RISK ASSESSMENT AND RISK MODELLING IN GEOTHERMAL DRILLING

Lilian Aketch Okwiri

Thesis of 60 ECTS credits
Master of Science in Sustainable Energy Engineering
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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 development 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 second part of the study 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 drilling project showed that the P50 values giving the most likely values for cost and schedule, gave a higher value than the base values determined for the project. P1/P99 range was 1,115,369 USD for cost and 343 hrs for schedule. The simulation showed that drilling the 8½" section has the largest influence on the well completion time and therefore greater effect on the cost and schedule of the drilling project.

For further studies, the cost effects of the risk events should be studied as this was not possible in this 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.

Key words: Drilling risks, Geothermal drilling, Risk management, Cost and schedule estimation

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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. In January 2016, the installed global capacity of geothermal power generation was about 13.3 GW across 24 countries. A further 12.5 GW of planned capacity across 82 countries is currently under development and if all the planned projects stay on course, the global geothermal industry is expected to reach about 18.4 GW by 2021 and 32 GW by the early 2030s (GEA, 2015). Despite this increased development and geothermal energy's advantage over other renewable sources such as 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 (IGA, 2013).

Geothermal drilling is a fundamental phase of geothermal development and it carries considerable risk in terms of costs, schedule and project completion. Drilling is carried out for several reasons, the main one being to produce steam and water for energy generation. Other objectives of drilling are to prove existence of a resource, the extent and size of the reservoir and to confirm the sustainability of the resource. Drilling conditions contribute significantly to risks during the drilling process. These risks are numerous and include down-hole geologic conditions, location of the target reservoir, prevailing reservoir conditions, available technology, equipment and resources, experience of the drilling personnel and well specifications. The consequences of these risks are undesirable and can have implications on project completion, economic performance, professional reputation, environmental impact and personnel safety. Risk management, especially cost and schedule risks, should consequently be an integral part of any geothermal drilling project to minimize events that threaten to delay the project, compromise quality of the drilled well, cause the project to go over budget and cause harm to project personnel.

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 costs comprise of approximately 40 percent of the total investment cost of a geothermal project (Þórhallsson & Sveinbjörnsson, 2012). This is directly influenced by the time taken to drill and complete the wells (Okwiri, 2013). Risks and uncertainty in the drilling process result in more days to complete the work than planned; this in turn increases the cost, as most of the charges for the drilling are based on a per-day rate.

Drilling risks and uncertainties result in drilling projects not only going off the critical path of the planned drilling operations, 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. These risks are usually not well accounted for in planning of projects costs and their control. There are several methods of project and schedule cost estimation. The two most common methods are the use of contingency or reserve amount and the three-point method to account for cost uncertainties that could arise from the project.

Contingency or reserve amount

Time contingency is the additional time allocated above the schedule time, while cost contingency is the additional funds allocated above the budgeted amount. This is done to cover any eventualities that would result in delay or additional cost as the project progresses. It can be a percentage increase of the activity duration and the budget, or it can be a fixed duration and amount of money added to the original estimates.

The three-point method

This method is used when duration and cost of activities are not known for certain and is based on determining three types of estimates (PMBOK, 2013):

i. Most likely. This scenario gives the most realistic time and cost an activity will require under normal conditions to achieve its goals.
ii. Optimistic. This is the best case scenario where conditions are favourable and the cost and time may be lower than the most likely estimate.
iii. Pessimistic. This gives the worst case scenario of the cost and time requirement when the conditions are unfavourable.

There are numerous project uncertainties including task duration, start and finish times, quality, safety, technology costs and resources uncertainties. The recommended practice (RP) of American association of cost engineering (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 risk on cost risk 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 schedule by resource-loading and costing the schedule's activities and risks. The risks and costs that they affect are then linked activities (Shen, Wu, & Ng, 2001).

It is important to understand and manage the level of risk involved in any drilling project, in terms of integrated cost and schedule risk management 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 then second, by allocating cost to materials and consumables such as casing and drilling bits used in the project. A further integration of risks into the cost and schedule planning reduces the instances of project cost and schedule overruns.

This thesis looks at a risk incorporated integrated cost and schedule risk management to allow for proper planning of budgeted costs and their control. This provides an easier way of accounting for activities outside the critical path that add cost and time to the planned project path.

This thesis is presented in five main parts. Chapter 1 introduces the study and gives the research purpose, objectives and goals. Chapter 2 gives the methods used in the thesis. It starts by outlining the structure of a drilling project and details it in a project life cycle. A general risk management foundation is then described. Chapter 3 deals with a detailed risk management process for a drilling project, drilling risk are identified and described. This chapter goes further and describes how these risks are analysed and evaluated. A questionnaire is used to gain insight on risks in the industry and its structure is described here. Finally, an integrated cost and schedule risk management tool – RiskyProject is introduced. In Chapter 4, the results obtained from the survey and the integrated cost and schedule risk management tool are analysed. Finally, Chapter 5 gives the summary and discussion of results. Finally, Chapter 6 gives the conclusion and Chapter 7 gives recommendation and future work.

