4 Analysis and Results

The workshop was conducted as explained and outcomes for the process were received as planned. The following will analyze the data and results. First, Objective 1 methodology and data will be reviewed and analyzed. Then, Objective 2 methodology and results will follow.

4.1 Objective 1

Objective 1 study execution included identification of terms and parameters by which to gauge the relevance of a barrier for application. A safety barrier is contextualised by the function which it intends to fulfill and defined within a setting of a particular hazard (PSA, 2001). This first objective identified specific and relevant barrier performance factors as applicable for onshore gas drilling operations. Based on the variables identifed from the cross industry review in the literature review chapter, a list of 19 variables were collated and shown in

. It also listed the operative definition of these parameters.

Factor Analysis was deemed suitable and assumes that different variables have relationships based on related factors (Hutcheson, Sofroniou; 1999, p. 222). This list of parameters by which to evaluate barrier effectiveness was a key purpose of the first objective. With the list of barrier effectiveness parameters being confirmed as having correlation through Factor Analysis, the first objective study could progress to verification of the appropriateness of the variables. The following will explain the proceedings of the research as the variables were reviewed by industry professionals for expert analysis on the relevance of the chosen variables.

Review of safety barrier performance parameters applicable to onshore drilling operations

Since the list of barrier variables for this objective were borrowed from other industries, it was important to validate their relevance to onshore drilling operations. The 19 safety barrier performance parameters were identified by various researchers under the context of various operations such as generic petroleum operations, nuclear industry and offshore operations (Sklet et al, 2006). Additionally, the safety barrier performance parameters were identified based on generic frameworks such as ARAMIS (Salvi & Debray, 2005). Based on this progress, a need was determined to identify the relevant safety barrier performance parameters specific for onshore gas drilling operations.

For this purpose, the identified set of parameters were discussed with industry experts in onshore gas drilling operations. The experts were decided based on a minimum of ten (10) years of experience in the area of onshore drilling operations or Process Safety operations. The experts needed to have senior roles in their respective organisations for consideration in this study. The roles of experts identified for this survey were Drilling HSE Manager, Senior Drilling Engineer, Drilling Operations Advisor, Vice–President Drilling, Team Leader-Safety, Senior Drilling Engineering Manager and Corporate HSE Technical Safety Manager. The cummulative years of experience for the identified experts was 321 with an average experience of about 22 years per expert which is more than twice the requirement for someone to be classified as an expert.

The survey was conducted with 15 expert participants, and started with 19 variables such as functionality and reliability and ending with level of confidence during operation. The chosen variables were related to the findings from the literature review. The survey questioned whether the variables were seen as applicable for drilling operations by the participants. Each response was given a score for quantitative analysis. For scores of eight (8) or less, the variables were omitted from the next stage of the survey to eliminate irrelevant variables. Simultaneously, where respondents indicated need for new variables, which occurred nine (9) times, these were introduced to the subsequent round of survey administration.

During the interviews with the experts, the experts were asked for their specific inputs on the variables' relevance in onshore gas drilling operations. The participants were requested to give explanation and reason for any variables with which they disagreed. Based on the aggregation of results, it was observed that for 17 of the 19 variables identified based on literature review, there was more than 50% agreement between the experts. Only two (2) of the 19 variables identified, efficiency and implementation delay, were agreed by less than 50% between the experts.

In addition to identifying irrelevant variables, the experts were requested to suggest new variables which were not part of the initial survey list. The experts cummulatively suggested eight (8) new variables. These were collated and verified with all the experts for addition of these variables to the master list. The suggested variables for addition were: error promptness, operational complexity of the barrier, barrier reputation, barrier test simulation, barrier inter-dependancy, redundancy, impact of safety critical tasks and survivability. The results of the expert interviews are presented in Appendix 2.

Based on the identified eight (8) new variables, the operative definitions are included in Table 4.1.

Table 4.1: Safety barrier performance parameters - expert interview additions

Barrier Performance parameters	**Operative Definitions**
Error Promptness	It is the feature of the barriers to alert the barrier of a potential error in the near future
Operational complexity of the barrier	It is used to characterize operating something with many parts where those parts interact with each other in multiple ways
Barrier reputation	A widespread belief that the barrier has a particular characteristic
Barrier Test simulation	Checking the performance of the barriers in a test environment to the exact conditions the barrier has a possibility to be subjected
Barrier inter-dependency	It is the mutual dependence between barriers of two or more groups
Barrier redundancy	Inclusion of additional barriers which are not strictly necessary to functioning, in case of failure of other barriers
Impact of safety critical tasks on barriers	Critical activities to be conducted on the barriers which impact the barrier performance
Survivability	Protection required by a barrier or equipment item to ensure continued operation during a major incident

With the conclusion of interviews with industry experts to validate the relevance of the barrier variables chosen and to identify any additional variables to add for consideration, the study progressed to further validate the variables via a broader survey and by then conducting a Factor Analysis. The following will explain the survey process and subsequent Factor Analysis.

Survey questionnaire

With the expert interviews complete and the list of relevant variables being more clearly specified, the project progressed to the public survey portion. The purpose of the survey was to compare inputs from the narrow pool of experts against a broader audience of industry personnel to either confirm agreement or expose variables that may not be as strongly considered relevant when perceived by other professionals. The following will explain how the target audience was identified, how the survey was administered, and by what means the responses were evaluated.

Target population

A total of 200 respondents were surveyed using the online questionnaire. Appendix 3 shows the inputs received from each of these respondents. The survey was distributed to safety engineers and drilling engineers. The survey was distributed to professionals in the drilling industry including drilling engineers, managers and vice-president. The questionnaire was also distributed to professors dealing with upstream courses within the academic framework. In addition, the survey was distributed to safety consultants working for the drilling industry.

Sampling frame

The sampling frame included professionals who had knowledge of safety in oil / gas drilling operations. Therefore, the various stakeholders related to the drilling operations were considered. The stakeholders included drilling regulators, drilling engineers, supervisors, managers, vice-presidents, academicians and other safety professionals who have been working with the drilling industry.

Sampling technique

Stratified random sampling was used during the data collection process. The population was classified and number of elements from each stratum with relation to its proposition in the total population was selected. The sample size was distributed to the following job profiles within the Drilling industry:

i. Drilling engineers
ii. Drilling supervisors, managers, vice-president
iii. Safety engineers with drilling experience
iv. Safety Consultants for drilling operations
v. Safety regulators

Questionnaire design

The data collection instrument used for this survey was a questionnaire. The questionnaire consisted of 25 questions (relating to each of the parameter). The questionnaire was designed based on a 5 point Likert scale. The survey questionnaire is attached in Appendix 4.

