systematic cause-based methodology for identifying appropriate sets of leading indicators was also proposed which can be applied effectively to any well operations including drilling, completion and workover.
2. Drilling, completion and well intervention operations were assessed thoroughly for developing suitable sets of indicators by following the proposed systematic approach. Primary well control barriers (hydrostatic head and cementing) were analyzed for drilling and completion activities, since the major focus of this study was on kick prediction and prevention. Well control barrier program is different in well wireline/slickline operations, and for that

reason these operations were analyzed separately. Fault tree analyses were performed to identify key causal factors for failure of the critical barriers while drilling, completion and wireline operations. Two different sets of leading indicators were proposed for monitoring integrity of two major primary well control barriers while drilling and completion – hydrostatic head and cementing. A set of leading indicators was also proposed for monitoring well control performance for preventing major events while conducting wireline operations.

3. Two major blowout incidents, Montara and Deepwater Horizon, were studied thoroughly for assessing applicability of leading indicators and the proposed framework for predicting potential abnormal conditions. This study suggested that for both of the incidents, appropriate sets of leading indicators could have provided early information on different operational and organizational issues that contributed towards the blowout. The analyses validate the critical need for a robust leading indicators program for preventing major incidents and the applicability of the proposed framework for developing appropriate sets of indicators.
4. Using the real-time indicators for detecting kicks while drilling, a couple of decision support algorithms were constructed. These algorithms provide crucial information on how different parameters change with progression of a kick and what actions need to be taken for confirming a kick scenario timely and efficiently.

5. For assessing barrier functions, probabilistic models were developed by integrating different groups of leading indicators. A Bayesian network tool was used to construct these models which can provide more realistic assessment of well control system. These models have multiple functions including –
    a. With leading indicators data, probabilities of kick initiating events or barrier failures can be assessed. Cementing failure event was analyzed by making different observations to certain leading indicators. This analysis showed the usefulness of these models in predicting barrier failure probabilities with information obtained from leading indicators.
    b. For a confirmed kick initiating or barrier failure event, influencing operational and organizational factors can be identified and corrected to reduce event probability. In this study, hydrostatic head failure event was analyzed for confirmed abnormal pore pressure and swabbing scenario.
    c. Efficiency of a kick detection system can also be assessed with the diagnostic analysis of these models. For example, both abnormal pore pressure and swabbing scenario were analyzed to observe how kick detection parameters behave for confirmed kick scenarios for the assumed sets of data. It was found that, the efficiencies of kick detection parameters are impacted by key organizational factors, *e.g.*, job planning and preparations, which can also be evaluated with the proposed models.

6.2. Recommendations for Future Works

Due to unavailability of appropriate leading indicators data, the base models were constructed with datasets assumed based on literature review, incident analysis and expert opinion. The next step of this study could be taking the proposed sets of leading indicators for drilling, completion or wireline operations, and collect data for a number of operations over a certain period of time. These data can be statistically treated to determine probability distributions for the leading indicators and the models can be updated with the new sets of data. This could provide more realistic estimation of kick initiating events or barrier failure probabilities.

The proposed models can be implemented and be used for assessing drilling, completion or wireline operations and leading indicators data/observation can be recorded for confirmed kick or failure scenarios. This study would help to identify crucial organizational and operational factors for preventing kicks and blowouts and validate criticality of each of the proposed indicators. This analysis would also help to determine the appropriate weightage factors of the indicator nodes that need to be assigned in the Bayesian network models. Based on the findings, the proposed models can be updated for accurate assessment of well control systems.

This study can also be extended for evaluating secondary barrier elements for drilling and completion operations, *e.g.*, blowout preventer, and pressure control equipment used in managed pressure drilling (MPD). For each of the drilling phases, probabilistic models for primary and secondary sets of barriers can be integrated together for assessing well control performance for total drilling operation. Similarly, other well operations, *e.g.*, hydraulic workover, abandonment, can also be studied for developing suitable sets of leading indicators.

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