1.1 Objectives and goals

The main objective of this thesis was to identify, through the relevant literature and drilling professionals' experience, the risks that threaten the on-time delivery of geothermal wells and increase the cost of drilling geothermal wells and to examine the impact these risks have on geothermal development projects. It also looked at how drilling professionals perceive risks in two countries, Iceland and Kenya. The thesis also intended to define a suitable framework for realizing a process-driven risk management for drilling projects.

To accomplish this, the following research topics were formulated:

i. Identify the key risk factors that can interrupt or delay the delivery, or compromise the quality, of a geothermal well in each phase of the drilling project.
ii. Assess the perception of the risk according to industrial practitioners in terms of probability of occurrence and severity.
iii. Review an integrated cost and schedule analysis model that can be used to support the risk management process and implement such a tool on a sample drilling project to quantify the impacts of the identified risk factors on the drilling project.

2. METHODS

This chapter describes in details the methodology and tools used to collect, analyse, assess and evaluate drilling risks in this project. It explains the data collection procedures and research strategy, design, target population and sample size.

The methodology adopted for this thesis is described in three parts. First, a literature review that was done is described, where a theoretical framework of the drilling industry and drilling risks were presented and the risk management process also discussed. This was followed by an online survey questionnaire sent to personnel in the geothermal drilling industry to quantify these identified risks. Finally, an integrated cost and schedule risk analysis was carried out using Monte Carlo simulation on a sample drilling project with a risk management support tool, RiskyProject.

2.1 Literature review

In this section the available literature on geothermal drilling is reviewed in order to identify risks involved. It starts out explaining the nature and organisation of the drilling industry, followed by project life cycle in the drilling project. Those risks that affect the drilling operation phase are discussed in detail. Risks in the drilling phase are identified both on individual jobs and on the whole process.

2.1.1 Nature of the drilling industry

The drilling industry is a unique industry where practically all construction goes on underground. It is an industry that requires specialized equipment and highly skilled personnel. Geothermal drilling adapts heavily from oil and gas drilling in terms of tools, equipment and even drilling methods. The operations are standardized worldwide, but there are differences in how different types of wells are drilled based on their purpose. Axelsson et al. (2013) lists eight types of geothermal wells and how they differ in terms of construction and purpose. These include:

i. Temperature gradient wells
ii. Exploration wells
iii. Production wells
iv. Step-out wells
v. Make-up well
vi. Reinjection wells
vii. Monitoring wells
viii. Unconventional wells

For most geothermal projects, drilling operations are usually contracted; however, some owners are choosing to own and carry out their own drilling operations in-house (Khan, 2015). There are three different types of contracts used in the drilling industry to provide the background for contractor payment and the allocation of risks in the drilling project (Anderson, 1971). Because each contract provides different incentives for the contractor, proper contract management is important in reducing drilling risks and ensuring well success. These contracts include:

i. Day rate – The day rate contract is commonly used today. The well owner or operator provides a comprehensive drilling program to direct the contractor on how to proceed with the well, along with all well consumables and any other services required for the well. The drilling contractor provides drilling equipment and personnel to drill the well. The owner and the contractor agree on a fixed daily rate for every day spent on drilling (Miyora, 2014). The daily rate usually covers for rental of drilling rig and other equipment and the cost of personnel and expatriates. When operations outside the definite jobs for the drilling contractor are carried out, a stand-by-rate is charged. Under a day rate contract, the operator normally shoulders all the risk of delay unless the incident is caused by negligence on part of the contractor (Anderson, 1971). The contractor in this type of arrangement is only liable for risks associated with the equipment, services provided and labour provision. All the other risks remain with the operator.

ii. Meter rate – also known as per footage rate. A few geothermal drilling project uses this type of contract including drilling projects in Iceland. Similar to the day rate, the owner or operator of the well provides the program for drilling the well. The drilling contractor provides the equipment and crew. The difference is that the contractor is paid an agreed sum based on the depth drilled to well completion or the specified depth. Anderson (1971) explains that some operations cannot be measured by depth. Therefore, parts of this contract will include day rate or fixed cost. Risks in this type of contract are assigned on the basis of the operation in question. The contractor carries more risks than in the day rate.

iii. Turnkey- in this contract, the owner or operator has no input on the day to day operation that takes place, he only serves to specify the target and establishes the quality controls for the finished well. He pays the drilling contractor a lump sum to deliver a well and it is up to the contractor to develop the drilling program, provide all services and consumables required for the well (Miyora, 2014). The contractor in this type of contract is required to accept more risks than in the day rate and meter rate contract since he is in charge of the entire operation’s contracts.

The industry typically relies on several other players to provide service and equipment, repair and maintenance and support the drilling operations. Some of these may be included in the drilling contracts, but sometimes they are offered as standalone services. Full service drilling contract may be a necessity in remote areas. These services include (Þórhallsson, 2016):

i. Mud logging / geology
ii. Well logging and testing
iii. Directional drilling
iv. Mud engineer
v. Cementing
vi. Air drilling
vii. Fishing tools
viii. Drill string inspection
ix. Drill site logistics
x. Water supply
xi. Waste disposal
xii. Security

2.1.2 Drilling industry organisation

The process of drilling a well is characterized by activities and interactions between several disciplines. This results in a complex and dynamic project organisation that changes as different personnel and players enter and exit the project during the drilling phase.