Questionnaire development

The questionnaire was built based on the variables identified from literature review and validated through the expert survey which was consolidated to a total of twenty-five variables. Seventeen variables were identified through literature review and eight (8) were suggested as additions during the expert interviews conducted prior to the design of the questionnaire. Cronbach alpha was used as a tool to check the reliability of the questionnaire. A Cronbach alpha value greater than 0.6 confirmed the reliability of the questionnaire (Nunally, 1970). The Cronbach Alpha check was conducted at two (2) stages – during pilot testing after 40 responses and at the end after data collection from 200 responses [(Osborne, J et al, 2004 – Sample Size of 1:5); Rule of 200 - Guilford suggested that N should be at least 200 cases (MacCallum et al, 1999)]. Cronbach alpha was found to be around 0.89 during both the test conditions. It has been stated that acceptable values of alpha shall range from 0.70 to 0.95. A maximum recommended value of alpha is suggested as 0.9 (Tavakol et al., 2011).

For review of responses collected after the full 200 respondents as well as the responses collected at the 40-respondent interval, these can be considered in Appendix 3 and Appendix 5 respectively. Cronbach alpha was found to be about 0.89 during both the test conditions. Therefore, it was concluded that the questionnaire was reliable.

Information request

The consolidated list of parameters from literature review and the initial expert survey was presented to the survey respondents in the form of questions. The respondents were sought to respond on a 5-point Likert scale whether the parameter was a critical consideration in evaluating safety barrier performance for onshore gas drilling operations.

Pilot testing of the questionnaire

The questionnaire was initially checked for technical correctness of the parameter and ambiguous questionnaire. Based on the feedback during the pilot stage, the questionnaire was modified to incorporate the suggestions.

Broad questionnaire distribution

The questionnaire was distributed primarily during seminars and conferences (related to safety topics or general oil / gas industry) personally to the respondents. Prior to distribution of the questionnaires, the context of the research and background of the questionnaire were briefly elaborated. The questionnaire was distributed both in paper and electronic formats as per the convenience of the respondents.

Criterion Validity Tests

Kaiser-Meyer-Olkin (KMO) test was conducted to check the correlation between the pairs of variables. A KMO value greater than 0.5 is required to proceed with Factor Analysis. In the current research, the KMO score was 0.83 which was adequate to proceed with Factor Analysis.

Bartlett's Test of Sphericity is a check for the level of correlation between the variables. The level of significance should be less than 0.05. In the conducted research, a low value was obtained 0.00 (4.38E-205) which demonstrated that there was good correlation between variables and validation to proceed with Factor Analysis. This result is shown in Appendix 6.

Meanwhile, the Bartlett's Test was conducted where variables are evaluated for being relatively equal in relevance. Results confirming relevance will display in showing a 1 for being related to itself, and a score of less than 0.05 which proves relevance to the other factors in the analysis. The results for the Bartlett's Test proved the relevance of the effectiveness parameters and can be reviewed in Appendix 7.

Factor Analysis

Factor Analysis was conducted for the data resulting in Objective 1. Using Factor Analysis in this instance offered a statistical approach for understanding which underlying factors may be most relevant to the effectiveness of barriers. Both the research and survey focused on identifying factors which would aid in the evaluation of safety barrier performance.

Factor Analysis is used as a method for data reduction. This objective is achieved by seeking underlying unobservable variables that are reflected in the observed variables. The amount of variance a variable shares with all other variables included in the analysis is referred to as "communality". The covariation among the variables is described in terms of a small number of common variables plus a unique factor for each variable. The intent of the Factor Analysis was to confirm statistically that the variables chosen were applicable and related.

Analysis methods

Exploratory Factor Analysis was chosen as the paper intended to explore the possible underlying factor structure of a set of observed variables without imposing a predefined structure on the outcome. Through this process, the underlying factor structure was identified based on the observed response from the sample group. The goal of the Factor Analysis was to either confirm correlation of the variables or to expose variables that may not be correlated.

Factor analysis usually proceeds in two stages. In the first stage, one set of loadings is calculated which yields theoretical variances and co-variances that fit the observed ones as closely as possible according to a certain criterion. These loadings, however, may not agree with the prior expectations, or may not lend themselves to a reasonable interpretation. Thus, in the second stage, the first loadings are “rotated" in an effort to arrive at another set of loadings that fit equally well the observed variances and co-variances, but are more consistent with prior expectations or are more easily interpreted. The rotated component

Table 4.2: Rotated Component Matrix for 25 variables after 23 iterations

Rotated Component Matrix							
	Component						
	1	2	3	4	5	6	7
Reliability			0.64728				
Response Time			0.75155				
Robustness							0.631
Triggering event				0.75076			
Capacity			0.40505	0.51192			
Barrier Fitness	0.396						
Integrity	0.49383		0.54714				
Adequacy		0.74036					

Safety-Critical Tasks	0.51744						
Human Factors						0.73991	
Availability	0.62389						
Validity	0.54067						
Completeness							
Maintainability	0.45928			0.49705			
Lagging Indicators	0.73607						
Effectiveness	0.59555						
Barrier Level of Confidence During Operations				0.41826	0.52421		
Error Promptness	0.45412				0.49031		
Operational Complexity of the Barrier					0.46529		
Barrier Reputation					0.7793		
Barrier Test Simulation	0.47084						
Barrier Inter-Dependency						0.51741	
Barrier Redundancy		0.6153					
Impact of Safety Critical Tasks on Barriers		0.53837					
Survivability		0.79007					

For the conducted study, the variables were loaded onto seven (7) factors. The rotation method used was Varimax with Kaizer Normalisations. The rotations were converged after 23 iterations. The variables usually load significantly on only one factor. Based on the variables that load, a suitable name is assigned to the variables.

Based on the identified parameters from cross industry literature review and identifying specific variables from onshore drilling experts and survey respondents, a total list of 25 parameters were finalized. With these parameters confirmed through Factor Analysis, it was appropriate to group them into organized categories for clarity.

Construct and Content Validity Criterions

Finally, the above table demonstrated construct validity (all values in the rotated component matrix shall be > 0.4, except for 1 value listed as 0.396 which can be approximated as 0.4) and content validity criterions (Each of the 25 variables were loaded into the 7 factors) had been met.

