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Risk Assessment and Risk Modelling In Geothermal Drilling

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ABSTRACT

Development of geothermal energy has advanced in the last few years and will continue to do so in the coming years. But this is slowed by the high risks and costs associated with the drilling phase of geothermal development. The goal of this study was to find out the risk factors that can interrupt or delay the delivery, or compromise the quality of a geothermal well and how these risks are perceived by drilling professionals in Iceland and in Kenya. Sixty-four (64) risk factors were identified, an online questionnaire developed and the survey tool QuestionPro used to send out the survey. The results showed that drilling risk analysis is subjective and risks are ranked, or perceived to be high or low, depending on the project setting such as physical, economic and political environments. Generally, toxic gas release was ranked the highest risk for drilling operations, followed by high cost of drilling and lost circulation.

The study also looked at the value of integrated cost and schedule risk in execution of drilling projects, allowing for accurate budget and schedule estimation. The project risk management software RiskyProject was used for this purpose to simulate a sample drilling project. The results show that cost and schedule risk management can play an important role in geothermal drilling projects. The deterministic method of costs and schedule estimation commonly in use could easily result in cost and schedule overruns or underruns due to the influence of risks and uncertainties encountered within and outside the project. A Monte Carlo simulation run on the sample project showed that the P50 values giving the most likely values for cost and schedule, was higher than the base values determined for the project.

In conclusion, the risk management process has the potential to create value for all aspects of drilling projects. It also recommends that the geothermal drilling industry need to embrace risk management especially integrated cost and schedule risk management as a tool for controlling of budget and schedule overruns.

1. INTRODUCTION

The role of geothermal in providing green renewable energy in a sustainable manner, particularly in mitigating climate change, is evident as its development increases. Despite this increased development and it's advantage over other renewable sources in terms of indifference to weather, base load capability, great stability and high thermal efficiency (Li, 2013), adoption of geothermal power is slowed by the uncertainty and risks involved in development, high initial costs and relative inaccessibility of easily tapped geothermal resources (GeothermEx Inc., 2013).

Geothermal drilling is a fundamental phase of geothermal development and it carries considerable risk in terms of costs, schedule and project completion. According to Kullawan (2012) drilling operations have three basic objectives:

i. Safe drilling, even in situations where the drilling project will be delayed or incur extra cost.
ii. Drilling a fit-for-use well that should fulfil the purpose for which it was constructed. Borehole integrity should be maintained, design requirements met and the well should allow for testing and production or any other future works to be done on it.
iii. Minimized cost of drilling a well, obtained through optimization of drilling process and by drilling time reduction.

Drilling risks and uncertainties result in drilling projects not only going off the critical path, but also create unsafe working conditions, diminish the integrity of the well and increase the cost of drilling significantly. Drilling risks also impact the project in terms of the schedule, such that drilling time is spent on mitigation measures instead of well construction, directly or indirectly adding to the cost of the well.

It is important to understand and manage the level of risk involved in any drilling project, to ensure that there are adequate resources to maintain and complete the project should the worst case outcomes occur. Integrated cost and schedule risk management provides a two-step process for allocating project cost to the projects: first, by allocating resource costs such as daily operating rates to drilling activities and materials and consumables used in the project, then secondly, allocating cost to the integrated risks experienced in the project.

This paper identifies the risks that threaten the on-time delivery of geothermal wells and increase the cost of drilling geothermal wells and examines the impact they have on geothermal projects. The paper aims to define a suitable framework for realizing a process-driven risk management for drilling projects.

2. RISK IN THE DRILLING PROCESS

Drilling risk can be defined as the chance that the drilling challenges encountered will disrupt or affect the drilling project timeline, budget, project completion or company reputation. Risk assessment starts with risk identification. Drilling risks were identified from previous work found in literature. The list was narrowed down to 64 risks. These risks were categorized into 6 main risk categories as discussed below. The list may not be exhaustive but most of the common risks have been captured.

2.1. Technical risks

These risks commonly related to the geological formation or equipment and material supply and delivery. These risks have a ripple effect that increases the chance of other risks to occur if not adequately handled. Technical risks were further divided into six broader categories.

2.1.1 Geological risks

Geothermal energy is found in complex geological formations and this is reflected in the amount of formation challenges experienced during drilling. Most of these geological risks manifest themselves in form of challenges described below:

- Loss of circulation
- Wellbore instability- *collapsing formation*
- Stuck pipe
- Hard and soft formation
- High pressures and temperatures
- Magma intrusions in deep wells

2.1.2 Casing and cementing

Cementing and casing are a critical part of geothermal drilling. Consequences of poor cement jobs and casing can be felt long after the rig has moved. Some of the casing and cementing challenges are described below:

- Casing wear during drilling
- Casing off-set (decentralized)
- Parted casing
- Collapsed casing due to poor cement job
- Cold inflows
- Difficult cementing jobs due to loss zones
- Cement hardening inside casing

2.1.3 Equipment and tools challenges

The drilling equipment is very costly and is also the project item exposed to most challenging environments. Equipment protection through continuous preventive maintenance and periodic inspection should also be of concern. Equipment failure results in non-productive time associated with equipment repairs, and sourcing for spare parts. Some equipment failure include: Drill pipe failures, BOP failure, Loss of tools- BHA, logging tools, drilling tools, Machine failures.

2.1.4 Drilling material and consumables

Drilling consumables and materials are critical for drilling. Risks that can be experienced include; long lead times of delivery, bureaucracy in the tendering process, failure to allocate risks properly in the contract, poor materials quality.

2.1.5 Force majeure

These are unavoidable catastrophes that interrupt the expected course of events and restrict stakeholders from fulfilling their obligations. They include, for example: extreme weather conditions, war and country insecurities, earthquakes

2.1.6. Well success

Sveinbjörnsson (2014), defines successful wells as those whose capacity was available or estimated sufficient for connection to the power plant or intended utilization. Unsuccessful wells include:

- Plugged and abandoned well
- Suspended well - not completed
- Non-productive well

2.2 Health, safety and environment (HSE)

HSE risks, is concerned with those risks that affect the personnel, property and the environment of operation. Eight HSE risks were identified and are as described below:

- Toxic gases (CO_2, H_2S released from the well)
- Noise
- Equipment and personnel safety
- Working environment
- Leakage or collapse of brine pond
- Improper disposal of drilling cuttings
- Air pollution
- Thermal and chemical pollution

2.3 Financial risk

Financial risks in geothermal drilling arise mostly from drilling duration and the risks involved in the drilling process, but some may be attributed to financiers. Eight items were identified for this risk category which include:

- High cost of drilling -
- Bankruptcy of project partner
- Interest and exchange rate fluctuation
- Reduction in annual budget allocation by government
- Delayed disbursement of funds from financiers
- Price instability of fuel and steel

- Credibility of shareholders and lenders
- Changes in bank formalities and regulations

2.4 Legal risk

There are several aspects of legal risk that could affect geothermal drilling, only two risks resulting from contract management were looked at.

- Breach of contract by project partner
- Improper verification of contract documents

2.5 Organization risk

In a constantly changing environment, organizations face varied risks. These risks have more global effect, not only affecting the drilling project but also the entire establishment, extending beyond the life cycle of the project. Two risk categories were looked at in this area:

2.5.1 Human resources:

The human resource requirement of the drilling industry differs from most other industries due to its nature, importance of safety, the stakeholders and a multi skilled workforce requirement. Human resource capital is a critical investment to operate evolving technologies and to remain productive and competitive (ILO, 2012). Some of the risks identified in this area include: inexperienced and less knowledgeable personnel, workforce stress due to inadequate staffing, work schedule and cyclic nature of drilling, unmotivated personnel, deficiencies in organizational culture,

2.5.2 Management risk

Proper management allows drilling entities to comply with regulations and guidelines in their environment of operation and follow through with compliance obligations from both state and private stakeholders. To drill a well, several different disciplines and companies come together to pool their resources. The volume of resources and information involved shows the degree of risk exposure drilling companies face when engaging with contractors and service providers. These risks include:-

- Change of organization ownership or management
- Inadequate project definition, planning and budgeting
- Inadequate management of drilling contracts
- Unclear contract specification
- Changes on scope of contract
- Stakeholders not consulted and/or kept informed about contract performance
- Unclear lines of communication- owner, contractor and operators

2.6 Policy and political risk

Policies and politics determine the way geothermal drilling projects are conducted depending on the country. They define how project finance is obtained and how it is used, who can work in the country as sometimes drilling is done by a foreign crew and how procurement is done. Five items were looked into in this section: cost increase due to changes of Government policies, loss incurred due to corruption and bribery, low/inadequate budgetary allocation, procurement policy (e.g. long tendering process), loss due to bureaucracy and late approvals

3. RISK ASSESSMENT OF THE DRILLING RISKS

3.1 Survey questionnaire

A questionnaire was sent out to 50 personnel in the drilling industry, ranging from drilling engineers, supervisors, project managers and drillers. They were asked to evaluate the 64 risks identified, in terms of quantifying the probability of occurrence and the impact to the drilling project. The online survey tool QuestionPro (http://www.questionpro.com/), was used to conduct the survey. The responses were anonymous. Nineteen responses were received. That is a 38% response rate.

