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Drilling Risk Identification, Filtering, Ranking and Management

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ABSTRACT

Drilling Operations are exposed to a variety of hazards, some of which may be location and activity dependent and each could pose different risk from different paths. Drilling operation may be vulnerable to hurricanes in one region and be exposed to Geohazards in another. However, there are other hazards, (e.g. corrosion, age degradation, poor maintenance), which equally affects every rig. Identifying what can go wrong and their likelihood and possible consequences provides insight into vulnerability of the operation and helps to generate mitigation options. Filtering and Ranking risk contributors enable to decide priorities and to focus on the most important risk contributors. This paper offers a framework to identify, assess, prioritize, and manage drilling risks, which includes: (1) a holistic approach to risk identification; (2) prioritization of a large number of risk influencing factors or risk scenarios; (3) structured elicitation of experts' opinion and effective integration of experts judgment into qualitative and quantitative analyses to supplement limited data availability; (4) extreme and catastrophic event analysis; and (5) use of multi-objective framework to evaluate risk management priorities.

1. Introduction

Drilling operation is a complex activity and it is subject to a variety of hazards, some of which are location and activity dependent. Thus, the drilling risk management should be commensurate with the site, water depth, available information and complexity of the situation. As the drilling commences, new information becomes available and some predicted hazards may still pose risk, while others may not. New hazardous situations may be encountered or identified, and the characteristics of those already identified could change. Thus, the risk management should be carried out periodically at all stages of the project; i.e. before, during and after drilling.

There are usually more than six hazard categories that influence the risk; also there may be several paths through them a hazard could threaten the operation. The main hazards are grouped under the distinctive headings, such as: Geohazards; Equipment & Material; Human Elements; Local environment; Human-Machine Interface; Design issues; Technology and Operation; Organizational elements; Maintenance & Integrity; Externalities and so on. In some situations the age of the equipment and procedures may also require special attention. The above categories are not exhaustive.

This paper proposes a framework, which starts with organizing hazards into a tree-like structure, consisting of three or more layers. The first level is the goal and the second level is all primary hazard categories. The identification of primary hazard groups is mainly based on engineering judgment, brain storming, QRA, reports and available data (accident databases). In the third level, each category is then broken down into several sub-categories. Each sub-category can be in turn broken into sub-sub-categories and so on (see Figure 2).

Hazards are placed in this hierarchical structure as they are identified, and it is organized by source (category), consequently, the total risk exposure can be better visualized, and the risk mitigation plans are more easily implemented. This process produces a catalogue of all possible hazards, termed Risk Influencing Factors (RIFs), which must be filtered, since there is no need to take forward hazards of lesser importance for more detail study.

2. Hazard Structuring

Hazard identification, or scenario building, is the first step in determining hazards affecting an activity. Identification also enable to documenting characteristics of hazards. Each hazard is a risk influencing factor, which are grouped under headings and subheadings. In risk analysis we envision what could go wrong, how often and what are the consequences if something goes wrong. For this we need to list all possible events or "scenarios". This approach produces triplets [1], i.e.

$$\langle S_i, L, C_i \rangle; \quad i = 1,2,\cdots,N \tag{1}$$

Where, $S_i$is the scenario i and $L_i$is the likelihood of scenario$i$. Risk is defined as a function of these triplets, i.e.