Organizing factors

Based on the results from the Factor Analysis, twenty-five variables were confirmed as being correlated. From this point, the variables were grouped into seven (7) factors. The seven factors along with the grouped variables are listed

Table 4.3: Factors influence safety barrier performance for onshore gas drilling operations

Factors	Factor interpretation	Factor loading	Variables included in Factor
Factor 1	Performance factor	0.624	Availability
		0.541	Validity
		0.736	Lagging indicators
		0.596	Effectiveness
		0.471	Barrier Test simulation
		0.517	Safety critical tasks
Factor 2	Defense factor	0.741	Adequacy
		0.615	Redundancy
		0.538	Impact of safety critical tasks
		0.791	Survivability
Factor 3	Trust factor	0.647	Reliability
		0.751	Response time
		0.547	Integrity
Factor 4	Limit factor	0.751	Triggering event
		0.512	Capacity
		0.497	Maintainability
Factor 5	Perception factor	0.524	Level of confidence during operations
		0.491	Error promptness
		0.465	Operational complexity

Factors	Factor interpretation	Factor loading	Variables included in Factor
		0.779	Barrier reputation
Factor 6	Dependency factor	0.739	Human dependence
		0.517	Barrier inter-dependence
Factor 7	Robustness factor	0.631	Robustness

Emergence of factors

After Factor Analysis of 25 variables from the research study based on the survey questionnaire data, a total of 7 factors emerge. The various aspects contributing to individual factors have been tabulated in Table 4.3.

It can be observed through the grouping of 25 aspects/ variables into 7 factors confirms the loading of all the individual aspects into a factor as applicable. The aspects related to "Operational complexity" and "barrier test simulation" have found less weightage. The respondents have possibly thought that complex operation of the barrier may not have a direct influence on the barrier performance as it may be balanced by specialized training provided to the operator. Similarly, for "barrier test simulation", it may be believed by the respondents that test simulation results do not have a direct influence on the barrier performance specifically in terms of a drilling operations environment.

Factor 1 was termed as Performance factor as the underlying variables grouped were oriented towards barrier performance such as effectiveness, validity and lagging indicators. Factor 2 was termed as defense factor as it included variables such as Adequacy, reliability and survivability. Defense is the action of defending from or resisting attack. Factor 3 was termed as Trust factor as it included variables such as reliability, response time and integrity. Since "trust" is defined as firm belief in the reliability, truth, or ability of someone or something. Factor 4 was termed as Limit factor as it associated with variables such as triggering event, capacity and maintainability. These variables were critical in defining the "limits" of barrier performance. Factor 5 was associated with variables such as error promptness, operational complexity and barrier reputation. These variables are related to human perception and thereby termed as perception factor. Factor 6 was termed as dependency factor as it included human dependence and barrier inter- dependence variables. Factor 7 was termed as robustness as it included only one (1) variable.

Based on the Factor Analysis, it has been identified that the above listed seven (7) factors are key to evaluate safety barrier performance specifically in the context of gas drilling operations

Discussions & Model feedback/ validation workshop

Based on the review of these grouped parameters, it is identified that this current study seems to be the first that has been carried out to identify factors related to safety barrier performance for drilling applications. The current study aims to bridge the gap related to absence of literature on evaluating safety barrier performance for onshore gas drilling applications. This work suggests to identify safety barrier performance factors which can form the basis evaluate safety barrier performance in future applications. A model feedback and validation workshop was conducted using multi-disciplinary feedback from various stakeholders which is presented further in this document.

Objective 1 summary and recommendation

Through the analysis conducted in this work, key factors or themes were established which could be critical for evaluating safety barrier performance. These factors and the underlying variables could form the basis for building future risk models. Through the evaluation of these factors for individual safety barriers, it could assist in the overall re-assurance of safety in drilling operations.

4.2 Objective 2

The research pertaining to Objective 2 focuses on presenting an active risk monitoring method which evaluates barriers and transforms the existing Bow-Ties to a Bayesian Risk Model considering an onshore gas drilling environment. The Bayesian Risk Model is used to identify the operational risks associated with the MAHs for personnel and asset impacts. Active monitoring of risks is critical as it provides feedback on barrier performance before the risk results in disastrous impacts such as personnel or asset damage. The result of this effort presents a transformed Bow-Tie to a Bayesian Risk Model. The following will review proceedings of the research and the results generated from the effort.

Baselining the barrier based model

It has been emphasized that active monitoring of risks is critical as it provides feedback on barrier performance before the risk results in disastrous impacts such as personnel or asset damage. It was identified that several reactive risk assessment techniques (post-incident investigation) have been developed linking incident investigation to facility risk assessment Bow-Ties, depicting which Bow-Ties have failed in order to have an accident through a review of various accident pathways (Pitblado et al, 2015).

Review of existing barrier based Risk Assessment frameworks

The current objective focuses on presenting an active risk monitoring method which evaluates barriers and transforms the existing Bow-Ties to a Bayesian risk model.

Based on the review of risk assessment frameworks, several gaps were identified. In isolation, the Bow-Tie cannot be used to quantify risk based on the barrier failure and it does not account for inter-dependency of barriers (Lewis, 2010). Several industry regulations (such as UK COMAH and ADNOC

HSEMS) stipulate the requirement to demonstrate the control of hazards by linking the safety controls to elements of the management system (HSE, 1999) (ADNOC, Health, Safety & Environment Management System Guidelines, 2002). In addition, ADNOC guidelines has an associated Code of Practice on Control of Major Accident Hazards (COMAH) elaborates on the Bow-Tie methodology to demonstrate the visual depiction of safety controls and its hazards (ADNOC, 2014).

There was no linkage identified in any of the risk frameworks between barrier performance and the associated risk impacts. Therefore, risk analyses reviewed were static and did not consider barrier performance. The following outlines a method and application of a dynamic risk assessment for MAHs which consider the failure of safety barriers.

Real application of transformed Bow-Tie to a Bayesian Risk model

The risk model resulting from this study was a transformed Bow-Tie to Bayesian Risk model. The model is intended to close the gaps identified in the previous risk frameworks by allowing for consideration of barrier performance within the context of barrier effectiveness or failure. The model was tested using a real scenario to validate the application to barriers and risk prevention or mitigation. The following will review this scenario and application.

Barrier assessment as a solution to mitigate risk of H_2S

Sour service refers to a well environment containing significant amounts of Hydrogen Sulfide (H_2S). H_2S is toxic and considered hazardous to human health, living organisms, and the environment in general. Failures in sour wells are a major concern to oil & gas companies due to their consequential effects (American Petroleum Institute (API), 2001). In the majority of areas, gas is categorized as sour if H_2S comprises of more than 2.5% of gas contents. The Middle-East region has highly sour fields with H_2S up to 30% in some fields. Canada was one of the earliest discovered sour fields for high H_2S with one of its wells containing up to 90% H_2S. H_2S can be found in oil and/or gas fields, onshore and offshore, High Pressure High Temperature Fields (HPHT) and conventional fields, etc. H_2S content can keep on increasing during the aging of the asset irrespective of initial composition.