3.1.1 Survey structure

A brief introduction and objectives of the questionnaire was explained. The survey consisted of two sections with the first collecting general information about the respondent such as country, years of experience and title. The part also asked participants to state risk analysis or performance indicators currently in place in their drilling projects and also to indicate how risks impacted drilling projects in terms of time scope and cost. The second part carried a total of 64 drilling projects associated with risk and participants were asked to rate them on a multi attribute Likert scale adapted from (Bertram, 2007). The questionnaire required the participants to consider two attributes for each risk: that is how probable the risk was to occur and how severe the impact would be if it did, see Table 1.

TABLE 1: Risk measurement scale

Score	Probability	Impact
5	Certain	Catastrophic,
4	very likely	Major/Critical
3	likely	Serious but tolerable
2	unlikely	Marginal
1	very unlikely	Negligible

3.1.2 Analysis of survey results

The results obtained were weighted to come up with the relative significance of each risk to the drilling project. The weighting system adopted from PMBOK (2013),determines risk significance by multiplying risk probability and impact values. (Shen et al., 2001) denotes these two values as: probability level of the risk occurrence, by α; while degree of impact by β. Then the significant score for each risk can be obtained by Equation 1.

$$S_j^i = \alpha_j^i \beta_j^i \quad \text{Eq. 1}$$

Where S_j^i= Significance score for risk i assessed by respondent j, α_j^i= Probability of occurrence of risk i assessed by respondent j, β_j^i= Degree of impact of risk i assessed by respondent j

To get the risk index score an average significance score from all the respondents is calculated as shown in Equation 2 below. Once the risk index score has been obtained, it was determine which risks are considered high, moderate or low. These values are then represented in a risk matrix where the high, moderate or low are denoted by colours red, yellow and green respectively.

$$RS^i = \frac{\sum_{i=1}^{n} S_j^i}{n} \quad \text{Eq. 2}$$

Where RS^i = Risk index for risk I, n = Number of respondents

3.2 Integrated cost and schedule

The recommended practice (RP) 57R-09 of AACE international presents methods for integrated analysis of schedule and cost risk to estimate the appropriate level of cost and schedule contingency reserve on projects. It presents the need to include the impact of schedule and cost risks in the project in a manner that mitigation can be conducted in a cost effective way. These methods allow for the integration of the cost estimate with the project scheduled by resource-loading and costing the schedule's activities and risks. The risks are then linked to activities and resources they affect (Bertram, 2007).

A systematic approach for integrated schedule and cost risk assessment modelling and simulation can be achieved using a software to simplify the process and aid in decision making. The risk management software RiskyProject, was used to carry out an integrated cost and schedule risk analysis.

RiskyProject is a project risk management software package created by Intaver Institute Canada, to perform integrated cost and schedule risk analysis. It has an inbuilt project schedule, risk register and a Monte Carlo simulation as the main tools for analysis. It performs both qualitative and quantitative risk analysis and allows up to 600 iterations. The input requirements included:

1. Project schedule - all jobs scheduled, resources loaded, unbiased estimates of durations
2. Cost estimate - resource cost, fixed cost
3. Risk data -risk list, probability and impact parameter data collected, risk weighting, risk and mitigation costs

3.2.1 Project schedule

The project schedule forms the basis of the integrated cost and schedule risk analysis. The sample project used as the input was a vertical well drilled to 3,000m. It included all of the drilling activities from start of well to completion. The duration of the job from spudding was estimated to be 60 days (1,440 hrs.). The well was drilled in four sections: the 26" section to 100 m, 17½" section to 450m, 12¼" section to 1,200m and 8½" section to 3,000m. There were 3 casing strings of 20", 13⅜", 9⅝" for the top three sections, that were cemented and 7" slotted liner installed at the finish of the well. The project was planned to have started on 4 February 2016 and end on 3 April 2016. To create the project schedule, Microsoft Project was used.

3.2.2 Cost estimates

Resource cost: Tying priced resources to the individual activities in the schedule allows for accurate project cost estimation. Several resources are required for a drilling project and different activities may require more than one resource. It was convenient therefore to combine the resource into one which was the daily operating cost. These costs were average industrial total costs for drilling a well for 60 days and comprised of the cost of equipment rental and services. The daily operating equipment cost included the cost of renting the rig with crew on both working days and standby days. The standby days were approximately 10% of the working days. Another equipment cost item was the aerated drilling equipment rental. Since this equipment will not be in use the entire drilling time 30 days were charged on standby rate while the remaining 30 days were charged on operation rate. Other equipment cost items charged for 60 days, included cementing equipment and operations, transportation and logistics, waste disposal, water supply and accommodation and catering for the drilling crew. The second part of the table shows the service cost. The cost information is summarised in Table 2. The first cost column shows the total cost for the 60 days, the second column shows the daily operating cost, while the last column shows the hourly operating cost. To note is that these costs do not include the materials and consumable. Total operating cost for 60 days was calculated to be 3,192,480 USD translating to 2,217 USD/hr. It was necessary to convert to hour rate as this was the required input to the system, as shown in Figure 1.

	Resource name	Chart	Risks	Type	Mat....	Initials	Max.Units	Rate	Cost/...	Base ...
1	Daily operating cost	☐	0	Work		D	100.00%	2217.00/hr	USD0.00	24 Hours
		☐								

FIGURE 1: Resources and costs

The day rate was put in as a labour type, meaning the longer the project the more costs are accrued. This allows for any duration changes in the project to change the associated cost. Other inputs available are material type meaning they will not be affected by time taken in the process and cost. The resource (day rate) was then applied to the summary activity whose duration is calculated from the underlying sub activities. The total cost of each main activity would therefore be the product of the day rate and the total hours of that section or main activity; this will be shown in the cost input.

Fixed cost estimates were developed and calculated for each of the three drilling sections. Inputs included the cost of all equipment and materials required to complete each section. The low and high cost was achieved through including ± 15% on the base estimates and probability distribution specified as a triangular distribution for each activity. Table 3 below shows the cost estimates in USD as determined for this well. These costs were added to the total resource cost to obtain the total cost of the project without risks. That was 6,041,320 USD, as shown in Figure 2.

TABLE 2: Daily operating cost

Daily operating costs for 60 days	Operating Cost		
	Total (USD)	Per Day (USD)	Per hr. (USD)
Equipment			
Rig rental with crew	2,208,500	36,808	1,534
Rig rental with crew-standby	210,000	3500	146
Aerated drilling fluid package operating rate	16,000	267	11
Aerated drilling fluid package stand-by rate	14,400	240	10
Cementing equipment	24,000	400	17
Transportation and cranes	12,000	200	8
Water Supply	126,200	2,103	88
Waste disposal, clean up and site maintenance	12,620	210	9
Accommodation and catering	151,500	2,525	105
Sum	2,775,220	46,254	1,927
Services			
Drilling supervision	24,000	400	17
Maintenance Engineering	24,000	400	17
Site geologist	12,000	200	8
Geological services	9,000	150	6
Reservoir engineering	6,000	100	4
Planning and logistics	12,000	200	8
Drill stem inspection	300,000	5,000	208
Logging services	30,000	500	21
Sum	417,000	6,950	290
Daily operating costs	**3,192,220**	**53,204**	**2,217**

TABLE 3: Cost estimation (USD)

26" hole (20" casing)		12-1/4" hole (9-5/8" casing)	
Rock bits and stabilizers	39,000	Rock bits and stabilizers	117,000
Drilling mud	7,134	Drilling mud	-
Drilling detergent	-	Drilling detergent	6,000
Diesel and Lubricating oil	118,125	Diesel and Lubricating oil	118,125
Total for 26" hole	**164,259**	**Total for 12-1/4" hole**	**241,125**
Casing	28,925	Casing	147,965
Cement	11,877	Cement	28,552
Cement additives	3,991	Cement additives	9,593
Total for 20" casing	**44,793**	**Total for 9-5/8" casing**	**186,110**
17-1/2" hole (13-3/8" casing)		**8-1/2" hole (7" casing)**	
Rock bits and stabilizers	39,000	Rock bits and stabilizers	195,000
Drilling mud	12,313	Drilling mud	-
Drilling detergent	3375	Drilling detergent	9,063
Diesel and Lubricating oil	118,125	Diesel and Lubricating oil	118,125
Total for 17-1/2" hole	**172,813**	**Total for 8-1/2" hole**	**322,188**
Casing	55,635	Casing (Slotted liners)	203,603
Cement	20,469	Cement	-
Cement additives	6,878	**Total for 7" casing**	**203,603**
Total for 13-3/8" casing	**82,982**	**wellhead**	**78,605**