$$R = \{\langle S_i, L_i, C_i \rangle\} \tag{2}$$

This equation is generally simplified as

$$R = \sum_{i}^{N} L_i \times C_i \tag{3}$$

Where, $C_i$is the consequence of scenario i

Table 1: The Risk Influencing Factors: showing major risks and their attributes

Category	Sub-categories
C1-Geohazards	C11- Formation pressure C12 Soil & Rock types and strength C13- Shallow faults C14- Gas hydrate C15- Multiple Geohazards C16-Top-hole Geology (sand, salt, carbonate, discontinuities, clay, loose formation) C17- Shallow soil (for jack-ups), sediment type and strength, Boulder bed, C18 -Salt or mud diapirs and diatremes, Calcareous soils, Coral, hard ground
C2-Equipment & material	C21- Material suitability & defects; Fabrication defects C22- Equipment used (robustness & dependability, maintenance) C23: Effect of Ageing; wear & tear , worn or fatigued part; C24- Operational and resource limits C25- Operational limit, failure to meet qualification & code compliance C26- Late changes to well design and procedures; C27- Equipment quality (special equipment; delay; damaged) C28 - Spare & material availability, C29- Unsuitability and unforeseen site condition, injuries, toxic emission
C3- Human Elements	C31- Skill & knowledge based mix, Training, Experience C32- Workload & Work coordination; Shift and stint duration C33- Quality of working environment. C34- Communication, Language barrier, Openness, C35- Performance evaluated & Suitability and Training; fit for the job C36 - Personnel exposure (qualification, experience, required presence, shift) C37 - Tiredness, boredom, C38 - Situational awareness
C4- Design; Technology and Operation	C41- Technology Readiness maturity, C42- New technology (e.g. packers and liner hangers); C43-Down-hole monitoring; C44- Kick tolerance; C45- Deviation versus hole size, Hole size contingencies, C46 - Cementing of long casing strings; C47- Well access and work over requirements, Well design and Job complexity C48- Blow out contingency;
C5-Automation & human Machine Interface	C51- Software error C52- Temporary disabling safety devises to get round annoying alarms, C53- Information overload C54- Design of Human-machine interface C55 - Failure of data processing function; failure of information support function; C56 - Failure of surveillance function; Failure of communication function; C57 - Expert system which by passes the operator involvement,
C6- Local condition	C61- Water depth C62- Local Weather C63 - Current , wave , tsunami, hurricane, ice, rain, storm surge, tropical cyclones C64- Wind and water borne debris C65 - Requires special equipment C66 - Existing infrastructure , surface and sub-surface, C67 - Shallow water flow, C68 - Preservation areas and sanctuaries
C7- Organizational elements	C71- Mix of cultures & compatibility (e.g. working to different procedures) C72- Organizational leaning C73- Personnel selection; Coordination C74- Training program, process and formalization C75- Safety commitment, perception & enforcement C76 Time and cost constraints C77- Bonus system and benefits upon performance C78 experience with operators or contractors, C79 Operational aspects (language barriers,, local marine traffic, shore proximity);

The set of triplets should be complete, namely it should include every possible scenarios, or at least those which are important. In fact, it is not obvious how even near completeness can be achieved [2]. Moreover, the set of scenarios must not overlap. This method generates a comprehensive list of all sources of hazards, i.e., categories of risks, in the order of dozens of entries. Consequently, there is a need to discriminate among these sources.

Tables 1 and 2 show a catalogue of hazards which might influence a drilling activity. The heading indicates that all hazards that might impact the drilling are identified during the hazard identification process. The sub-headings are attributes of each heading which facilitates the judgment process. Of course each sub-category can be in turn broken into sub-sub-categories and so on.

Tables 1 and 2 contain major risk influencing factors reported in the literature. These tables show a two-level risk break down structure. More remote or obscure hazards may not be identified and hence making the set of scenario incomplete.

It can be seen that there are numerous Risk Influencing Factors (RIFs) which could influence a drilling operation, and there is a certain probability that only a number of RIFs to affect a given operation. How strongly a RIF influences the risk is described by its weight relative to other RIFs.

Table 2: The Risk Influencing Factors: showing major risks and their attributes

Category	Sub-categories
C8- Complexity	C81- Multiple paths to failure; -Uncontrollability; Un-detectability; Cascading effect; Irreversibility C82- Latency (duration effect); C83- Demanding job; C84- High pressure & high temperature C85- Combination of Several adverse conditions C86 - First time experience; the number of components, novel assemblies, New skill set C87 Complexity mix (Combination of Several adverse conditions
C9-Uncertainty	C91- Phasing and planning; C92 Scope change C93- Complex procedures C94- Management of change(design , operating conditions, equipment substitution, plans, personnel) C95- Unforeseen events C96- Safety critical equipment
C10-Seabed Condition	C101- Seabed topography and relief, Seabed channels and scours, Seafloor sediments C102- Fault escarpments, Unstable slopes Sand banks, waves, and mega-ripples, Collapse features C103- Cold water C104- Rock outcrops, Pinnacles, Boulders, Rock outcrop, Hard grounds, Seafloor sediments, Reefs C105- Mud flows gullies, Volcanoes, Lumps, Lobes, Slumps, Fluid expulsion features C106- Sand banks, Sand waves, Mega-ripples C107- Gas hydrate mounds, Gas vents, Pockmarks, shallow gas, as cut mud sections, C108 - Seabed channels and scours C109- Diapiric structures, escarpment, Collapse features, shallow faults
C11- Regulation	C111- lack of Independent oversight C112- Inadequate regulation C113- mandatory regular inspection C114-periodial re-certification C115- regulator involvement and visibility
C12 -Wellbore Integrity	C121- Mechanical Wellbore Instability (Rock type & strength, C122- Wellbore geometry (hole inclination and azimuth) C123- manmade related stress, poor hole cleaning , excessive drilling vibration C124: Drilling into pre-stressed rock, excessive wellbore pressure, vibration C125 - Shale type & instability , time dependent swelling, reaction between fluid and shale C126 - Shale hydration mechanism, forces holding plates together, pore presses. stresses C127 - Inadequate well planning (wrong drilling fluid, wrong inclination &azimuth)
C13- Manmade	C131 - Hazardous waste C132 - Pipelines, Umbilicals, Power cables , Communication cables, Wellheads C133 - Dumped Munitions or chemicals C134- Sanken ships C135 – Debris; disposed wastes
C14- Miscellaneous	C141 - Shipping route C142 - Military training area C143 - Spill prevention C144- External Interferences, wilful acts, Third party present C145 - Anchor System limitation, Boat support needs C146- Weight restriction, riser length, draught limitation C147 - Cost sensitivities,