The International Energy Agency (IEA) published in their 2014 medium term gas market report a 1.2% growth in global natural gas demand over the span of 2013. BP forecasted in their energy outlook an increase in global natural gas demand by an average of 1.9% per year to 2035. With increasing demand of gas worldwide, some highly sour oil and gas reservoirs are being explored. Such explorations are occurring mainly in Russia, the Middle East, China, North America, and are now more and more associated with complex well profiles – such as deep reservoirs or extended reach wells. As time passes, more of the previously uneconomical sour fields will become viable development projects.

MAHs put personnel, production, capital investment and corporate reputations at risk. The management of MAH risk includes a structured approach to minimize the event likelihood and reducing the consequence of a Major Accident Event (Dalzell & Ditchburn, 2003). A review of MAH was conducted for three (3) onshore sour gas drilling operations within the region of the United Arab Emirates (UAE). The review was conducted to compare the various MAH along with the number of threats and consequences identified for each of the drilling operations. The summary of the review is presented in Table 4.5. Additionally, the comparison between the Drilling Assets are added in Table

Table 4.4: Comparison of the selected drilling Assets

	Asset – A	**Asset- B**	**Asset-C**
Location (Type)	Onshore	Onshore	Onshore
Location (distance)	400 kms south-west of Abu Dhabi City	Man-made Island is located- 55 nautical miles to the south -west of Abu Dhabi	180 kms -south west of Abu Dhabi City
Type of drilling	Vertical and horizontal deviated holes	Vertical and horizontal deviated holes	Vertical and horizontal deviated holes
Total Depth (ft)	10500	10232-10895	8700-11000
Type of wells	Sour Gas (Low)	Medium Sour Gas	Highly Sour Gas
No. of wells to be drilled	13	1	20
Surrounding local populations	600 people (50 kms radius)	No human inhabitations; Surrounded by Second largest population of dugongs - Ecologically sensitive site	Moreeb Hill populations (6000 -12000 people)
H_2S concentration in the well fluid	0.05 % (500 ppm)	18% (180000 ppm)	23% (230000 ppm)
Safety barriers	Threat barriers - 18; Recovery measures -14;	Threat barriers - 21; Recovery measures - 15	Threat barriers - 28; Recovery measures -18;

Based on the review, Asset-C was selected as the asset for application of the transformed Bow-Tie and Bayesian Risk model due to the comprehensive listing of the MAH and the associated safety barriers. The listed information in Table 4.4 was sourced from the Health, Safety and Environment Impact

Assessment (HSEIA) and details were referred in the COMAH Reports. Based on the identified MAHs for Asset-C, only six (6) out the eleven hazards were related to core drilling operations. Due to the confidential nature of such reports, it has been kept anonymous and not referenced.

Table 4.5: Review of MAHs from 3 onshore gas drilling assets

Asset	MAH No.	MAH description	Risk Classification category	Applicable to Drilling operations	No. of threats	No. of consequences
Asset - A	1	Loss of containment during site preparation	People	No		
	2	Loss of sub-structure stability during 26-inch hole drilling	Asset	Yes	2	1
	3	Loss of containment during 16-inch hole drilling	Asset	Yes	1	1
	4	Loss of containment during 12.25 inch and 8.5-inch hole drilling	People	Yes	4	1
	5	Loss of well bore integrity during 12.25 inch and 8.5-	People, Asset	Yes	2	2

Asset	MAH No.	MAH description	Risk Classification category	Applicable to Drilling operations	No. of threats	No. of consequences
		inch hole drilling				
Asset - B	1	Loss of containment during Onshore well drilling	People, Asset	Yes	4	5
		- during Casing		Yes		
		- during wireline logging		Yes		
		- during drilling		Yes		
		- retrieving core to the surface (logging)		No		
Asset - C	1	Loss of containment during well operations - During drilling activities - During work over	People, Asset	Yes	3	2

Asset	MAH No.	MAH description	Risk Classification category	Applicable to Drilling operations	No. of threats	No. of consequences
		- During Well testing Resulting in multiple fatalities onsite and offsite and asset damage				
	2	Loss of containment (Blowout scenario) - during drilling through Habshan Reservoir - while running 9 5/8" x 10 3/4" casing	People	Yes	2	2
	3	Loss of containment (Blowout scenario) - during drilling 8	People	Yes	1	3

Asset	MAH No.	MAH description	Risk Classification category	Applicable to Drilling operations	No. of threats	No. of consequences
		1/2" Pilot Hole through Arab Reservoir				
	4	Loss of containment - Formation fluid influx (kick) during coring - Induced well control while retrieving core to the surface - Unstable well conditions from pumping HC's into the well bore while logging on the drill pipe	People	Yes	3	3
	5	Loss of containment	People	Yes	3	3

Asset	MAH No.	MAH description	Risk Classification category	Applicable to Drilling operations	No. of threats	No. of consequences
		(kick and well flow) during - Drilling 8 1/2" hole through Arab reservoir - Well flow while running 7" casing - Running 7" CRA liner				
	6	Loss of containment (kick) during - Drilling 6" hole through Arab reservoir	People	Yes	1	3
	7	Loss of containment (kick) during - while running 7" CRA Production tubing	People	No	3	3

Asset	MAH No.	MAH description	Risk Classification category	Applicable to Drilling operations	No. of threats	No. of consequences
		- while installing XMT - while nippling down BOP and nippling up XMT				
	8	Loss of containment - Equipment failure in riser while coil tubing within hole - Down hole conditions leading to stuck well tools in the tubing	People	No	2	3
	9	Loss of containment - Human Error while stimulating the well	People	No	1	3

Asset	MAH No.	MAH description	Risk Classification category	Applicable to Drilling operations	No. of threats	No. of consequences
	10	Loss of containment during Well operations (surface related issues) - Erosion - Corrosion - Vibration - Hydrate formation - Overpressure in the downstream of choke manifold - Improper operation of 3 phase separator - PAGE 692	People	No	11	3
	11	Loss of containment during flaring	People	No	1	3

The following will briefly explain the context for each MAH listed in Table 4.5.

MAH 1 - focuses on the Simultaneous Operations (SIMOPS) aspect of the well campaign. SIMOPS typically occur within process facilities when multiple activities (two or more) occur at the same time and place. This may introduce risks that are not identified when each activity is considered in isolation (Baybutt, 2016) (IMCA, 2010). The consequences of this MAH have been subdivided into the affected group, neighboring field personnel (e.g. second drilling rig, construction personnel etc.) and the general public.

MAH 2 - focuses on the loss of well control whilst operating in the Habshan section (deeper drilling depths) of the wells.

MAH 3 - relates to loss of well control whilst drilling the pilot hole through the Arab Reservoir.