Figure 1 shows personnel involved in a typical drilling project. The operator is usually either the owner of the field being developed or company responsible for the work. The operator's main duty is to plan the job and design the wells. The operator will then hire a drilling contractor for the drilling job and the service companies provide the equipment and materials and other support services.

i. Operator - Manages drilling and production operation, plans the job and designs the wells, makes decisions affecting the drilling process of the well and organizes supplies of consumables to the rig (Anderson, 1971). Formal leadership of the project is executed by a Company man representing the operator.
ii. Drilling contractor – the company contracted to construct the well with its own rig and drilling personnel (Miyora, 2014). The drilling contractor typically has a drilling superintendent and a toolpusher at the rig who are in overall charge of the rig and crew.
iii. Service companies – provide specialized skills and equipment to the operator such as listed in 2.1.1 above

The drilling organisation structure exposes drilling operations to risks and uncertainties due to presence of various interest groups: including the project operator, drilling contractor and service providers, as well as financiers, consultants and vendors. A well-documented, cohesive, understandable risk management plan is required in order to ensure that the risks have been identified, analysed, managed and allocated properly.

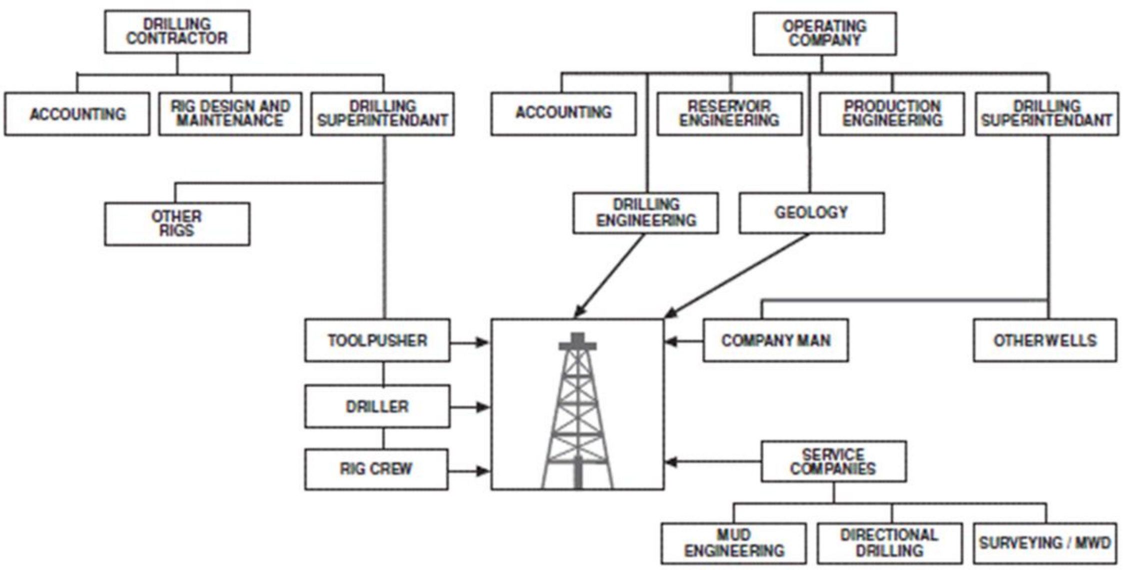

FIGURE 1: Personnel involved in drilling a well (Miyora, 2014)

2.2 Project life cycle

To understand risks in drilling, an overview of how a drilling project is structured and organized is important. An understanding of the drilling project life cycle will provide a basis for risk identification, analysis and evaluation in any drilling project. This section starts off by looking at the well drilling process from preparation to completion of a well and then identifies the drilling process risks involved in the project.

British Standard BS 6079 'Guide to Project Management', defines a project as: *'A unique set of coordinated activities, with definite starting and finishing points, undertaken by an individual or organisation to meet specific objectives within defined schedule, cost and performance parameters.'* Geothermal development is a large scale project with several smaller projects, drilling of a well being one such small project. Every drilling project requires adequate planning as there are various activities undertaken to deliver a fit- for-use well.

A project life cycle is a natural framework for analysing the nature and scope of decision making in project management. This understanding allows for an appreciation and management of the potential risks. A well-structured project life cycle provides a framework for planning for uncertainties and for appreciating how the risk management process will change as project life cycle evolves (Chapman & Ward, 2003). Figure 2 shows the Comprehensive Project Life Cycle Model with 6 phases as proposed by Archibald et al. (2012). Their report claims that a project begins long before the start phase and its outcomes remain after the closeout phases and consequently will require assessment at the end of the project. It is important to recognize that each project is unique when using any project life cycle model and therefore adjustments and an individual approach should be taken depending on project scope and structure. Table 1 shows how these project life cycle phases apply to drilling projects.