Table 3: Questionnaire for sifting hazards (After [1])

Question	Meaning
Is this hazard detectable	The system has redundant means of detecting and arresting a hazard before a harm could occur.
Is this hazard controllable	There are controls by which it is possible to take action or make an adjustment to prevent harm.
Is there multiple paths to failure	There are multiple and possibly unknown ways for events to cause harm, e.g. by circumventing safety controls.
Is the effect irreversibility	The system cannot be returned to the normal condition once the adverse event occurred.
Is the event duration of long enough to cause harm	Prolonged events with adverse consequence
Would the event trigger a cascading events	The event can trigger a cascading events which easily and rapidly propagate which cannot be contained
Does the event originate from external sources?	Risk due to external interferences with little or no control over them.
Can the system take more wear and tear	Would further degradation lead to degraded performance or accident
Does the machine-human interface aggravate the problem	Interfaces among diverse subsystems (e.g., human, software and hardware) causing adverse events
Do we understand the complexity?	Too many complexity create a potential for system level behaviours that are not anticipated from a knowledge of components and the laws governing their interactions
Is technology qualified for the task?	Immature or inappropriate technology or other lack of concept qualification

This risk influencing structure can be viewed as a means leading to a set of actions or behaviour that are required of the system in order to succeed in functioning safely; conversely, each risk factor defines a scenarios in which the system fails to deliver in one or more ways. The union of all risk scenarios should then be complete. This completeness is a very desirable feature. However, the intersection of two of our risk scenario sets, corresponding to two different heading, may not be empty. The method allows the set of subsets to be overlapping. Thus, by a filtering process overlapping hazards must be rationalised.

Risk Filtering

Filtering is performed at the sub-category level, to eliminate overlapping and less relevant RIFs. RIFs are filtered according to their perceived levels of likelihood and consequences. Filtering is achieved on the bases of expert experience and knowledge, as well as function, and operation of the drilling system being assessed. This activity often substantially reduces the number of RIFs. In this, the joint contributions of two different types of information-the likelihood of what can go wrong and the associated consequences-are estimated on the basis of the available evidence and engineering judgment. The evidence for taking forward a hazard for detailed studies, can be determined by answering questions noted in Table 3.

Risk matrix is a useful tool for visualising risk. This type of tool is commonly used with the assistance of experts. Since risk is defined as triplet then its likelihood and consequence must be judged. Commonly, 5x5 Matrix is used, but the 8x8 matrix (Figure 1) provided a better resolution. Figure 1 defines eight scales and their linguistic description. Each risk scenario is characterized using qualitative assessment of both consequence and likelihood. In risk matrix, the likelihoods and consequences are combined into a joint concept called "severity" [2]. The group of cells in the upper right indicates the highest level of severity. The mapping is achieved by first estimating the likelihood of a hazard then judging its consequence, and finally determining which cell it belongs to. The cells position determines the relative levels of severity.

In quantitative risk assessment, risk is defined as the product of likelihood of a hazards and its impact should it happen [2]. The multiplication method could yield the same numerical value for a high consequence but low likelihood event to be the same as high likelihood but low consequence event. This is a misleading picture, though both events are damaging, the high consequence event can wipe out an organisation. The problem is more pronounced for event in the middle of the risk matrix. Thus, cells in Figure 1are numbered to indicate their position importance. This importance numbering gives more emphasis to the middle range, compared with the multiplication approach.