MAH 4 - relates to loss of containment whilst performing data acquisition in, and plugging of the pilot hole.

MAH 5 - relates to loss of containment whilst drilling the 8 ½" hole to the landing point in the Arab Reservoir and cementing the 7" Corrosion Resistant Alloy (CRA) Liner.

MAH 6 - relates to loss of well control while drilling through the Arab reservoir to Total Depth.

MAH 7 to MAH 11 have not been analyzed due to their non-applicability to core drilling operations.

The MAHs discussed above were further decomposed into relevant Threats and consequences in Table 4.6.

Table 4.6: Decomposition of MAHs into Threats and Consequences

MAH number	Threats	Consequence
1	Loss of containment due to - during well operations (T1) - During drilling activities (T2)	Loss of containment resulting in multiple fatalities onsite and offsite and asset damage - affecting offsite personnel (C1) - affecting onsite personnel (C2) - affecting public (C3)
2	Loss of containment (Blowout scenario) due to - Formation fluid influx into well bore during drilling through Habshan Reservoir (T3) - Formation fluid influx into well bore while running 9 5/8" x 10 3/4" casing (T4)	Loss of containment resulting in - Major Toxic release (C4) - Fire (C5) - Explosions (C6)
3	Loss of containment (Blowout scenario) - during drilling 8 1/2" Pilot Hole through Arab Reservoir (T5)	Loss of containment resulting in - Major Toxic release (C4) - Fire (C5) - Explosions (C6)
4	Loss of containment due to - Formation fluid influx (kick) during coring (T6)	Loss of containment resulting in - Major Toxic release (C4) - Fire (C5) - Explosions (C6)

MAH number	Threats	Consequence
	- Induced well control while retrieving core to the surface (T7) - Unstable well conditions from pumping HC's into the well bore while logging on the drill pipe (T8) - Plug failure while plugging pilot hole (T9)	
5	Loss of containment (kick and well flow) due to - Drilling 8 1/2" hole through Arab reservoir (T10) - Well flow while running 7" casing (T11) - Running 7" CRA liner (T12)	Loss of containment resulting in - Major Toxic release (C4) - Fire (C5) - Explosions (C6)
6	Loss of containment (kick) due to - Drilling 6" hole through Arab reservoir (T13)	Loss of containment resulting in - Major Toxic release (C4) - Fire (C5) - Explosions (C6)

Based on the above decomposed MAHs, thirteen (13) threats and six (6) consequences were identified.

Risk model application

Based on the review of the Company Risk Analysis report, Bow-Tie analysis was applied to all six (6) applicable MAHs to identify and assess the prevention, control, and mitigation measures proposed to manage these hazards and risks. The approach adopted was based on material presented in the ADNOC COMAH Code of Practice (ADNOC, Code of Practice on Control of Major Accident Hazards (COMAH), ADNOC COP V05-01, 2014). The below sub-sections list the transformation of the Bow-Tie into a Bayesian based dynamic risk model, as well as the evaluation of risk using this approach and results of a model validation workshop.

Conversion of Bow-Ties to Bayesian Networks

Initially the drilling major accident hazard Bow-Ties were transformed into potential threat and consequence accident pathways. This approach proposed by Pitblado and Fischer transformed the full Bow-Ties into various incident Bow-Ties (Pitblado & Fischer, 2010). An illustration of the approach is shown in

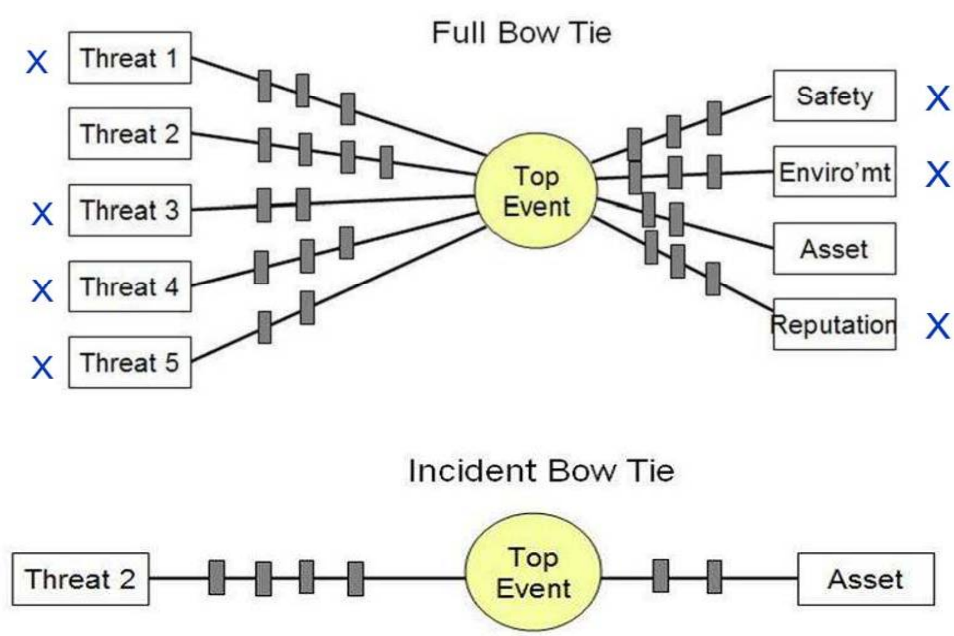

Figure 4.1: Transformation of full Bow-Tie to an incident Bow-Tie

The above approach was modified to meet the purposes of risk calculations. The term "risk" is according to international standards (such as ISO 2002), which is a "combination of the probability or an event and its consequence". Other standards, like ISO 13702 (ISO 1999), have a similar definition: "A term which combines the chance that a specified hazardous event will occur and the severity of the consequences of the event" (Vinnem, 2014).

An operational expression for practical calculation of risk is the following, which underlines how risk is calculated by multiplying probability and numerical value of the consequence for each accident sequence i, and summed over all (I) potential accident sequences:

Equation 1

$$R = \sum_i (p_i \cdot C_i)$$

where:

p = probability of accidents

C= consequence of accidents

Therefore, based on the above definition of risk, it was decided to split the Bow-Tie into Threat and Consequence event pathways respectively. The next section focuses on evaluating risk impacts on personnel and assets.