FIGURE 2: Project life cycle phases (Archibald et al., 2012)

TABLE 1: Drilling project in project life cycle

PLC	Drilling phase
Incubation/feasibility	Well design
Project starting	Operations planning
Project, organizing, definition, planning	Mobilization
Project execution	Drilling operations
Project close out	Demobilization
Post project evaluation	Documentation and experience transfer

The success of drilling a well is shaped by the interaction of personnel and activity taking place in the entire drilling project life cycle. Well prognosis forms the basis of any drilling project and is the most important activity in drilling. This thesis did not discuss risk associated with the well prognosis but focused on the problems and risks that occur during the project execution phase (i.e., the drilling operations), though an overview of the entire project life cycle is discussed.

2.2.1 Well design

Well design is the construction of a well on paper. It involves several disciplines and experience to predict subsurface conditions likely to be encountered, selection of the right equipment and materials for the expected conditions and the selection of the right drilling practices. Well design involves the prediction of reservoir rock and fluid conditions and use of this information to model every aspect of the well. As the well progresses, the gathered information is used to modify the design to suit the actual conditions encountered (New Zealand Standard 2015). The goal is to come up with a drilling program for a well that can be drilled safely at a minimum cost and that is fit-for-use for the intended purpose. A good well design will define main objectives and fall back objectives if unable to meet main objectives and allows for review, verification and design changes as actual wellbore conditions become known. Well design usually involves the following tasks, which are described in more detail below:

i. Well classification and characterization
ii. Subsurface and geological conditions
iii. Casing string, cement, drilling fluid and drill-string design
iv. Well head design and completion considerations

i. Well classification and characterization provides a way of describing wells for the purposes of well management, not only during well construction but also for purposes of monitoring and maintenance during well use. It allows for cost-benefit evaluations as it is possible to follow the well through its lifetime, allowing for communication and assessment. Geothermal wells are classified mostly by location, purpose, depth and orientation. Well design characteristics involve specifying type of well, intended vertical depth, well head location and well targets (New Zealand Standard 2015). They establish the well depth, casing diameters, materials, casing thickness and lengths. Data collection demands are specified for the well, including temperature and pressure logs and geological information. These form the basis for determining other parameters such as wellbore diameter, drilling methods, drilling fluid pump rates and other critical decisions that must be made during drilling.

ii. Subsurface and Geological conditions: A profound knowledge of the geological conditions of the proposed well path is important in well design. This involves studying information from nearby wells and relevant scientific appraisals to shed light on the expected stratigraphy and lithology.

iii. Casing string, cement and drilling fluid design and pressure containment: Casing strings are designed to maintain full control of the well at all times and this is done by taking into account the geology, pressures, temperatures and other harsh wellbore conditions encountered such as corrosive fluids caused by H_2S and CO_2 during drilling and production, abrasive formations, friction, buckling and hard banding effect of casing wear (Standards Norway, 2007). Geothermal cementing design is critical to ensure that the total length of the annulus is completely filled with a good quality cement and is able to withstanding high temperature without compromising its properties. This is needed in order to provide necessary support for the casing and also to be able to absorb the force involved in drilling the rest of the well. A drilling fluid and hydraulics program must be designed to suit the reservoir conditions and the intended drilling technique and guides the selection of drilling fluid equipment. The design takes into account the annular velocities for cutting removal, pressure losses through components in the circulating system, formation pressures to be encountered, ability to cool and quench the well and power requirements (New Zealand Standard, 2015). It is also important to plan for excess drilling fluid and lost circulation materials on site in anticipation of lost circulation. Geothermal Drill String design is done according to API RP 7G standards (New Zealand Standard, 2015).

iv. Well head design and completion considerations: Geothermal wells are mostly completed by running in perforated liners in the open hole section. In some cases, the production zone is left open without a perforated liner. The perforated liner's weight is important in the design as it is either hung from the production casing or rests on bottom. The material selected should be able to withstand well environment such as high temperature and corrosive fluids through the lifetime of the well. A well head is designed and selected to withstand the pressures expected from the well while it is flowing and when shut-in.

2.2.2. Operations planning

Every geothermal well is different and may require different schedules, budgetary allocation and available resources. Therefore, planning should be done for each well to ensure that all requirements are in place and contractors and operators are aware of their responsibilities and timelines and there are clear communicating channels. Proper planning is critical to the success of any drilling project and it involves the following tasks which are described in more detail below:

i. Work organisation
ii. Personnel training and safety
iii. Drilling site
iv. Drilling equipment and services
v. Back-up equipment and spares
vi. Drilling programs and other operations
vii. Health safety environment (HSE)

i. Work organisation ensures that the project plan, schedule and budget are established and responsibilities are clearly defined. It involves decisions such as choosing the right drilling team and other sources of experience to support the team, identifying and selecting suitable drilling rigs and equipment and securing service contracts early on. It plans for procurement of materials and consumables which often have long lead times and identifying special regulatory provisions, license obligation and restrictions ahead of time. It also determines the need and capabilities of emergency response and environmental considerations among other things (Standards Norway, 2007).

ii. Personnel training and safety: Drilling is a complex and high risk operation demanding diverse knowledge and disciplines. All personnel require a working knowledge of these disciplines in order to successfully drill a well. New and even experienced personnel require continual training to equip them with basic skills to succeed and prepare them for high-risk rig environment. Key persons receive formal well control training and some countries require a certificate from an accredited course (such as the International Well Control Forum IWCF or International Association of Drilling Contractors WellCAP) and regular blow-out drill response to be carried out on site. Employee competency is important not only for the drilling crew but also the support crew who require a basic understanding of drilling operations for effective collaboration and communication with the drilling team.