Each RIF from the catalogue is placed into a cell, according to its perceived likelihood and impact, to represents a failure scenarios. Each scenario has its own combination of likelihood and consequence. These hazards can also be filtered based on scope, spatial & temporal domain considerations. Since we are considering the safety at the planning stage, we start by presenting an initial set of relevant hazards which could be validated by all stakeholders. RIFs falling in the low-severity boxes are filtered out and set aside for later consideration. The completed matrix shows which events are the major risk drivers.

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	< 10^{-6}/yr	10^{-5} to 10^{-6} /yr	10^{-4} to 10^{-5} /yr	10^{-3} to 10^{-4} /yr	10^{-2} to 10^{-3} /yr	10^{-1} to 10^{-2} /yr	1 to 10^{-1} /yr	> 1/yr			
	Catastrophic event	Extreme event	failure of the entire system	susbtaial systm failure	Partial failure	two or equipment fail	Equipment failure	Component Failure			
	RISK LEVELS										
	1	2	3	4	5	6	7	8	Consequenc Defintion		
Consequence Level Designation	A similar event has not yet occurred in our	A similar event has not yet occurred in our industry, but it	Similar event has occurred somewhere in our	Similar event has occurred somewhere within	Similar event has occurred, or is likely to occur,	Likely to occur once or twice in the facility lifetime	Event likely to occur several times in the facility	Common occurrence	Safety Implication (Worst case)	Environmental Implication	Business loss
A	8	9	10	11	12	13	14	15	>100 fatalities	-	>$20 bn
B	7	8	9	10	11	12	13	14	>50 fatalities	-	$5 bn - $20 bn
C	6	7	8	9	10	11	12	13	>10 fatalities	>20,000m3 condensate spill to sea	$1 bn - $5 bn
D	5	6	7	8	9	10	11	12	3 or more fatalities	10,000m3 condensate spill to sea	$100 m- $1 bn
E	4	5	6	7	8	9	10	11	1 or 2 fatalities	2000m3 condensate spill to sea	$5m -$100 m
F	3	4	5	6	7	8	9	10	1 or more DAFWC	100m3 spill to sea of condensate / MEG	$500k-$5m
G	2	3	4	5	6	7	8	9	1 or more recordable	1-10m3 spill to sea of condensate / MEG	$50k -$500k
H	1	2	3	4	5	6	7	8	First Aid	50litre spill to sea of condensate / MEG	<$50k

Figure 1: A typical industry risk matrix for filtering (and ranking) risks.

Risk Ranking

The boundaries of the different levels of risks are not symmetrical, because a catastrophic event, irrespective of its probability, could cause very large loss. The risk matrix doesn't provide a numerical relative importance of each rating, so the tool divides the risks into groups, but does not say anything about the ranking within each grouping. Thus, after filtering of minor hazards, the remaining hazards must be ranked to determine their relative strength. This enables to prioritise expenditure for avoiding, controlling and mitigating impact of hazard if they were to occur.

There are two types of comparisons: absolute and relative. In absolute comparisons, two hazards are compared with a standard or a baseline which exists in one's mind and has been formed through experience. In relative comparisons, hazards are compared in pairs according to a common attribute. Saaty, [8] and [9], proposed a pairwise comparison for determining the relative importance of two criteria known as analytic hierarchy process (AHP). The input to AHP models is the experts' answers to a series of questions of the general form, e.g. 'How important is Category 'C1' relative to Category 'C2'?' These are termed 'pairwise comparisons' [8]. Within AHP, questions of this type may be used to establish, both weights for categories and importance scores for different categories, using a suitable scale (see [8] or [10]). Very often qualitative data cannot be known in terms of absolute values. AHP allows the integration of both, quantitative and qualitative criteria [9].

It is difficult to be completely consistent because of the complexity and diversity of subjective judgment. The AHP does not require that judgments to be totally consistent. But, priorities make sense only if derived from consistent or near consistent matrices, and hence consistency check must be applied. Saaty [8] Proposed a consistency index (CI) to measure the degree of consistency (or inconsistency) of the judgments for each stage of the AHP process. If the comparisons are not reasonably consistent, then this check provides a mechanism for improving consistency by going back to the pairwise comparison. The mathematical background can be found in [10]

Case Study

The ranking process is illustrated using an example case, which is a drilling operation in a seismically active area. In a hazard filtering process, it was determined that the categories C1 to C7 (Table 1) have the largest direct effect on the risk, which are as listed in the first column of Table 3. The rest of hazards listed in (Tables 2) are considered either not to apply or to be of no importance and hence were filtered out. Figure 2 shows the content of Table 3 in its hierarchal format.