	Task Name	Cost Actual	Cost Low	Cost	Cost High	Accrual	Res.Cost	Tot.Cost
1	REVIEW MEETINGS	USD 0.00	USD 0.00	USD 0.00	USD 0.00	Prorated	USD 0.00	USD 0.00
10	VERTICAL WELL DRILLING TIMELINE TO 30	USD 0.00	USD 0.00	USD 0.00	USD 0.00	Prorated	USD 4,544,850	USD 6,041,328
11	26" SECTION	USD 0.00	USD 139,620	USD 164,259	USD 188,898	Prorated	USD 297,078	USD 461,337
17	20 CASING	USD 0.00	USD 38,074	USD 44,793	USD 51,512	Prorated	USD 352,503	USD 397,296
23	17½" SECTION	USD 0.00	USD 146,891	USD 172,813	USD 198,735	Prorated	USD 527,646	USD 700,459
37	13-3/8 CASINGS	USD 0.00	USD 70,535	USD 82,982	USD 95,429	Prorated	USD 611,892	USD 694,874
43	12¼" SECTION	USD 0.00	USD 204,956	USD 241,125	USD 277,294	Prorated	USD 747,129	USD 988,254
59	9-5/8 CASING	USD 0.00	USD 158,194	USD 186,110	USD 214,026	Prorated	USD 747,129	USD 933,239
65	8½" SECTION	USD 0.00	USD 273,860	USD 322,188	USD 370,516	Prorated	USD 1,261,473	USD 1,865,869

FIGURE 2: Cost view in RiskyProject

3.2.3 Risk data

Ideally, schedule and cost risk estimates in traditional approaches have always been incorporated using a 3-point estimate results from the workings of several potential risks. The limitation of this method is that it is difficult to capture the entire influence of a risk on the activities (Hulett & Nosbisch, 2012). To conclusively capture the effect of risk on the activities, a risk register was uploaded in the RiskyProject software, allowing for assigning of the individual risks to activities. Risk items identified in the literature were used as inputs. The risk probabilities and impact factors resulting from the survey were used, and the risks were assigned to drilling activities. To complete the risk register mitigation and response plans were developed and assigned to the risks. Figure 3 is a screen shot of the populated risk register from RiskyProject.

	Risk Name	Open...	Risk/Issue	Threat/O...	Risk Assigned To	Pre-Mitigation			
						Pro...	Imp...	Sco...	Score
1	Loss of circulation	Opened	Risk	Threat	Assigned to 16 tasks/resourc	81.3%	50.0%	40.6%	
2	Wellbore instability- collapsing formation	Opened	Risk	Threat	Assigned to 16 tasks/resourc	67.8%	50.0%	33.9%	
3	Stuck pipe - clays formation collapse dog legs	Opened	Risk	Threat	Assigned to 15 tasks/resourc	83.3%	70.0%	58.3%	
4	Challenges of soft formation - too high ROP	Opened	Risk	Threat	Assigned to 16 tasks/resourc	61.6%	30.0%	18.5%	
5	Challenges of hard formation - too slow ROP	Opened	Risk	Threat	Assigned to 15 tasks/resourc	63.4%	50.0%	31.7%	
6	High pressures and temperatures	Opened	Risk	Threat	Assigned to 15 tasks/resourc	66.4%	90.0%	59.8%	
7	Magma or intrusions in deep wells	Opened	Risk	Threat	Assigned to 6 tasks/resource	39.8%	50.0%	19.9%	
8	Casing wear during drilling	Opened	Risk	Threat	Assigned to 18 tasks/resourc	41.0%	90.0%	36.9%	
9	Casing off-set (decentralized	Opened	Risk	Threat	Assigned to 3 tasks/resource	38.4%	30.0%	11.5%	
10	Parted casing	Opened	Risk	Threat	Assigned to 3 tasks/resource	40.5%	50.0%	20.3%	
11	Collapsed casing due to poor cement job.	Opened	Risk	Threat	Assigned to 3 tasks/resource	45.4%	70.0%	31.8%	
12	Cold inflows- poor cementing	Opened	Risk	Threat	Assigned to 3 tasks/resource	39.6%	70.0%	27.7%	
13	Difficult cementing jobs due to loss zones	Opened	Risk	Threat	Assigned to 3 tasks/resource	66.0%	50.0%	33.0%	
14	Cement hardening inside casing	Opened	Risk	Threat	Assigned to 3 tasks/resource	36.8%	30.0%	11.0%	
15	Drill string failures- buckling fatigue	Opened	Risk	Threat	Assigned to 19 tasks/resourc	48.6%	50.0%	24.3%	
16	BOP failure	Opened	Risk	Threat	Assigned to 14 tasks/resourc	33.1%	70.0%	23.2%	
17	Loss of tools- BHA logging tools drilling tools	Opened	Risk	Threat	Assigned to 28 tasks/resourc	100.0%	50.0%	50.0%	
18	Machine and equipment failures	Opened	Risk	Threat	All tasks (global)	49.0%	50.0%	24.5%	
19	Long lead times of material delivery	Opened	Risk	Threat	Assigned to 3 tasks/resource	58.3%	50.0%	29.2%	
20	Bureaucracy in the tendering process	Opened	Risk	Threat	All tasks (global)	60.0%	50.0%	30.0%	
21	Failure to allocate risks properly in the contract	Opened	Risk	Threat	All tasks (global)	54.0%	50.0%	27.0%	
22	Poor Quality of materials quality	Opened	Risk	Threat	All tasks (global)	44.0%	50.0%	22.0%	
23	Extreme Weather conditions	Opened	Risk	Threat	All tasks (global)	46.0%	50.0%	23.0%	
24	War and country insecurities	Opened	Risk	Threat	All tasks (global)	27.0%	50.0%	13.5%	
25	Suspended well - not completed	Opened	Risk	Threat	All tasks (global)	41.0%	70.0%	28.7%	
26	Earthquakes	Opened	Risk	Threat	All tasks (global)	32.0%	70.0%	22.4%	
27	Abandoned/plugged well - total loss high pressu	Opened	Risk	Threat	All tasks (global)	42.0%	70.0%	29.4%	
28	Non-productive well- low enthalpy Injectivity dry	Opened	Risk	Threat	All tasks (global)	51.0%	70.0%	35.7%	
29	Toxic gases (CO2 H2S) released from the well	Opened	Risk	Threat	All tasks (global)	65.0%	90.0%	58.5%	
30	High noise levels	Opened	Risk	Threat	All tasks (global)	69.0%	50.0%	34.5%	
31	Inadequate/improper use of Personal Protective	Opened	Risk	Threat	All tasks (global)	51.0%	50.0%	25.5%	
32	Unconducive working environment	Opened	Risk	Threat	All tasks (global)	40.0%	50.0%	20.0%	
33	Leakage or collapse of brine pond	Opened	Risk	Threat	Assigned to 16 tasks/resourc	44.9%	50.0%	22.5%	

FIGURE 3: Part of the risk register from RiskyProject

Risk weighting was required in order to assign the relative importance of the risk categories. RiskyProject uses a form of the analytical hierarchy process (AHP) to weigh the relative importance of one risk category over another. The analytical hierarchy process allows one to objectively analyse the effect of risk on a project by determining the probability of its occurrences. According to Saaty (1987), when objectivity is required, using judgment can be misleading. People make decisions and choices based on their experiences. The analytical hierarchy process is a system of measurement that uses pairwise comparisons where different elements are prioritized based on given attributes. This provides a more accurate way of prioritizing relative importance of objectives than assigning weights.

The relative importance ranking obtained from the survey was used for this purpose. A pairwise comparison was done using the information in Table 4. The final result of the pairwise comparison is shown in Table 5. Each cell in the pairwise comparison matrix on top is divided by the column sum to form the normalized matrix. The weight in the score column in the lower matrix was obtained by averaging the values across each row.

Risk and mitigation costs: To fully analyse the effects of each risk on project cost, the expected cost of each risk was included by any additional cost incurred due to the risk encountered and the cost of mitigation measures used to returning the project to normal.