iii. Drilling site: The preparation of a well site involves excavation and levelling stable enough to support the drilling rig and its auxiliary equipment. Other considerations are access roads to the well pad to accommodate the transportation of large and heavy equipment, overhead power lines in consideration of rig moves and buried pipeline and utilities in consideration of excavations. Surface water and proximity to a source of drilling water are also important. New Zealand Standard (2015) cautions that surface thermal activities and geology of the area should be considered to ensure smooth construction and suitability of the site for drilling operations. It is also important to ensure the site allows for proper dispersion of dangerous gases.

iv. Drilling equipment and services: Selection, inspection and maintenance of drilling rig equipment and evaluation and procurement of drilling services are done according to accepted industrial standards. The selection of the equipment follows assessment of drilling operation power load requirements as determined in the well design including safety margin. Drilling equipment are selected to perform drilling to the desired depth and all other associated works required to deliver the well to said depth. For example, derrick and substructure should be able to support the casing load requirement for the well being drilled and the selected mud system should be able to effectively circulate drilling fluid to the depths being drilled. Improperly selected rig equipment and accessories could result in lost drilling time and increase drilling costs.

v. Back-up equipment and spare parts: Critical spare parts and redundant equipment should be planned for in good time. Equipment will always fail and having a fall back for critical equipment while the main equipment is being repaired will reduce the non-productive time (NPT) due to wait on repairs or wait on spares. Spares for preventive maintenance should be ordered with good lead times and efficient supply channels be in place to handle rush orders for spares.

v. Drilling programs and other operations: A drilling program is a document prepared by a multi-disciplinary team providing specific instructions for the drilling of a particular well. It contains the design drawings and detailed description of the planned tasks to be undertaken during drilling of each section of the well and the materials and drilling methods to use. Deviations from this program due to unavoidable circumstances are usually recorded. Other operational programs that are created for drilling operations include casing and cementing programs, fishing programs and well logging program.

vii. Health Safety Environment (HSE): There are numerous unforeseen hazards in the geothermal drilling environment that can happen and therefore employee safety and environmental protection standards have been put in place to guide health safety and environment management such as ISO 14001 as an environmental management standard, ISO OHSAS 18001 occupational health and safety management system and ISO 9001 as a quality management standard. Employees are to be trained and advised on hazards related to their work and also preventive measures should be put in place. Drilling companies are responsible for provision of protective equipment and putting systems in place for reporting incidents and accidents, work related illness and unsafe acts and conditions. Companies also aim to reduce environmental pollution in their operations, by reducing fuel and chemical use in their well delivery, proper waste disposal handling procedures.

2.2.3. Mobilization

This involves team, resource and equipment mobilization, following careful operations planning and determination of the well requirements. The drilling team will depend on the type of rig selected and also the scope of work to be done. A modernized rig with robotics will require smaller crew than a conventional rig. Enough crew should be selected to cover all the shifts for that particular drilling job. Other than human resources, logistical concerns such as transport and storage of spares and consumable should be planned for.

Once the team and all the requirements are ready the drilling rig is brought to site. Rig up and testing takes place once all the other preparations are done. Specific equipment such as the blow-out preventer (BOP) requires pressure testing once installed. Rig up, like any other drilling job, requires at least one pre-job safety meeting.

2.2.4. Drilling operations

All the planning and organisation that takes place from the beginning of the drilling life cycle climaxes at this point. All personnel of different disciplines work together in the delivery of a well to the desired depth.

Drilling operations are preceded by a pre-operation meeting to familiarize staff, operators and contractors of the planned program and timelines. In this meeting roles and responsibilities are described to ensure safe and efficient operation. Communication systems and reporting channels are also defined. Daily and weekly activities are clearly outlined to ensure planning for equipment, resources, materials and consumables. All crew members are made aware of HSE goals and well targets. During drilling operations there are regular review meetings to update and check progress. Most geothermal wells are drilled in four sections, Table 2 shows a typical well design of wells in Kenya.

TABLE 2: Typical geothermal well design in Kenya

Section	**Width**		**Depth**	
	Hole Section	**Casing Size**	**From**	**To**
Surface hole	26"	20"	0	80
Intermediate hole	17½"	13⅜"	80	500
Production hole	12¼"	9⅝"	500	1,200
Open hole	8½"	7"	1,200	3,000

2.2.5. Demobilization

Once a well is completed to the target depth, the drilling equipment and facilities are transported from the site. This demobilization is known as rig move. The drilling rig is dismantled and wheeled out of the site by trucks. Job safety analysis is performed. Documentation of the activities for compliance and safe practices is performed.

2.2.6. Documentation and experience transfer

Once a well is completed, a post-project analysis and evaluation are conducted. Here, economic, technical, safety and environmental related aspects are evaluated on the completion of the well. Performances are reviewed and experience ("lessons learned") transferred to subsequent wells. Record keeping is an important part of this process throughout the life cycle of the drilling project, starting from well design through to completion. During drilling daily reports are prepared e.g. by the toolpusher on standardized forms for the rig operations and also a report on data collected by the site geologist and loggers.