Evaluation of safety barriers performance using the factors

Research was conducted to identify safety barrier performance factors for onshore gas drilling operations. The factors included performance, defense, trust, limit, perception, dependency and robustness. The grouped variables under each of the factors are listed below from Objective -1:

i. Factor 1 – Performance factor

- Availability
- Validity
- Lagging indicators
- Effectiveness
- Barrier test simulation
- Safety critical tasks

ii. Factor 2 – Defense factor
- Adequacy
- Redundancy
- Impact of safety critical tasks
- Survivability

iii. Factor 3 – Trust factor
- Reliability
- Response time
- Integrity

iv. Factor 4 – Limit factor
- Triggering event
- Capacity
- Maintainability

v. Factor 5 – Perception factor
- Level of confidence during operations
- Error promptness
- Operational complexity
- Barrier reputation

vi. Factor 6 – Dependency factor
- Human dependence
- Barrier inter-dependence

vii. Factor 7 – Robustness factor
- Robustness

Data was collected from all HSE / Drilling personnel on all the barriers for the identified asset (Asset-C) with respect to the identified factors from Objective

1. HSE personnel included a Drilling HSE Manager and a Senior HSE staff member. The data from these personnel is included in Appendix 8 along with master consolidation of all inputs.

The ratings were carried on a five (5) point scale, where one (1) related to Very Low (ineffective) and five (5) related to Very High (effective). A total of 28 threat barriers and 18 recovery measures were identified. The threat barriers and recovery measures were mapped against the major accident hazards, which is shown in Appendix 9.

Table 4.7: Threat and consequence barrier types

Type of Barrier	**No. of Barriers on Threat Side**	**No. of Barriers on Consequence Side**
Hardware	15	7
Operating Procedures	10	3
Training	1	1
Design	1	2
Maintenance Management	1	-
Emergency Response Planning	-	4
Communications	-	1
Total	**28**	**18**

The summary of the ratings based on the average score is listed as part of Appendix 10 for threat barriers and in Appendix 11 for recovery measures. The average scores from all the participants were normalized by conversion of the rating scale from 1-5 to a normalized scale of 0-1 for usage as input in the Bayesian Networks.

Operational risk evaluation through Bayesian Networks

The Bow-Tie method has not been recognized as a dynamic analysis technique as is composed of static methods such as a fault tree and event tree (Khakzad et al., 2013a). Weber has highlighted the usage of Bayesian Networks in reliability, risk and maintenance function due to their ease of use with domain experts. Bayesian Networks are particularly suitable for collecting and representing knowledge on uncertain domains. It also enables probabilistic calculus and statistical analyses in an efficient manner (Weber et al., 2012). In this stage, the static Bow-Ties are transformed into a dynamic risk model using Bayesian Networks (Ale, et al., 2006) (Ale, et al., 2009) (Khakzad et al., 2011) (Khakzad et al., 2013b).

Bayesian Network is a graphical technique that has started to be widely applied in the field of risk analysis. As noted earlier within this work, the Bayesian Network is composed of nodes, arcs and probability tables to represent a set of random variables and the conditional dependencies among them. (Khakzad et al., 2013a). The Bayesian Network for this analysis was developed using AgenaRisk Version 6.0 software. For this research, the drilling Bow-Ties were transformed into a dynamic Bayesian Network as shown in Figure 4.2, Figure 4.3, Figure 4.4 and Figure 4.5. The complete sequence of events for this