TABLE 4: Gradation scale for quantitative comparison of alternatives (Saaty, 1987)

Intensity of Value	Interpretation
1	Requirements i and j are of equal value
3	Requirement i has a slightly higher value than j
5	Requirement i has a strongly higher value than j
7	Requirement i has a very strongly higher value than j
9	Requirement i has an absolute higher value than j
2, 4, 6, 8	Intermediate values to reflect fuzzy inputs
Reciprocals	If requirement i has a lower value than j

3.3 Simulation

Probabilistic methods such as Monte Carlo simulation provide an effective way of statistically analysing project uncertainty and risks in order to predict the project cost, end-delivery date, or budget within certain marginal probability value. A Monte Carlo simulation was done on the sample drilling project to simulate the outcome of uncertain costs and schedule in the project. The costs and drilling risk information for the built-in risk register in the risk management software, was compiled from average values in the industry.

4. RESULTS AND DISCUSIONS

4.1 Questionnaire results

A total of 19 responses were received and analysed. One limitation of the questionnaire was that it was not able to seek clarity from the respondents as with interviews as the replies were confidential and non-traceable.

Demographic survey: The first three questions were general questions about the respondents. The following results in Figure 4, Figure 5 and Figure 6 were obtained for country of respondent project, years of experience, position of respondent respectively.

TABLE 5: Pairwise comparison in RiskyProject

		j						
Factors	Weight	Schedule and scope	Financial and cost risk	HSE	Legal risk	Policy and political risk	Technical risks	Organizational risk
Schedule and scope		1	0.33	0.33	5	3	3	7
Financial and cost risk		3	1	0.33333	7	5	3	9
Health, safety and		3	3	1	9	7	5	9
Legal risk	i	0.2	0.14286	0.11111	1	0.33333	0.2	3
Policy and political risk		0.33333	0.2	0.14286	3	1	0.33333	5
Technical risks		0.33333	0.33333	0.2	5	3	1	7
Organizational risk		0.14286	0.11111	0.11111	0.33333	0.2	0.14286	1
Column Sum		**8.00952**	**5.12063**	**2.23175**	**30.3333**	**19.5333**	**12.6762**	**41**
Normalized matrix to determine the weight for each risk category.								
Schedule and scope	15.2%	0.1249	0.0651	0.1494	0.1648	0.1536	0.2367	0.1707
Financial and cost risk	23.7%	0.3746	0.1953	0.1494	0.2308	0.256	0.2367	0.2195
Health, safety and	38.3%	0.3746	0.5859	0.4481	0.2967	0.3584	0.3944	0.2195
Legal risk	3.5%	0.025	0.0279	0.0498	0.033	0.0171	0.0158	0.0732
Policy and political risk	6.3%	0.0416	0.0391	0.064	0.0989	0.0512	0.0263	0.122
Technical risks	10.9%	0.0416	0.0651	0.0896	0.1648	0.1536	0.0789	0.1707
Organizational risk	2.1%	0.0178	0.0217	0.0498	0.011	0.0102	0.0113	0.0244
	100.0%							

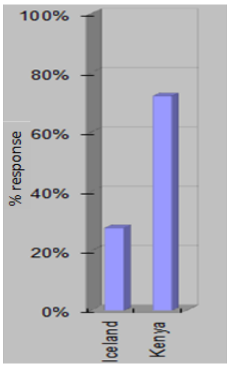


FIGURE 4: Respondent by country

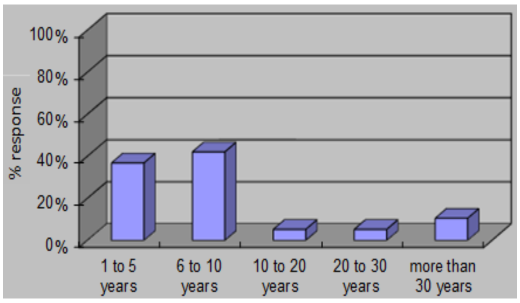


FIGURE 5: Respondent by years of experience

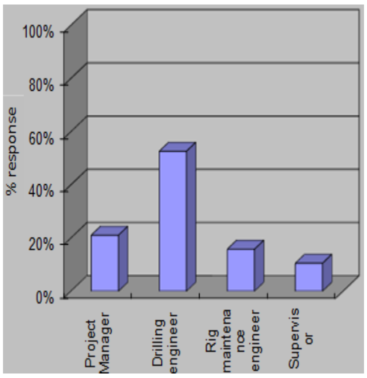


FIGURE 6: Respondent by position held

The next three questions were general questions about the respondents' general experience with risk management systems. They yielded the following results: on experience with using risk management tools the results are shown in Figure 7. The tools used are as listed a.)Modified from petroleum drilling company, b.)Risk matrix, c.)Both commercial and internal d.)Risk mitigation fund (from African Development Bank) and insurance of equipment, e.)OSHA, f.)Job safety analysis. While the respondent's perception of the impact of drilling risks on the project was as shown in Figure 8.

Drilling risk ranking: In the second part of the questionnaire, the list of 64 drilling challenges was provided and the respondents were requested to rate the probability that that elements of risk will occur on a scale of 1 to 5 on the first part of the matrix. In the second part of the matrix they were to rate the degree of impact or level of loss if each particular risk occurs. The rating scale for probability and impact was provided to guide the meaning of the values 1 to 5. Table 6 shows the ranking of top 10 risk of all the respondents. Table 7 shows the ranking of the Icelandic respondents and Table 8 shows the results of the Kenyan respondents. The full results are shown in the Table 8.

4.2 Integrated cost and schedule results

Once the well was defined in Microsoft Project, the project was loaded onto RiskyProject. The risk register was populated with identified risks and their probabilities and impacts. Mitigation measures were determined and also loaded into the project. The mitigation measures were assigned to risks and in turn the risks were assigned to the task. The resulting risk register is as shown in Figure 9. The risks are ranked from the highest to the lowest. The difference in ranking of the critical risks in this system compared to the results obtained from the questionnaire is due to the use of analytical hierarchy process in weighing the importance of the risk categories in this risk management tool.

Two risk matrices were generated with all the risks in cells corresponding to the likelihood and impact. Figure 10 shows the risks before mitigation. In this diagram, more than half of the identified risk fell into the red area which is the "high" risk category. This shows that the risks are critical to the project's cost and schedule and require immediate mitigation measures to eliminate or reduce probability of occurrence. A few other risks fell in the orange zone which is the "medium" risk category. These risks require the development of risk mitigation action immediately if possible. Only one risk made it to the "low" category. Such risks should be solved when it is considered economical to do so, but should be monitored so that they do not reach the medium or high risk areas.

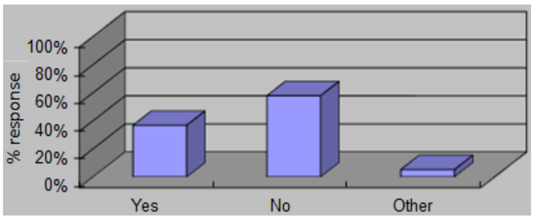


FIGURE 7: Using risk management systems

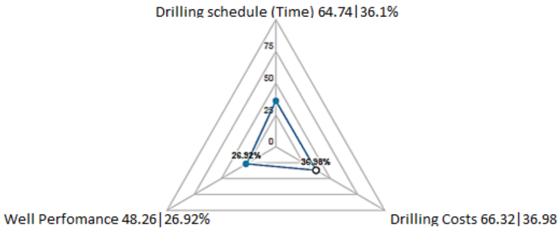


FIGURE 8: Impact of drilling risks on drilling schedule, cost and well completion

Figure 11 shows the risk matrix after mitigation measures had been included. The arrows points to the new position of the risk in the matrix. There was not enough statistical information on how much these mitigation measures could reduce the risks. Therefore, the assumptions made when adding the mitigation measure were that the probability of the risks will be reduced by 20% while the impact, if the risk occurs, will be reduced by 5%. This was not done for all risks as some mitigations are meant to prevent the occurrence of the risk but cannot reduce the impact of the risk. A few risks still remain in the boundary of the high and medium categories.