2.3 Concept of risk and risk management process

Risk and risk management are a very wide subject and there are many definitions in the literature to suit different industries and projects. For the purpose of this thesis, the IEC/ISO 31000 definition will be used.

2.3.1 Risk

Risk is defined in ISO 31000 - Risk Management as the "effect of uncertainty on objectives" (Standards Australia, 2009), where uncertainties are the unforeseeable outcomes of the challenges encountered, while effect could be a positive or negative deviation from what is expected. Objectives have different aspects such as financial, schedule, project completion and health, safety and environmental goals; these apply at different levels such as strategic, organisation-wide, or project. PMBOK (2013) defines risk as any "uncertain event or condition that, if it occurs, has a positive or a negative effect on at least one project objective, such as time, cost, scope, or quality", while Wideman (1992) defines project risk as "the cumulative effect of the chances of uncertainty occurrences adversely affecting project objectives" All these definitions agree on three components of risk which include:

- The event: What might happen to the disadvantage or in favour of the project
- Probability of occurrence: The chance that that event will occur
- Outcome: The consequence associated with the event happening whether positive or negative.

For the purposes of this thesis, effects of uncertainty on objectives will be used to define risks (Standards Australia, 2009).

2.3.2 Risk management

Risk management involves dealing with risks in a methodical way, with the aim to increase the likelihood and impact of positive events while reducing those of the negative events (PMBOK, 2013). It allows for putting control measures in place to solve problems before they occur and also to prepare for any eventualities if they occur. Wideman (1992) defines project risk management as "the art and science of identifying, assessing and responding to project risk throughout the life cycle of a project and in the best interests of its objectives." A risk management process must involve formal planning of activities, identification of potential risks, analysis of risk through estimation of the probability of occurrence and prediction of the impact on the project, creation of a risk response strategy for selected risks and the ability to monitor and control progress in reducing these selected risks to the desired level (Kerzner, 2009). PMBOK, 2013 explains further that risk management process should be able to establish an appropriate context; set goals and objectives; identify and analyse risks; and review risk responses.

For the purpose of this thesis, the definition of risk management used in Risk management: Principles and guidelines (AS/NZS ISO 31000:2009). It includes five components of the risk management process that should be accomplished. These are: communication and consultation, establishing the risk context, risk assessment, risk treatment and monitoring and review (Figure 3).

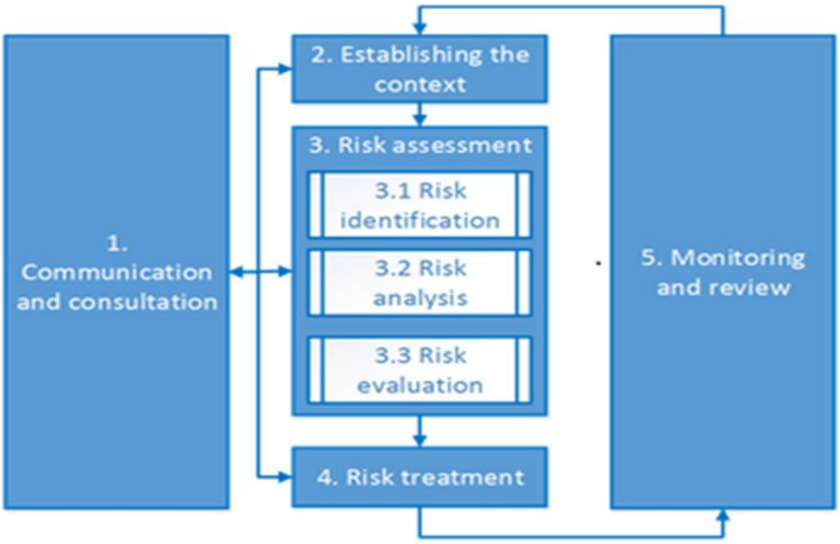

Figure 3: Risk management process (Standards Australia, 2009)

1. Communication and consultation

Communication and consultation are integral parts of the risk management process aiming to identify who will participate in each of the components of the risk management process. Communication and consultation mechanisms also provides a means to constantly communicate the progress and concerns at each step of the process with the parties involved.

2. Establishing the risk context

Effective risk management requires an established scope boundary and risk criteria against which the risks will be assessed. Establishing the context takes into account the organisation's background and articulates the parameters to be taken into account when managing risk within the organisation's objectives.

To establish the context, one needs to define the internal and external parameters that affect the organisation.

i. The external context – is the external environment in which the organisation operates and has limited influence over. These may include the external stakeholders, the organisation's local, national and international regulatory environments and market conditions.

ii. The internal context – is the internal environment of the organisation including its internal stakeholders, approach to governance, contractual relationship and capabilities, culture and standards.

3. Risk assessment

The risk assessment process is accomplished in three different steps: identification, analysis and evaluation (Standards Australia, 2009). It is the most complex part of the risk management process. Risk identification is concerned with the identification of sources of risks and areas of impacts. Risk analysis focuses on the causes and sources of the identified risks, their consequences and the likelihood that those consequences can occur. Finally, risk evaluation compares the level of risk defined in the risk analysis, with risk criteria established taking into account tolerance to risk.