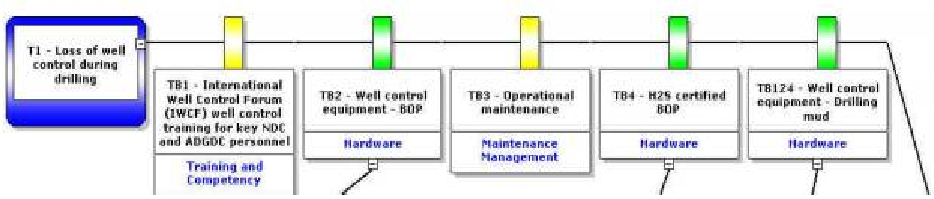

Figure 4.2: Static Bow-Tie for a threat in the drilling Bow-Tie

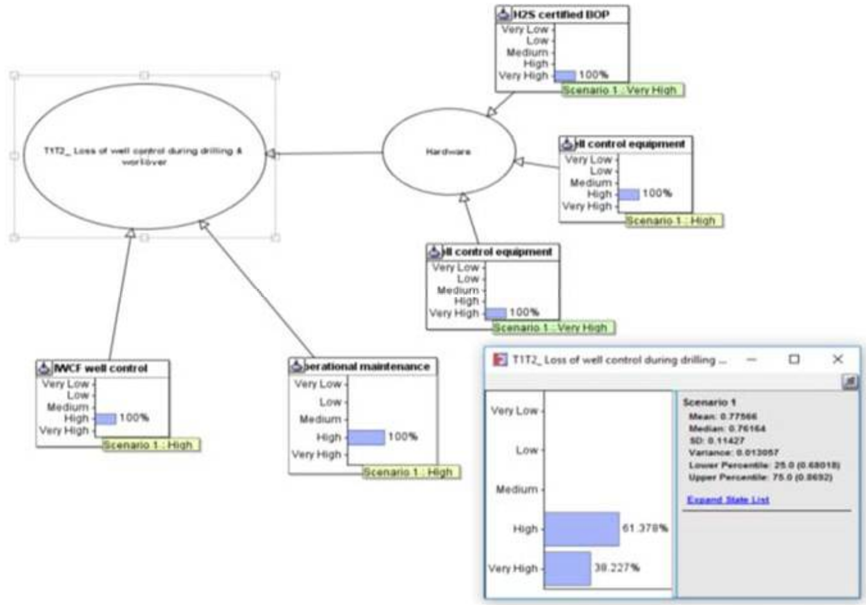

Figure 4.3: Transformed Bayesian Network – threat line

Figure 4.4: Static Bow-Tie for a consequence in the drilling Bow-Tie

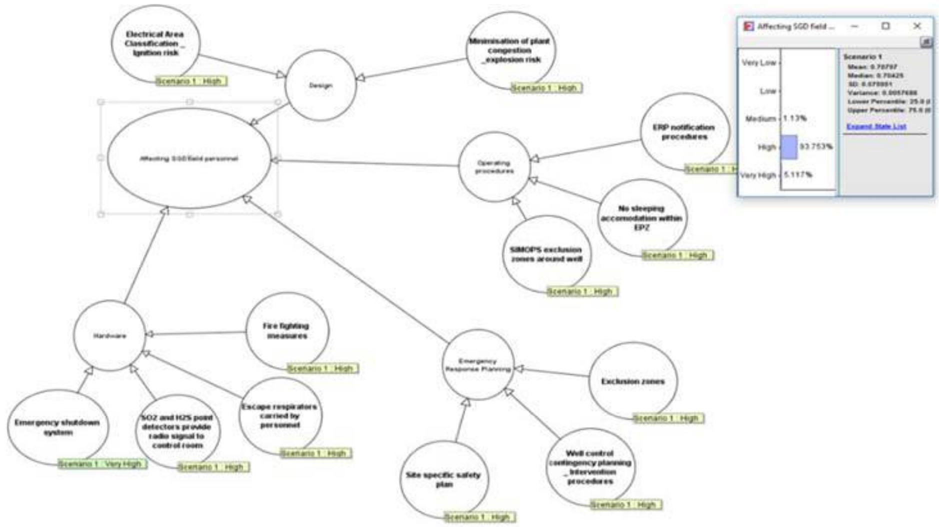

Figure 4.5: Transformed Bayesian Network – consequence line

Each of the safety barriers were modeled using the ranked nodes. Ranked nodes represent discrete variables whose states are expressed on an ordinal scale that can be mapped onto a bounded numerical scale that is continuous and monotonically ordered (Fenton et al., 2007). Ranked nodes have been defined on an underlying unit interval [0-1] scale. A five-point scale such as {very low, low, average, high, very high}, is chosen to model the individual safety barriers in the Bayesian Network. The interval width for each state is 0.2. Thus, "very low" is associated with the interval [0 - 0.2), "low" is associated with the interval [0.2 - 0.4), and so forth. Ranked nodes enable the Bayesian Network construction and editing task much simpler than is otherwise possible. Through this method, each of the threats and consequences were transformed into a dynamic Bayesian Network diagram.

Threat barriers and consequence barriers were evaluated using the constructed Bayesian Networks – an overall barrier performance is thereby evaluated for each threat and consequence associated with a MAH is presented in Figure 4.3 and Figure 4.5.

IR is evaluated as a criterion for MAH identification considering "NO" safety barriers. MR is ranked considering Safety barriers are perfectly functional (100%). Inherent and MR were ranked using ADNOC 5 X 5 Semi-quantitative Risk Matrix (ADNOC, 2014). Typically, these rankings are usually agreed in a HAZID Risk Ranking workshop. Meanwhile, risk control is built on the reduction of the frequency of occurrence of the major dangerous phenomena, taking into account the safety barriers' performance so that the dangerous phenomena are defined with an acceptable couple, i.e. gravity-frequency of occurrence. In reality, the AR exposure should be directly correlated with safety barriers' performance.

Table 4.8: Summary of barrier effectiveness - threat and consequence

MAH number	MAH description	Risk Classification category	Inherent Threat (without barriers)	Mitigated Threat (with barriers)	Actual Threat barriers effectiveness (%)	Actual Threat (considering barriers effectiveness)	Inherent Consequence (without barriers)		Mitigated Consequence (with barriers)		Actual Consequence barriers effectiveness (%)		Actual consequence (considering barriers effectiveness)	
							P	A	P	A	P	A	P	A
1	Loss of containment during well operations - During drilling activities Resulting in multiple fatalities onsite and offsite and asset damage - affecting ADCO personnel (offsite) - affecting AHG personnel (onsite) - affecting public	People, Asset	E	C	78%	Between C & D	5	5	2	1	75% (ADCO field personnel) 70% (AHG-SGD field personnel) 75% (General public)	75% (ADCO field personnel) 70% (AHG-SGD field personnel) 75% (General public)	3	2
2	Loss of containment (Blowout scenario) - Formation fluid influx into well bore - during drilling through Habshan Reservoir - while running 9 5/8" x 10 3/4" casing resulting in major toxic release, fire and	People	E	C	78%	Between C & D	5		2		70% (toxic) 70% (fire) 70% (explosion)		3	
3	Loss of containment (Blowout scenario) - during drilling 8 1/2" Pilot Hole through Arab Reservoir	People	E	C	78%	Between C & D	5		2		70% (toxic) 70% (fire) 70% (explosion)		3	
4	Loss of containment - Formation fluid influx (kick) during coring - Induced well control while retrieving core to the surface - Unstable well conditions from pumping HC's into the well bore while logging on the drill pipe - Plug failure while plugging pilot hole	People	E	C	78% (Coring) 68% (Induced well control) 70% (while logging) 68% (plugging pilot hole)	Between C & D	5		2		70% (toxic) 70% (fire) 70% (explosion)		3	
5	Loss of containment (kick and well flow) during - Drilling 8 1/2" hole through Arab reservoir - Well flow while running 7" casing - Running 7" CRA liner	People	E	C	78% (Drilling) 76% (Casing) 78%(CRA Liner)	Between C & D	5		2		70% (toxic) 70% (fire) 70% (explosion)		3	
6	Loss of containment (kick) during - Drilling 6" hole through Arab reservoir resulting in major toxic release, fire and	People	E	C	78%	Between C & D	5		2		70% (toxic) 70% (fire) 70% (explosion)		3	

It is identified that the actual operational risk is between 3C and 3D in terms of the Abu Dhabi National Oil Company (ADNOC) Risk Matrix. IR, MR and the calculated AR have been mapped in the ADNOC Risk Matrix for personnel in Figure 4.6. It is observed that the AR is very close to the High Risk region and the risk is in the higher ALARP [1]region in comparison to the MR. The medium Risk region is considered to be acceptable but must be managed by ALARP. Reducing risks to ALARP means reducing them to a level at which the cost and effort of further risk reduction is grossly disproportionate to the risk reduction achieved (ADNOC, 2014). The inference from these results would prompt the organizations to focus on enhancing the performance of the safety barriers to

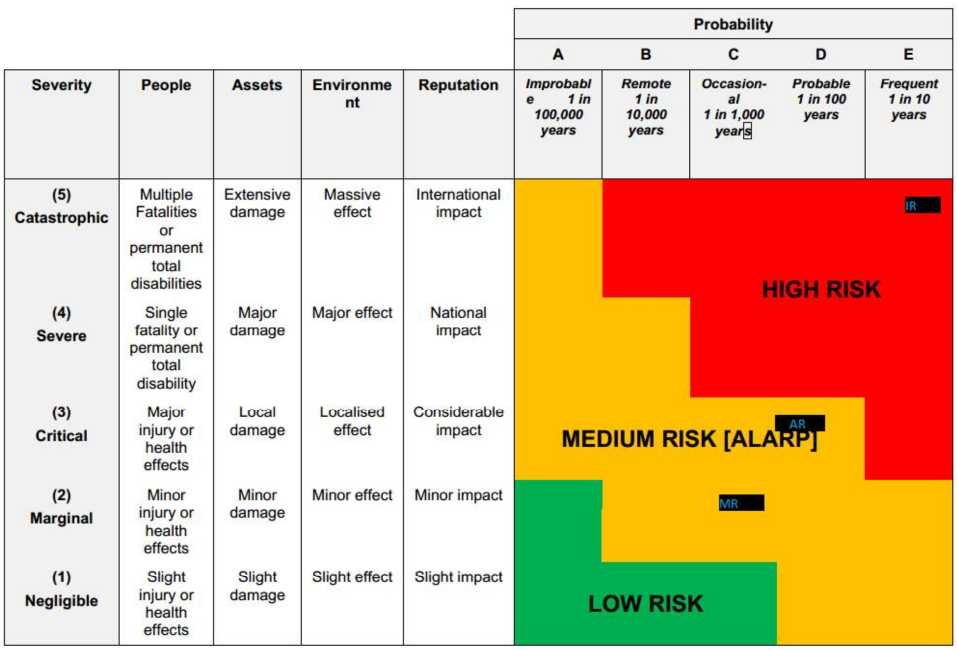

Figure 4.6: Mapping of IR, MR and AR in ADNOC's semi-quantitative risk matrix (personnel)