TABLE 6: Top risks as scored by all respondents

Toxic gases (CO_2 H_2S) released from the well	12.53
High cost of drilling	12.4
Loss of circulation	11.73
Stuck pipe	11.33
Procurement policy (e.g. long tendering process)	11.2
Reduction in annual budget allocation by government	11
Wellbore instability- collapsing formation	10.87
High noise levels	10.87
High pressures and temperatures	10.6
Long lead times of material delivery	10.27

TABLE 7: Top risks as scored by Icelandic respondents

Toxic gases (CO_2 H_2S) released from the well	14.67
High noise levels	14.67
High pressures and temperatures	13.67
Inexperienced and less knowledgeable personnel	13.33
Challenges of hard formation	13
Magma or intrusions in deep wells	13
Loss of circulation	12.67
Long lead times of material delivery	12.67
Abandoned/plugged well - total loss high pressures	11.33
Workforce stress due to inadequate staffing	11.33

TABLE 8: Top risks as scored by Kenyan respondents

High cost of drilling	12.75
Toxic gases (CO_2 H_2S) released from the well	12
Loss of circulation	11.5
Wellbore instability- collapsing formation	11.5
Stuck pipe	11.42
Procurement policy (e.g. long tendering process)	11.33
Reduction in annual budget allocation by government	11.17
Delayed disbursement of funds from financiers	10.83
Loss due to bureaucracy for late approvals	10.67
Loss of tools- BHA logging tools drilling tools	10

4.3 Monte Carlo analysis results

Figure 11 shows the project timeline after simulation. It depicts how the project timelines shift from the base duration given the risk and uncertainty introduced. The transparent bar shows the current schedule while the opaque bar shows the resulting duration after Monte Carlo calculation. Each simulation runs the project schedules and costs in the critical paths and measures the degree of activity sensitivity and the likely impact of activity cost and duration on the project objective. This project ran 432 iterations to produce the probability distribution of possible results for cost, duration and finish time. The start time was not affected and hence it has been left out. The results of the Monte Carlo simulation are shown in Figures 13-15.

Figure 13 shows the probability distribution and cumulative distribution of the drilling cost. The most likely cost of the project is calculated to be 6,678,425 USD. It differs from the determined base schedule which was 6,070,120 as earlier calculated. The range of the distribution falls between 5,871,069 USD and 7,271,681 USD giving a range of 1,400,613 USD. Corresponding percentiles values are shown below in Table 10. It shows that as the project is currently, the cost of the project has a P5 value or 5% chance of costing 6,287,760 USD and a P95 or 5% chance of costing 7,056,467 USD.

Figure 14 shows the probability distribution and cumulative distribution of the project duration. The project was planned for 60 days – a total of 1,440 hours. From the simulation, the most likely project duration is calculated to be 1,693 hours. The range of the distribution falls between 1,436 hours and 1,905 hours giving a range of 469 hours, or 19.5 days. Table 11 shows the corresponding percentiles values for the project duration, with P5 value or 5% chance of spanning 1,557 hours and a P95 value or 5% chance of spanning 1,816.68 hours.

Figure 15 shows the probability distribution and cumulative distribution of the project finish time. The project was planned to start on 4 February 2016 and be completed on 3 April 2016. From the simulation, the most likely project completion date was given as 4

TABLE 9: Results from questionnaire

	ALL			KENYA			ICELAND		
	Probability	Impact	Score	Probability	Impact	Score	Probability	Impact	Score
Loss of circulation	4	3	12	4	3	12	3	4	13
Wellbore instability- collapsing formation	3	3	11	3	4	12	3	3	8
Stuck pipe - clays formation collapse dog legs	3	4	11	3	4	11	3	4	11
Challenges of soft formation - too high ROP	3	2	8	3	2	8	3	2	7
Challenges of hard formation - too slow ROP	3	3	10	3	3	9	4	3	13
High pressures and temperatures	3	3	11	3	3	10	4	3	14
Magma or intrusions in deep wells	2	3	8	2	3	6	3	5	13
Casing wear during drilling	2	3	6	2	3	6	2	3	7
Casing off-set (decentralized	2	3	5	2	3	5	2	3	5
Parted casing	2	3	7	2	4	7	2	3	5
Collapsed casing due to poor cement job.	2	4	9	2	4	9	3	4	10
Cold inflows- poor cementing	2	4	8	2	4	8	3	4	10
Difficult cementing jobs due to loss zones	3	3	10	3	3	10	3	3	9
Cement hardening inside casing	2	2	5	2	2	4	4	2	9
Drill string failures- buckling fatigue	3	4	9	3	4	9	3	4	10
BOP failure	2	4	7	2	4	6	2	4	8
Loss of tools- BHA logging tools drilling tools	3	3	10	3	4	10	3	3	10
Machine failures - drill string breakdowns	3	3	8	3	3	9	2	3	8
Long lead times of material delivery	3	3	10	3	3	10	3	3	13
Bureaucracy in the tendering process	3	3	9	3	3	10	3	3	7
Failure to allocate risks properly in the contract	3	3	8	3	3	8	3	3	9
Poor Quality of materials quality	2	3	8	2	3	7	2	3	8
Extreme Weather conditions	2	3	7	2	3	6	3	3	11
War and country insecurities	1	3	5	2	4	6	1	1	1
Earthquakes	2	4	6	1	4	6	2	3	8
Suspended well - not completed	2	4	7	2	3	7	2	4	10
Abandoned/plugged well	2	4	8	2	4	7	3	4	11
Non-productive well	3	4	10	3	4	9	3	4	11
Toxic gases (CO2 H2S) released from the well	3	4	13	3	4	12	4	4	15
High noise levels	4	3	11	3	3	10	4	3	15
Inadequate/improper use of PPE	3	3	9	3	3	9	3	3	8
Unconducive working environment	2	3	6	2	3	6	2	2	5
Leakage or collapse of brine pond	2	3	7	2	3	7	2	3	6
Improper disposal of drilling cuttings	2	2	5	2	2	5	2	2	4
Air pollution due to using diesel generator	3	3	8	3	2	7	3	3	11
Thermal and chemical pollution	2	3	7	2	3	7	2	2	5
Induced seismicity	2	3	5	2	3	5	3	2	6
High cost of drilling	4	3	12	4	3	13	4	3	11
Bankruptcy of project partner	2	4	8	2	4	8	2	3	7
Interest and exchange rate fluctuation	3	3	8	3	3	9	2	2	4
Reduction in annual budget allocation by government	3	4	11	3	4	11	3	3	10
Delayed disbursement of funds from financiers	3	4	10	3	4	11	2	3	7
Price instability of fuel and steel	3	3	8	3	3	9	2	2	5
Low credibility of shareholders and lenders	2	3	8	2	3	7	3	3	9
Changes in Bank formalities and regulations	2	3	7	3	3	7	2	3	8
Breach of contract by project partner	2	3	7	2	3	8	2	3	5
Improper verification of contract documents	2	3	7	2	3	8	2	2	4
Change of ownership or top management	3	3	7	3	3	7	3	3	10
Inadequate well planning and budgeting	2	3	8	2	3	8	3	3	9
Inadequate management of drilling contracts	2	3	8	2	3	9	2	3	5
Unclear contract specification	2	3	7	2	3	8	2	3	7

April 2016 with a maximum completion date of 23 April 2016. This could add 10 and 15 days to the determined finish date. The range of the distribution is 19.5 days. Table 12 shows the corresponding percentiles values for the project finish dates with P5 value or 5% chance of being finished on 9 April 2016 and P95 value or 5% chance of being finished on 20 April 2016.

4.4 Sensitivity analysis

The software used only modelled the sensitivity of activity to finish time; but when considering the day rate, this could also imply sensitivity to cost. This is because the day rate has to be paid on more days than planned, which in turn increases the total drilling cost. Figure 16 shows a tornado chart of the project activities sensitive to finish time. It is shows that the 8½"section (the production hole section) has the most influence on when the project will be completed. The task that affects the drilling finish time the least is the breaking up the drill stands. A further sensitivity analysis of the 8½" section was done to determine if there are activities that could be optimised to reduce this duration. The sensitivity analysis is shown in a tornado chart in Figure 17. The tornado chart shows that drilling on bottom accounts for the bulk of the time spent in this section, other than running in of liners, well logging and tripping in to break stands. This could be as a result of drilling at deeper depths as this section spans from 1,200m to 3,000m. Drilling on bottom is influenced by several factors, one of which is the rate of penetration (ROP). This is largely influenced by bit performance and parameters such as weight on bit (WOB), revolutions per min (RPM), formation strength, formation compaction and pressure differential. This has been discussed in other research including Miyora (2014).