In consultation with the industry experts seven pairwise comparison matrices were developed to determine the categories and sub-categories weights. The weights for all the pairwise comparison matrices were computed using a spreadsheet. By aggregating the hierarchy, the preferential weight of each criterion is found. A consistency check is then performed. If the comparisons are not reasonably consistent, then this check provides a mechanism for improving consistency by going back to the pairwise comparison. Aggregating opinion of more than one expert, in principle, would enhance the decision making process [6] and [7].

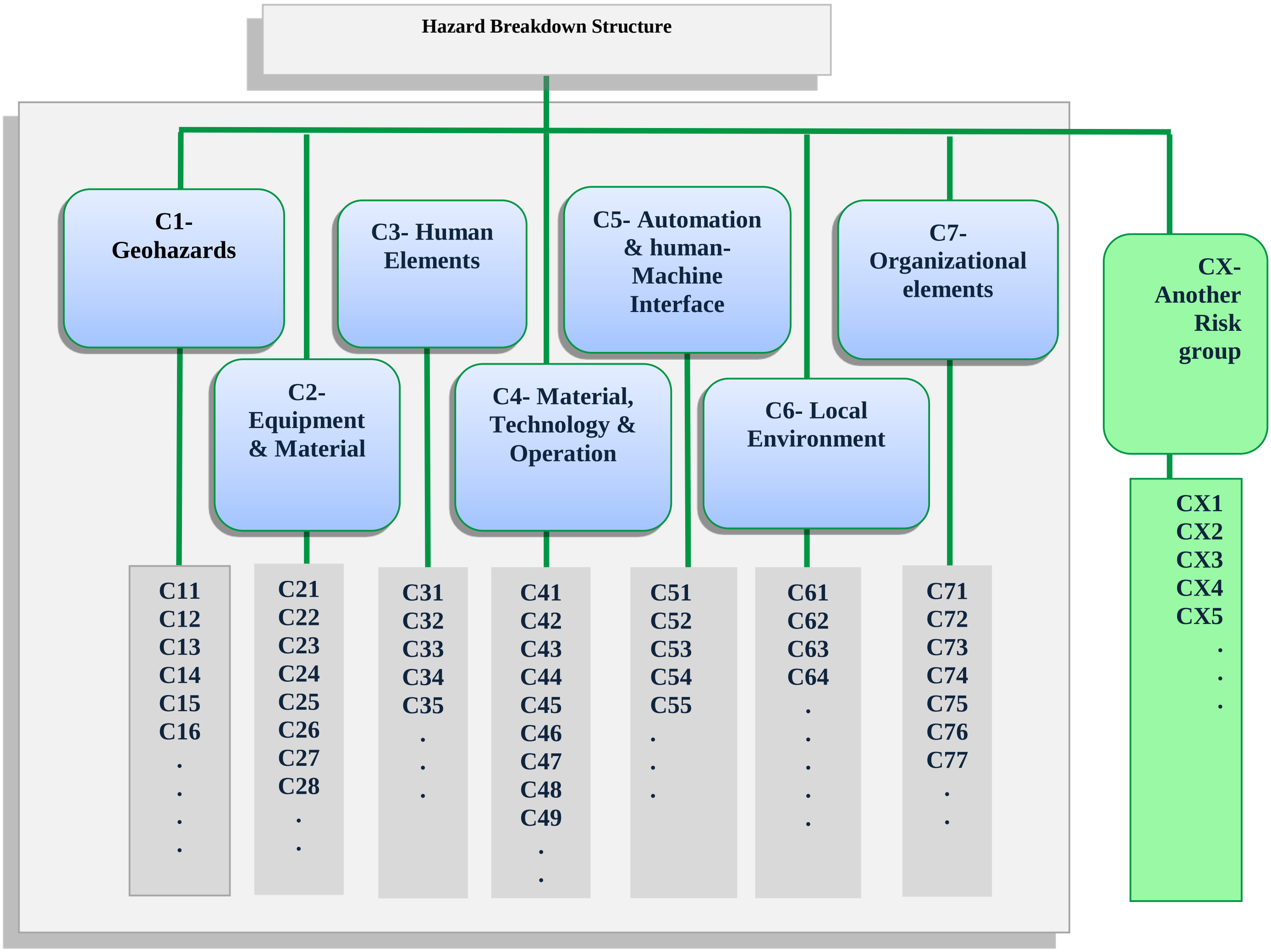

Figure 2: Hazard Breakdown Structure for the case study

	C1	C2	C3	C4	C5	C6	C7	Weight
C1	1	2	1	1	1	2	6	0.20
C2	1/2	1	1/2	2	2	1	6	0.17
C3	1	1	1	1	2	3	2	0.19
C4	1	1/2	1	1	2	2	2	0.16
C5	1	1/2	1/2	1/2	1	1	4	0.12
C6	1/2	1	1/3	1/3	1	1	5	0.11
C7	1/6	1/6	1/2	1/2	1/4	1/5	1	0.05
Sum	6 1/6	4 5/6	6 1/3	9 1/4	10 1/5	26	6 1/6	**1.00**
CR= 0.0589								

Figure 3: First level pairwise comparison matrix

Figure 3 shows the pairwise comparison of the primary categories (the second layer). Each column is summed up first, and then each element is divided by the sum of its column. The weight is then averaged of each row. The pairwise comparison matrices for subcategories are not shown here, but the results are given in the column 4 of Table 4. Table 4 summarizes these