[1] ALARP – As Low As Reasonably Practicable

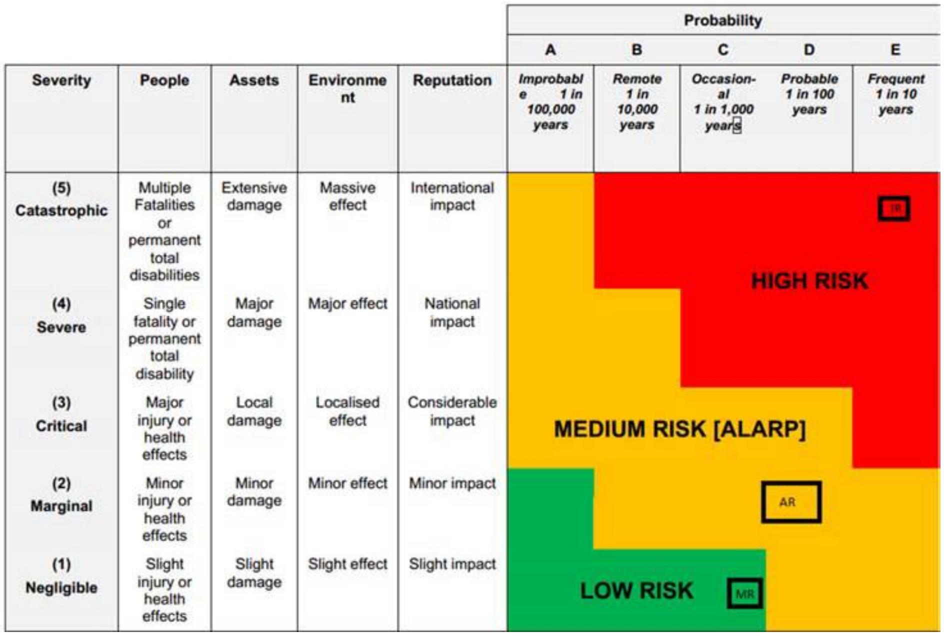

Figure 4.7: Mapping of IR, MR and AR in ADNOC's semi-quantitative risk matrix (assets)

Meanwhile, for the Asset related MAH which was identified only for MAH 1, the AR is 2A which can be around the lower ALARP region as shown in Figure 4.7.

Therefore, comparing the Personnel and Asset Risk, the AR exposure of personnel risk is slightly higher.

Inferences from the Risk Assessment for Objective -2

Based on the developed Bayesian barrier based Risk model the follow inferences could be listed for Asset-C:

- From the analysis of overall barrier performance, it was observed that the threat barrier effectiveness ranges from 68% (Induced well control and plugging pilot hole threats) to 78% (related to core drilling operations).

- Similarly, consequence barrier effectiveness ranged from 70% on controls related to mitigate on- field impacts (Fire, explosion and toxic) to 75% on controls related to off- site and public impacts.

- For the Personnel risk, the AR is very close to the High Risk region and the Risk is in the higher ALARP region in comparison to the MR which was in the lower ALARP region.

- For the Asset Risk, the AR is around the lower ALARP region in comparison to the MR which is in the Low Risk region.

- Therefore, comparing the Personnel and Asset Risk, the AR exposure of personnel risk is slightly higher.

Model Feedback and Validation

The barrier based risk model & results were validated through a workshop consisting of mixed group comprising of HSE Manager, Process Safety Engineers, Senior Drilling Engineers, Senior Well Integrity and Regulators (Safety Department Manager). A total of ten (10) members participated in the workshop conducted in December 2016. The primary data used for the development of the model was abstracted from Bow-Tie exercises conducted in the onshore drilling industry. This exercise leveraged the Bow-Tie framework to identify major hazards and related accidents. Six frameworks were leveraged to identify relevant barriers for common top events.

The model development approach and the results were presented to the audience, followed by a question and answer session for further clarification.

The proposed model validation approach has been used in validation of prior Risk assessment models. A five-point scaling technique was used through a structured questionnaire. In the five-point scale, one (1) represents the least and five (5) represents the best situation, meaning the degree of the validity of the model varies from 1 to 5. The validation parameters included were overall conceptual framework (barrier performance factors), relevance of data, models / techniques, interpretation of risk and overall applied value of the risk model (Abbas & Routray, 2013). The individual feedback forms are listed in Appendix 13. The summary of the scores and the average scores for each of the

Table 4.9: Summary of scores - Model feedback and validation workshop

Member	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Avg. score**
Overall Conceptual framework - Barrier Performance factors	5	5	5	5	5	5	5	4	5	4	4.8
Relevance of data	4	4	5	5	5	4	4	4	4	4	4.3
Models and Techniques	5	5	5	5	5	5	4	5	5	5	4.9
Interpretation of results	5	4	5	5	5	3	5	4	5	4	4.5
Overall applied value of the Risk model	5	4	5	5	5	4	4	5	5	4	4.6

Based on the scores listed, the respondents have given a score of 4.8 to overall conceptual framework and models/ techniques, 4.6 overall applied value of the risk model, 4.5 for the interpretation of the results and 4.3 for the relevance of the data. The average of all the components was 4.62 which means that the model is highly reliable. In conclusion, the respondents found value for the model application in real life. Apart from the ratings, the respondents gave positive comments in the feedback form. Excerpts from the forms are given below:

- Use of Bayesian Network and combination of Bow-Tie is a very excellent idea & its self-learning ability will maintain a dynamic overview of Barrier Risk Management.
- Excellent presentation. Clearly a deep understanding of the topic. The presentation was well received.
- Very good project and good research.

It is clear that the second objective is fulfilled in a way that is practical and usable based on the results of the study and the feedback of the participants. The risk assessment model allows for real analysis of barrier effectiveness in an onshore drilling application. Having a risk evaluation tool is a significant contribution to this field of study, and it will be categorized as a contribution of research to the industry in the next section.