	Risk Name	Open/Cl	Risk/Issue	Threat/Opp	Risk Assigned To	Proba	Impac	Score	Score	Cost (Pre-Mi	Cost (Mitigat	Probab	Impact (P
1	High pressures and temperatures	Opened	Risk	Threat	Assigned to 15 tasks/resourc	66.4%	90.0%	59.8%		USD 195,00(	USD 0.00	56.4%	80.0%
2	Toxic gases (CO2 H2S) released from the well	Opened	Risk	Threat	All tasks (global)	65.0%	90.0%	58.5%		USD 0.00	USD 0.00	65.0%	90.0%
3	Stuck pipe - clays formation collapse dog legs	Opened	Risk	Threat	Assigned to 15 tasks/resourc	83.3%	70.0%	58.3%		USD 312,597	USD 100,00(	58.3%	45.0%
4	Loss of tools- BHA logging tools drilling tools	Opened	Risk	Threat	Assigned to 28 tasks/resourc	100.0%	50.0%	50.0%		USD 266,04(	USD 0.00	100.0%	50.0%
5	Loss of circulation	Opened	Risk	Threat	Assigned to 16 tasks/resourc	81.3%	50.0%	40.6%		USD 831,375	USD 101,12	71.3%	40.0%
6	Casing wear during drilling	Opened	Risk	Threat	Assigned to 18 tasks/resourc	41.0%	90.0%	36.9%		USD 0.00	USD 0.00	11.0%	60.0%
7	High cost of drilling	Opened	Risk	Threat	All tasks (global)	73.0%	50.0%	36.5%		USD 0.00	USD 0.00	63.0%	40.0%
8	Non-productive well- low enthalpy Injectivity dry col	Opened	Risk	Threat	All tasks (global)	51.0%	70.0%	35.7%		USD 0.00	USD 0.00	51.0%	70.0%
9	High noise levels	Opened	Risk	Threat	All tasks (global)	69.0%	50.0%	34.5%		USD 0.00	USD 0.00	64.0%	45.0%
10	Wellbore instability- collapsing formation	Opened	Risk	Threat	Assigned to 16 tasks/resourc	67.8%	50.0%	33.9%		USD 130,80	USD 22,084	52.8%	35.0%
11	Difficult cementing jobs due to loss zones	Opened	Risk	Threat	Assigned to 3 tasks/resource	66.0%	50.0%	33.0%		USD 831,375	USD 0.00	51.0%	35.0%
12	Collapsed casing due to poor cement job.	Opened	Risk	Threat	Assigned to 3 tasks/resource	45.4%	70.0%	31.8%		USD 0.00	USD 0.00	40.4%	65.0%
13	Challenges of hard formation - too slow ROP	Opened	Risk	Threat	Assigned to 15 tasks/resourc	63.4%	50.0%	31.7%		USD 815,856	USD 100,00(	53.4%	40.0%
14	Procurement policy (e.g. long tendering process)	Opened	Risk	Threat	All tasks (global)	62.0%	50.0%	31.0%		USD 0.00	USD 0.00	52.0%	40.0%
15	Work schedule and cyclic nature of drilling	Opened	Risk	Threat	All tasks (global)	60.0%	50.0%	30.0%		USD 0.00	USD 0.00	30.0%	20.0%
16	Bureaucracy in the tendering process	Opened	Risk	Threat	All tasks (global)	60.0%	50.0%	30.0%		USD 106,416	USD 0.00	45.0%	35.0%
17	Loss due to bureaucracy for late approvals	Opened	Risk	Threat	All tasks (global)	59.0%	50.0%	29.5%		USD 0.00	USD 0.00	44.0%	35.0%
18	Reduction in budget allocation by government	Opened	Risk	Threat	All tasks (global)	59.0%	50.0%	29.5%		USD 0.00	USD 0.00	54.0%	45.0%
19	Abandoned/plugged well - total loss high pressures	Opened	Risk	Threat	All tasks (global)	42.0%	70.0%	29.4%		USD 0.00	USD 0.00	42.0%	70.0%
20	Long lead times of material delivery	Opened	Risk	Threat	Assigned to 3 tasks/resource	58.3%	50.0%	29.2%		USD 106,416	USD 0.00	28.3%	20.0%
21	Suspended well - not completed	Opened	Risk	Threat	All tasks (global)	41.0%	70.0%	28.7%		USD 0.00	USD 0.00	41.0%	70.0%
22	Cold inflows- poor cementing	Opened	Risk	Threat	Assigned to 3 tasks/resource	39.6%	70.0%	27.7%		USD 0.00	USD 0.00	29.6%	60.0%
23	Interest and exchange rate fluctuation	Opened	Risk	Threat	All tasks (global)	55.0%	50.0%	27.5%		USD 0.00	USD 0.00	50.0%	45.0%
24	Price instability of fuel and steel	Opened	Risk	Threat	All tasks (global)	55.0%	50.0%	27.5%		USD 0.00	USD 0.00	50.0%	45.0%
25	Workforce stress due to inadequate staffing	Opened	Risk	Threat	All tasks (global)	55.0%	50.0%	27.5%		USD 93,114	USD 0.00	45.0%	40.0%
26	Failure to allocate risks properly in the contract	Opened	Risk	Threat	All tasks (global)	54.0%	50.0%	27.0%		USD 0.00	USD 0.00	44.0%	40.0%
27	Delayed disbursement of funds from financiers	Opened	Risk	Threat	All tasks (global)	53.0%	50.0%	26.5%		USD 0.00	USD 0.00	48.0%	45.0%
28	Inexperienced and less knowledgeable personnel	Opened	Risk	Threat	All tasks (global)	53.0%	50.0%	26.5%		USD 0.00	USD 0.00	48.0%	45.0%
29	Change of ownership or top management	Opened	Risk	Threat	All tasks (global)	52.0%	50.0%	26.0%		USD 0.00	USD 0.00	52.0%	50.0%
30	Organizational culture	Opened	Risk	Threat	All tasks (global)	52.0%	50.0%	26.0%		USD 0.00	USD 0.00	47.0%	45.0%
31	Personnel not motivated	Opened	Risk	Threat	All tasks (global)	51.0%	50.0%	25.5%		USD 0.00	USD 0.00	36.0%	35.0%

FIGURE 9: The resultant risk register from RiskyProject

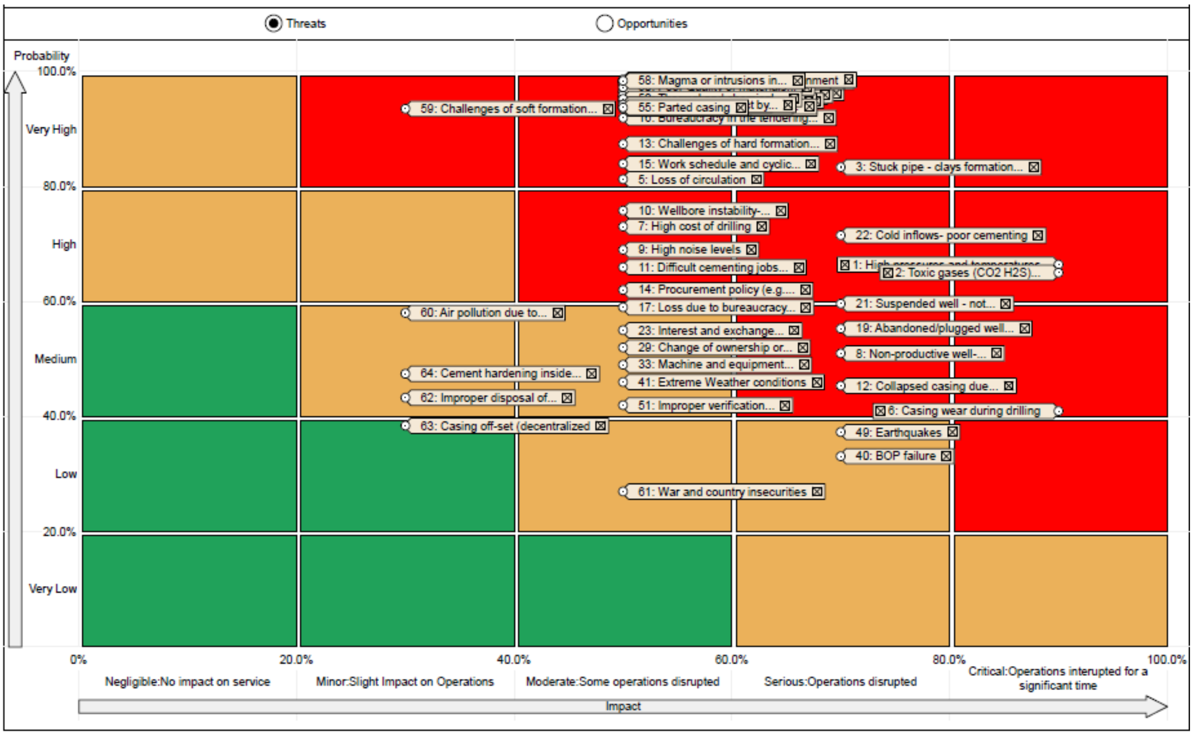


FIGURE 10: Risk matrix without mitigations

5. CONCLUSION

This paper identified analysed and evaluated 64 risks in the drilling process. Finally an integrated cost and schedule risk analysis was carried out to quantify the impacts of the identified risk factors on the drilling project. It was determined that the drilling schedule and cost are influenced by risks and uncertainties that are encountered both within and outside the project. It was also able to show which activities were prone to increase project duration and cost. Such knowledge forms a basis for clearer decision making, better resource allocation and proper project planning. Risks management systems in place allows for earlier identification of risks in the project, and hence mitigation and control measures can be applied in time to lower or totally eliminate these risks.