results. The second column gives the ranking of the top level categories as calculated in Figure 4. The fourth column give the ranking of all hazards within each category. The last column is the multiplication of the second and the fourth columns. These results are plotted in Figures 4 and 5.

Table 4: Summary of pairwise comparison matrices

Primary Criteria	Weight/Primary	Sub-criteria	Sub-criteria weight	Combined weight
C1-Geohazards	0.20	C11	0.213	0.043
		C12	0.343	0.069
		C13	0.153	0.031
		C14	0.146	0.030
		C15	0.073	0.015
		C16	0.073	0.015
C-2 Equipment & material	0.17	C21	0.228	0.040
		C22	0.125	0.022
		C23	0.039	0.007
		C24	0.218	0.038
		C25	0.098	0.017
		C26	0.098	0.017
		C27	0.098	0.017
		C28	0.098	0.017
C3- Human Elements	0.19	C31	0.183	0.034
		C32	0.212	0.040
		C33	0.195	0.037
		C34	0.196	0.037
		C35	0.213	0.040
C4- Design; Technology and Operation	0.16	C41	0.028	0.005
		C42	0.026	0.004
		C43	0.058	0.009
		C44	0.053	0.009
		C45	0.115	0.019
		C46	0.180	0.029
		C47	0.180	0.029
		C48	0.180	0.029
		C49	0.180	0.029
C5-Automation & human-Machine Interface	0.12	C51	0.147	0.017
		C52	0.107	0.013
		C53	0.285	0.033
		C54	0.261	0.030
		C55	0.199	0.023
C6- Local environment	0.11	C61	0.151	0.017
		C62	0.201	0.022
		C63	0.367	0.041
		C64	0.281	0.031
C7- Organizational elements	0.05	C71	0.215	0.010
		C72	0.247	0.012
		C73	0.148	0.007
		C74	0.077	0.004
		C75	0.115	0.005
		C76	0.090	0.004
		C77	0.106	0.005