3.1 Risk identification

Risk identification is a systematic process that identifies, classifies and determines the significance of risks associated with the project. It should be an integral part of the planning process but can be carried out at any time in the project phases as new risks emerges. PMBOK (2013) lists some of the inputs to risk identification as the organisation's risk management plan, project planning outputs, risk categories and historical information. The tools and techniques are listed as documentation review, information-gathering techniques (i.e. interviews and questionnaire), checklists, assumptions analysis and diagramming techniques. The output of risk identification process includes risk lists, triggers and inputs to other processes.

3.2 Risk analysis

Risk analysis studies the identified risks and their causes and determines their effect in terms of probability of occurrence and level of impact on the project. There are three methods of risk analysis and they are described below:

i. Qualitative methods
ii. Semi-quantitative methods
iii. Quantitative methods

i. Qualitative risk assessment

Qualitative risk assessment methods use a descriptive scale and are suitable where numerical data are insufficient or unavailable. It is easy to use and does not require sophisticated tools. In qualitative methods, once the risks have been identified they are classified based on the potential of loss in terms of "acceptable" or "unacceptable" or in terms of "low", "medium", "high". Mitigation measures are then undertaken on high risks while the rest are subjected to semi quantitative or quantitative risk assessment (Radu, 2009). Probability of occurrence and impact of the risks are usually not determinative; all that is evaluated is the potential loss. Qualitative risk assessment allows for the description of risks and offers an easy, less time consuming method of risk assessment, therefore it is more commonly used than quantitative as most of the times numerical values are not readily available.

ii. Semi-quantitative risk assessment

Food and Agriculture Organisation (2009), defines semi-quantitative methods as the use of numerical values of quantitative risk assessment to estimate risks while interpreting the results with the textual evaluation of qualitative risk assessment. Data requirement and treatment are similar to those of qualitative risk assessment, but can be applied where comprehensive data for quantitative methods are inadequate. The difference between semi-quantitative and qualitative methods is that in the qualitative method risks are ranked and organized according to their probability, impact or severity using a predefined scoring system. Semi-quantitative methods result in a hierarchy of risks against a quantification, reflecting the order in which these risks should be evaluated with no real connection between them (Radu, 2009). This is the method used for the risk assessment later in the thesis. The main tools here are the following and are described below.

a) Risk probability, impact and severity
b) Risk matrix

a) Risk probability, impact and severity

Risks are defined in two dimensions and commonly referred to as probability and impact. These dimensions form the basis on which risk assessment is conducted.

Probability, also known as likelihood, gives the uncertainty dimension of the risk as it shows whether the risk event or condition is likely to occur, measured in a broad range from impossibility to certainty. This range is defined differently depending on the project and the risks being assessed (Hillson & Hulett, 2004) as shown in Table 3.

TABLE 3: Probability definitions

Labels	Very low, Low, Medium, High and Very High
Phases	improbable, possible, or likely
Odds	1:50, 1:10, 1:3
Numbers, percentages or decimals	1, 3, 5, 55%, 40%, 70%, or 0.05, 0.4, 0.7
Ranges	1-10%, 25-50%, 70-90%).

Impact, on the other hand, gives the magnitude that the occurrence of the event will have on the project (Hillson & Hulett, 2004). It describes the effects or consequences that will arise as a result of a risk event occurring. The impact is usually measured in terms of money or time lost, organisation's reputation, loss of business, injury to people, or damage to property. Impact is defined in terms of "High, Medium, Low" or by use of numbers (1 - 5). Table 4 and 5 describe the probability and impact scales used in this project.

TABLE 4: Probability categories

Probability	< 5%	5-10%	10-20%	20-40%	>.40%
Descriptions	Very unlikely	Unlikely	Likely	Very likely	Certain
	Improbable	Remote	Occasional	Probable	Frequent
	May never occur	At least once in a well	At least once in a section of the well	At least once in every section of the well	Multiple times during drilling of the well

TABLE 5: Risk rating consequences/impact

Score	Rating	Cost of the well	Schedule	Technical Risk	Health and Safety Risk	Environmental	Reputation
5	Catastrophic	>5 MUSD + 25%	More than a week	Loss of well and loss of well control	Fatality	Massive irreversible damage to the environment	International media coverage
4	Major/Critical	>2MUSD	More than 24 hours	Loss of more than 1 hole section	Serious injury (amputation, permanent disability)	Extensive damage to the environment	National media coverage
3	Serious but tolerable	>250KUSD	Up to 24 hours lost	Loss of hole section	Disability in excess of 3 months	Harm to the outside environment	Local media coverage
2	Marginal	>50,000 USD	up to 12 hours lost	Loss of more than 50 meters of hole section	Disabling injury less than 5 work days	Temporary harm to the environment	Local community complaint/ recognition
1	Negligible	< 50,000 USD	Up to an hour lost	Loss of a less than 50 meters	Minor first aid or no injury	Minor harm to the environment	Internal complaint/ recognition

Severity is the combination of the probability of risk occurring or likelihood of an event and the impact or consequence of the event if it happens. Risk severity was evaluated through a risk matrix developed in this thesis as a combination of the probability and impact of drilling risks on drilling projects.

b) Risk matrix

A risk matrix is a simple, effective graphical tool to rank and prioritize risks. It usually has two components: the probability of occurrence on one axis and the impact on the second axis. The matrix uses different colours to show the level of risks. A 5 by 5 matrix was used in this project as shown in Table 6. Risk matrixes are usually applied in decision-making to evaluate how much risk is acceptable and prioritize which risk needs to be addressed first.