In conclusion, the geothermal drilling industry needs to embrace risk management, especially integrated cost and schedule risk management as a tool for controlling of budget and schedule overruns. A proper risk management plan is able to put in place control measures and allows for proper cost planning resulting in significant cost reductions for the drilling project, as well as the entire geothermal project. If put in use in geothermal drilling, a risk management system can improve the possibility of project success in all aspects of delivery of geothermal wells. There will be fewer cost and schedule surprises and more understanding of the current risks impacting the project.

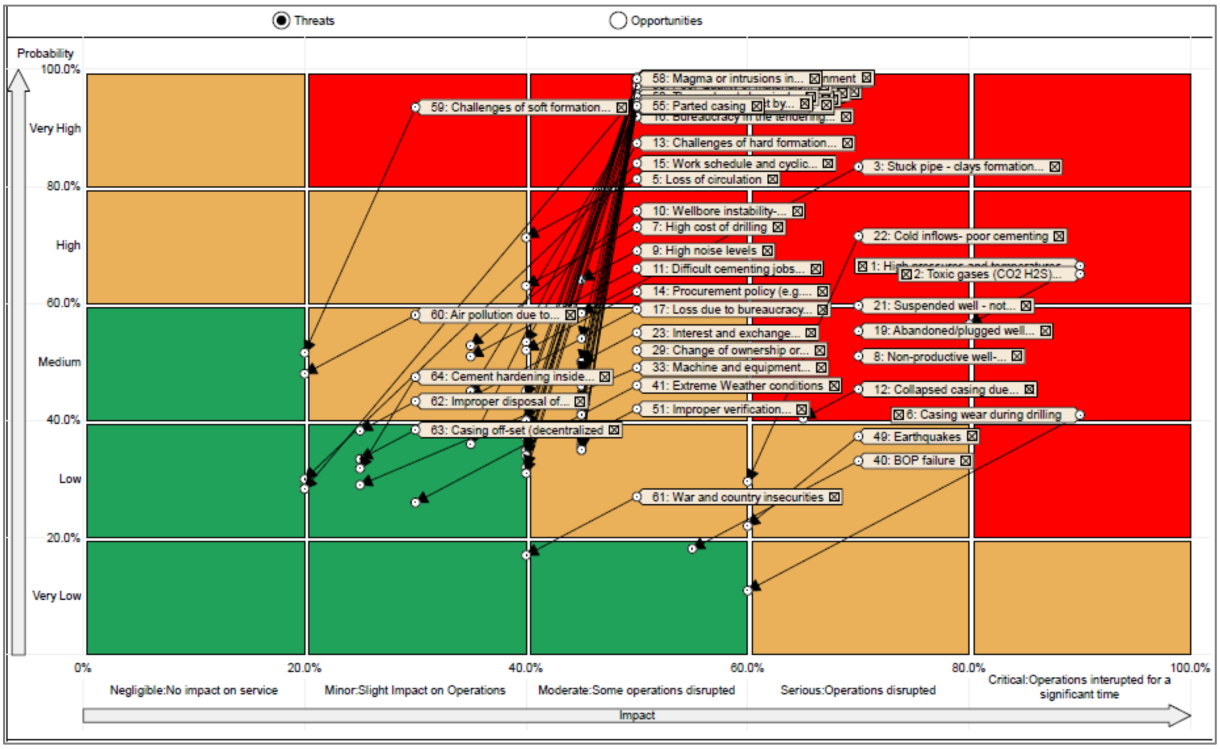


FIGURE 11: Risk matrix with mitigations

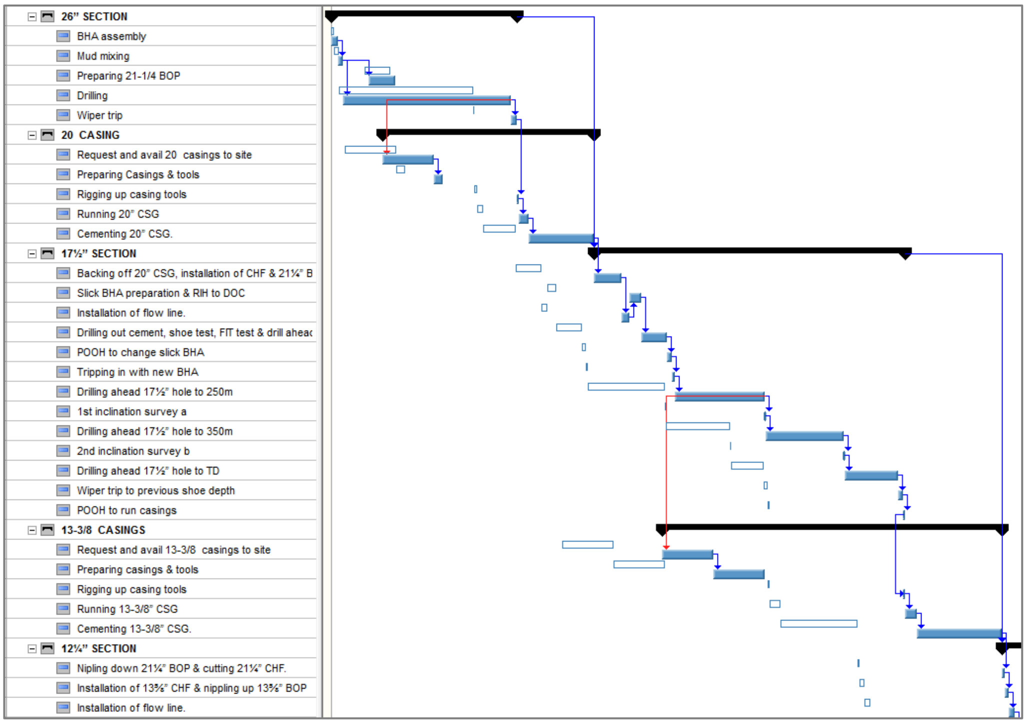


FIGURE 12: Drilling timeline after simulation

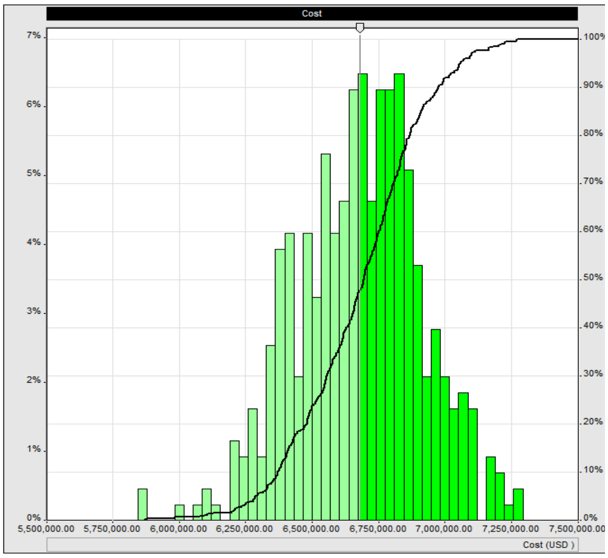


FIGURE 13: Probability and cumulative distribution of the drilling cost.

TABLE 10: Corresponding percentiles values for the project costs

Percentile th	USD		
5	6,287,760	No. of samples	432
10	6,370,918	Minimum	USD 5,871,069
15	6,413,027	Mean	USD 6,678,425
20	6,478,954	Maximum	USD 7,271,681
25	6,519,058	Range	USD 1,400,613
30	6,554,290		
35	6,598,237	P1/P99 range	USD 1,115,369
40	6,629,252	P5/P95 range	USD 768,707
45	6,661,986	P10/P90 range	USD 603,348
50	6,695,263	P20/P80 range	USD 386,631
55	6,722,963	P30/P70 range	USD 252,359
60	6,752,532		
65	6,778,458	Variance	USD 56,201,026,580
70t	6,806,649	SD	USD 237,068
75	6,834,620	Semi Std. Dev	USD 250,849
80	6,865,585	Skewness	-0.215114
85	6,912,176	Kurtosis	0.124418
90	6,974,266		
95	7,056,467		

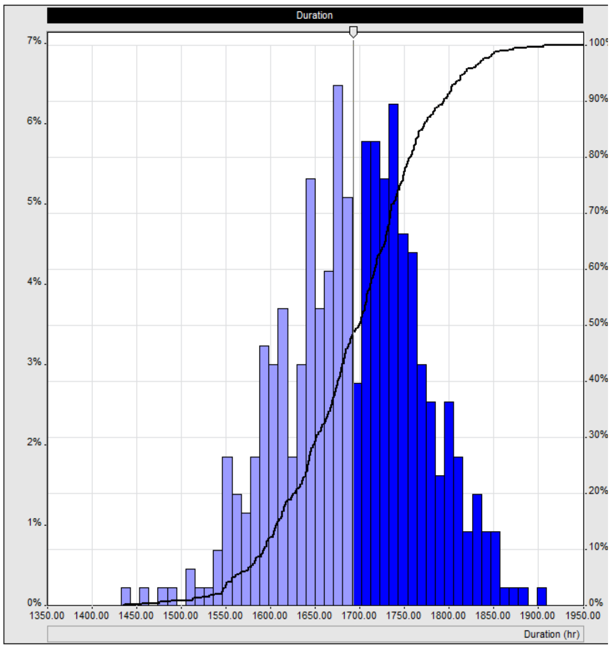


FIGURE 14: Probability and cumulative distribution of drilling duration.