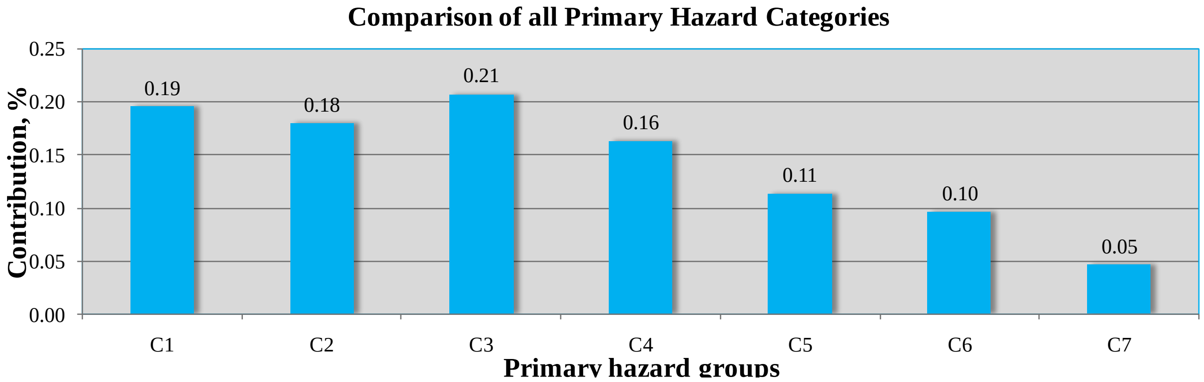

Figure 4: Ranking of all hazard sub-categories

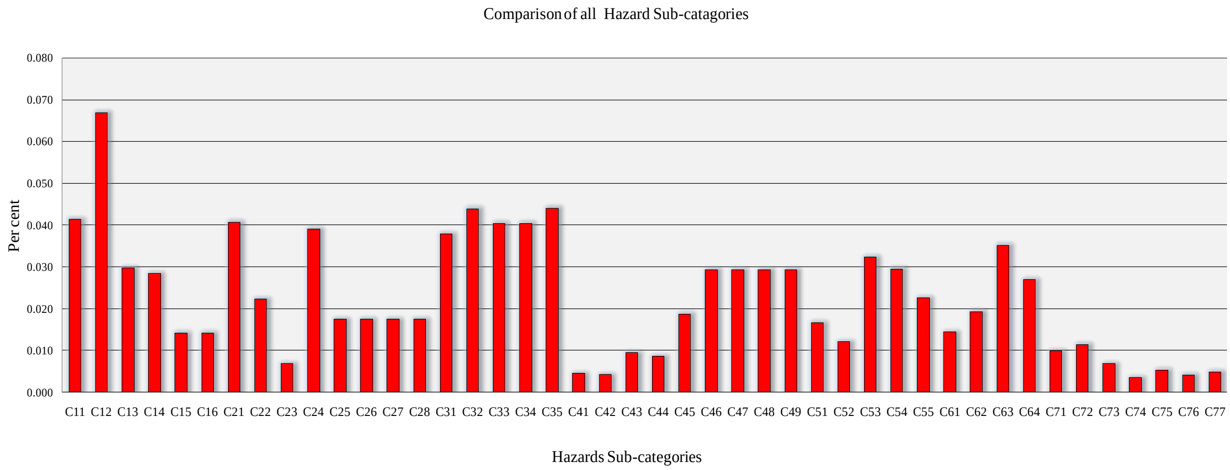

Figure 5: Ranking of all hazards sub-categories to risk.

Risk Management

The hazard control is based on the concept of safety barriers. The safety barrier approach in turn is based on two models, the Swiss cheese accident model and the bow tie method. For this, imagine a row of Swiss cheese slices, (Figure 6), in which each slice is a barrier and the hole represents a weakness in the barriers that may fail to prevent an accident. If the holes line up, which may occur when multiple robust barriers are not in place or they are properly functioning, accidents can occur. This simple model is surprisingly a useful tool – the more barriers, i.e. more Swiss cheese slices, the safer the facility, and the smaller the holes, the smaller is the weaknesses of the barrier. Barrier management is an effective tool to connect facility operations with HSE cases, design features and regulatory requirements in an integrated fashion.

The tool that captures the Swiss cheese concept and carries it further is the Bow Tie Diagram (Figure 7). For each “Top Event”, such as a major leak, blowout, or explosion, , and all of other threats, e.g. equipment malfunctions or failure to follow operating procedures are shown on the left, while the effects, such as injuries, asset or environmental damage are shown on the right. The prevention barriers are then between the threats and the top event, while the mitigation barriers are between the top event and the outcome.

The bow tie risk model can address hardware, administrative and procedural controls, either on the main pathways as shown in the simplified diagram of Figure 6, or on separate branches [5]. The bow tie is a simplified representation of a fault tree diagram where each barrier is an AND gate with two inputs – a demand AND barrier fails. An escalation branch is just building out the barrier fails arm from an undeveloped event to one that is developed – showing the means in place to maintain that barrier. A requirement of fault trees and thus of bow ties is an assumption of barrier independence.

Human intervention can cause degradation of many barriers if their intention is to reduce time or resources from what was originally planned. A system with multiple barriers can in fact has fewer if resources are not devoted to maintaining them. The bow tie, like the fault tree, is poor at capturing these overarching influences, but they important to overall system safety and a systems process is important [3].

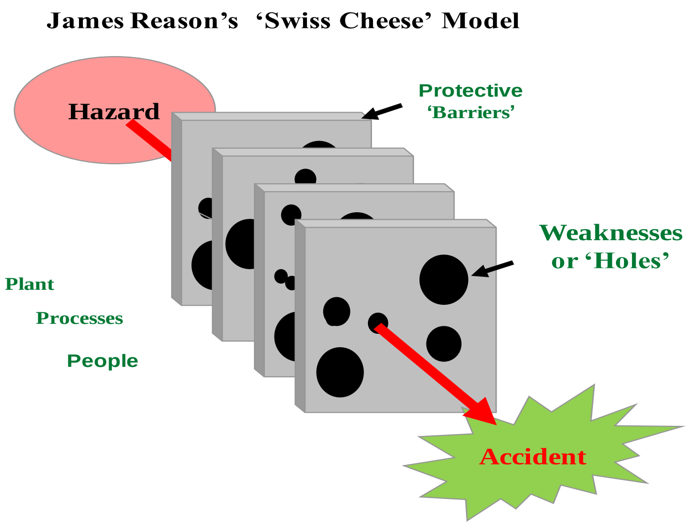

Figure 6: Reason’s Accident model

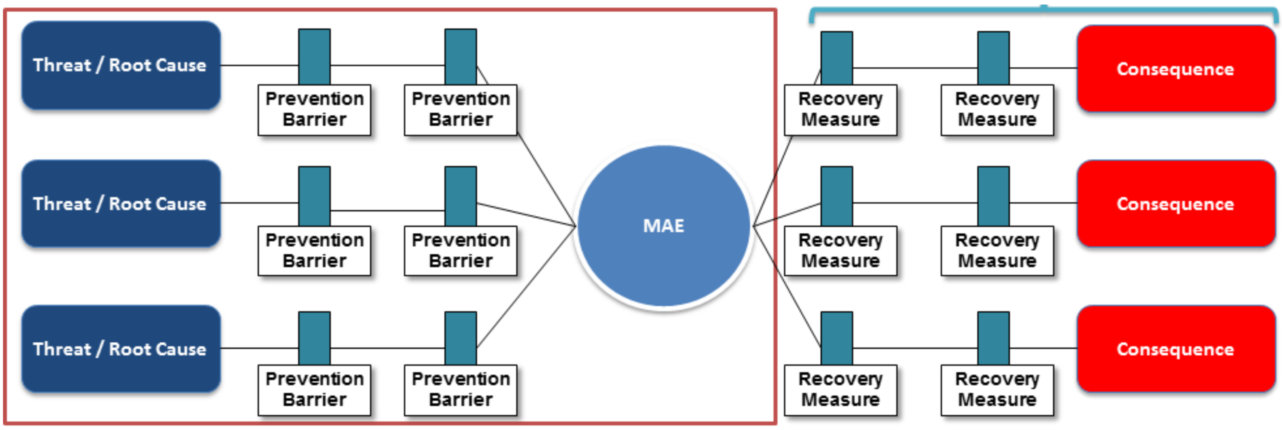

Figure 7: A typical bow-tie model

There are three levels of well control: primary, secondary and tertiary. Primary refers to control during the drilling phase with mud weight. Secondary refers to well control with a blowout preventer, and tertiary refers to a worst-case scenario – a blowout. Conventional well-control strategies include casing, fluid programs, and other barriers to well control incidents in the well design and BOP, and other mitigation procedures that help minimize the impact of an incident should one occur. The primary barrier is the hydrostatic pressure of mud which is larger than of the pore pressure. In underbalance drilling, this barrier must be adjusted. In this case it is composed of the drilling fluid column and a separate back pressure choke. The secondary barrier is the envelope consisting of the blowout preventer, the casing, the exposed wellbore below the casing shoe and the drill string. If the primary barrier is failed, this barrier is closed.

Conclusions

The purpose of risk analysis is to obtain robust design. Risk analysis identifies all factors which influences a design. Measuring risks is essential to reduce exposure, and it can be used for other purposes such as upgrading an existing drilling rig for life extension, change of use, reducing corporate risk exposure or measuring cost effectiveness of expenditures. The proposed approach is an effective tool for such purposes.

We used the risk matrix to filter out less important hazards and AHP to rank the remaining hazards by eliciting opinion of several experts [4]. Opinions of several experts can be aggregated after going through the process described above and then averaging the calculated ranks. Such averaging may be done before processing the data. Using fuzzy mathematics was also proposed for aggregation in the literature, but their value is uncertain as AHP itself is dealing with fuzzy situation and it is doubtful if further complication would add value. There are other methods for aggregation [6] which involve more calculations.

The AHP is a versatile decision aid which can handle problems involving both multiple objectives and uncertainty. It is popular with many decision makers who find the questions it poses easy to answer. It should, however, not be forgotten that the purpose of any decision aid is to provide insights and understanding, rather than to prescribe a "correct" solution. Often the process of attempting to structure the problem is more useful in achieving these aims than the numeric output of the model.

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