TABLE 11: Corresponding percentiles values for the project duration

Percentile th	hours		
5	1,557	No. of samples	432
10	1,593	Minimum	1,436.37 hr.
15	1,608	Mean	1,693.03 hr.
20	1,626	Maximum	1,905.75 hr.
25	1,642	Range	469.38 hr.
30	1,652		
35	1,667	P1/P99 range	342.97 hr.
40	1,675	P5/P95 range	259.3 hr.
45	1,684	P10/P90 range	199.97 hr.
50	1,700	P20/P80 range	130.23 hr.
55	1,708	P30/P70 range	83.15 hr.
60	1,718		
65	1,729	Variance	5,988.7 hr.
70	1,735	SD	77.39 hr.
75	1,746		
80	1,756	Skewness	-0.187572
85	1,770	Kurtosis	-0.014914
90	1,793		
95	1,816		

5. CONCLUSION

This paper identified analysed and evaluated 64 risks in the drilling process. Finally an integrated cost and schedule risk analysis was carried out to quantify the impacts of the identified risk factors on the drilling project. It was determined that the drilling schedule and cost are influenced by risks and uncertainties that are encountered both within and outside the project. It was also able to show which activities were prone to increase project duration and cost. Such knowledge forms a basis for clearer decision making, better resource allocation and proper project planning. Risks management systems in place allows for earlier identification of risks in the project, and hence mitigation and control measures can be applied in time to lower or totally eliminate these risks.

In conclusion, the geothermal drilling industry needs to embrace risk management, especially integrated cost and schedule risk management as a tool for controlling of budget and schedule overruns. A proper risk management plan is able to put in place control measures and allows for proper cost planning resulting in significant cost reductions for the drilling project, as well as the entire geothermal project. If put in use in geothermal drilling, a risk management system can improve the possibility of project success in all aspects of delivery of geothermal wells. There will be fewer cost and schedule surprises and more understanding of the current risks impacting the project

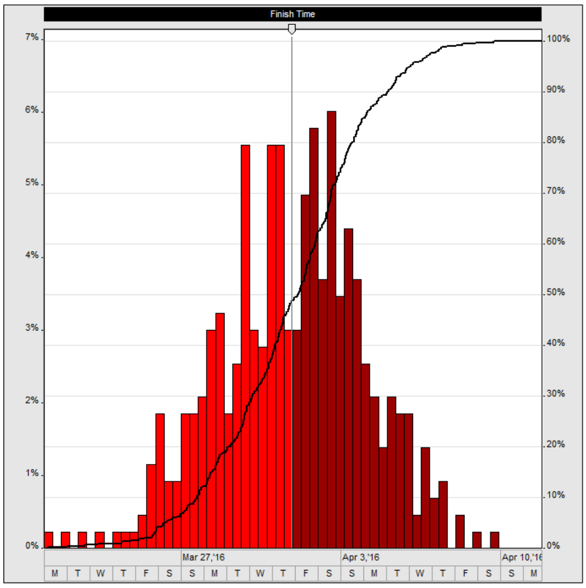
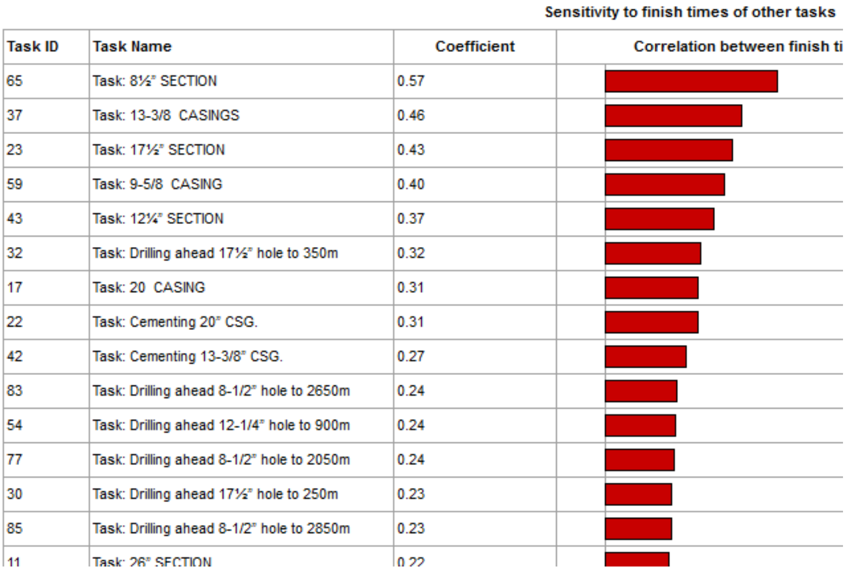


FIGURE 15: Probability and cumulative distribution of the finish time.

TABLE 12: Corresponding percentiles values for the project finish dates

Percentileth	Date		
5	04/09/2016 05:23	No. of samples	432
10	04/10/2016 17:15	Minimum	04/04/2016 04:22
15	04/11/2016 07:45	Mean	4/14/2016 21:01
20	04/12/2016 01:41	Maximum	4/23/2016 17:45
25	04/12/2016 18:13	Range	469.38 hr.
30	4/13/2016 3:28		
35	4/13/2016 19:06	P1/P99 range	342.97 hr.
40	4/14/2016 3:13	P5/P95 range	259.30 hr.
45	4/14/2016 12:04	P10/P90 range	199.97 hr.
50	4/15/2016 3:38	P10/P90 range	199.97 hr.
55	4/15/2016 12:07		
60	4/15/2016 21:31	Variance	5,926.77 hr.
65	4/16/2016 8:35	SD	76.99 hr.
70	4/16/2016 14:37		
75	4/17/2016 1:31	Skewness	-0.188952
80	4/17/2016 11:55	Kurtosis	-3.020995
85	4/18/2016 1:54	Sens. Threshold	0.16
90	4/19/2016 1:13		
95	4/20/2016 0:41		



Sensitivity to finish times of other tasks

Task ID	Task Name	Coefficient	Correlation between finish ti
65	Task: 8½" SECTION	0.57	
37	Task: 13-3/8 CASINGS	0.46	
23	Task: 17½" SECTION	0.43	
59	Task: 9-5/8 CASING	0.40	
43	Task: 12¼" SECTION	0.37	
32	Task: Drilling ahead 17½" hole to 350m	0.32	
17	Task: 20 CASING	0.31	
22	Task: Cementing 20" CSG.	0.31	
42	Task: Cementing 13-3/8" CSG.	0.27	
83	Task: Drilling ahead 8-1/2" hole to 2650m	0.24	
54	Task: Drilling ahead 12-1/4" hole to 900m	0.24	
77	Task: Drilling ahead 8-1/2" hole to 2050m	0.24	
30	Task: Drilling ahead 17½" hole to 250m	0.23	
85	Task: Drilling ahead 8-1/2" hole to 2850m	0.23	
11	Task: 26" SECTION	0.22	

FIGURE 16: Sensitivity to finish time of tasks

Task ID	Task Name	Coefficient	Correlation between finish times
12	Task: Drilling ahead 8-1/2" hole to 1850m	0.37	
20	Task: Drilling ahead 8-1/2" hole to 2650m	0.36	
16	Task: Drilling ahead 8-1/2" hole to 2250m	0.36	
22	Task: Drilling ahead 8-1/2" hole to 2850m	0.35	
14	Task: Drilling ahead 8-1/2" hole to 2050m	0.35	
8	Task: Drilling ahead 8-1/2" hole to 1450m	0.31	
10	Task: Drilling ahead 8-1/2" hole to 1650m	0.31	
31	Task: RIH liners + POOH escorting DP breaking to singles _laying them down	0.30	
18	Task: Drilling ahead 8-1/2" hole to 2450m	0.29	
32	Task: Well logging.	0.18	
24	Task: Drilling ahead 8-1/2" hole to 3000m	0.18	
33	Task: RIH stands POOH breaking the stands into singles _laying them down.	0.17	

FIGURE 17: Sensitivity of activities in the 8½" section to finish time

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