TABLE 6: Risk matrix

			Likelihood / Estimate of potential Frequency / Probability				
			Very unlikely	Unlikely	Likely	Very likely	Certain
			A	**B**	**C**	**D**	**E**
Impact / Consequence	Catastrophic	**5**	A5	B5	C5	D5	E5
	Critical	**4**	A4	B4	C4	D4	E4
	Moderate	**3**	A3	B3	C3	D3	E3
	Marginal	**2**	A2	B2	C2	D2	E2
	Negligible	**1**	A1	B1	C1	D1	E1

Low (A1, B1, C1, A2, B2)	Risks acceptable: remedial action discretionary if they can be implemented at low cost in terms of time, money and effort
Medium (D1, E1, C2, D2, B3, C3, A4, B4, A5)	Take remedial action at appropriate time
High (E2, E3, D3, E4, D4, C4, E5, D5, C5)	Risks unacceptable: operations are not permissible unless mitigation measures are in place

iii. Quantitative risk assessment

Quantitative risk assessment methods are based on numerical estimations to determine the probability and impact of risks and produce an outcome in terms of numerical ranking of these risks based on the impact they have on the project outcome. These methods are work intensive and may require complex software and experienced personnel. Therefore, their value can mostly be applicable for larger projects but not for smaller ones. According to PMBOK (2013), quantitative methods are usually executed on risks that have been prioritized by qualitative methods as those having the most impact on the projects. Quantitate risk analysis methods are listed below.

a) Modelling technique - Sensitivity analysis
b) Scenario technique - Monte Carlo simulation
c) Diagramming technique – decision tree analysis, fault tree analysis, event tree analysis

Only the Monte Carlo simulation is described further for the purposes of this thesis, as it will be used in the cost and schedule analysis of the project.

Monte Carlo simulation

A Monte Carlo simulation is a mathematical method commonly applied in quantitative risk analysis and used for forecasting and estimation of the distribution of possible outcomes based on probabilistic inputs (Lev Virine & Trumper, 2013). It presents an effective method for analysing project schedules with risks. For cost and schedule risk analysis, the input data is usually task duration, cost, start and finish time. More often the pessimistic, most likely and optimistic values for time and cost are required in order to generate different scenarios. The output is usually the total project duration, total project cost and project finish time in the form of frequency or cumulative probability charts or histograms.

Figure 4 shows the Monte Carlo simulation process. Each simulation is generated by randomly drawing a sample value for each input data by selecting a suitable distribution function for the data e.g. uniform, normal, lognormal, rectangle, triangular, betaPERT, etc. (Lev Virine & Trumper, 2013). These input sample values are then used to calculate the results. The process is the repeated till an acceptable level of accuracy is attained.

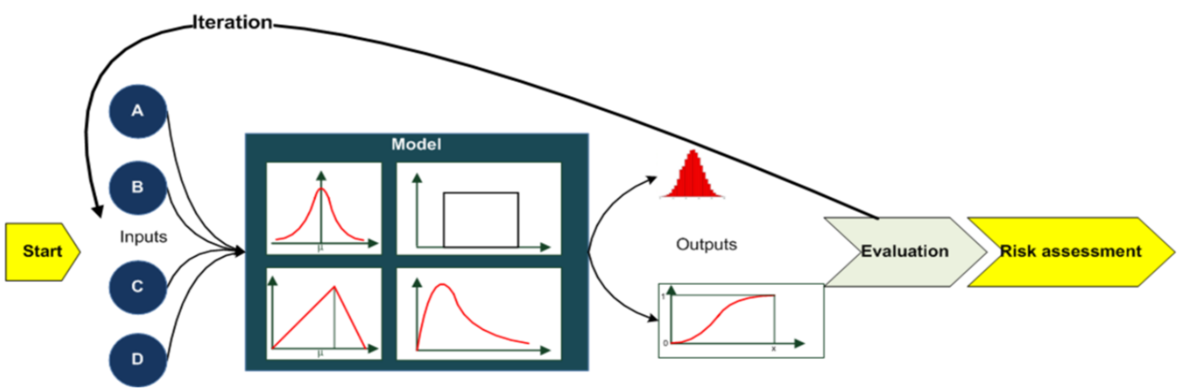

FIGURE 4: Monte Carlo simulation process (Schwarz, 2015.)

3.3 Risk evaluation

Risk evaluation forms the basis of decision making by comparing the level of risks defined and the risk criteria, to determine if the risk level is acceptable or tolerable (IEC/ISO 31010). This tolerable risk level is usually documented with the risk matrix. The matrix will show the different levels of risks, which form the basis for choosing appropriate mitigation measure. Risks can be evaluated as:

Class I	-Unacceptable
Class II	-Undesirable
Class III	-Action recommended
Class IV	-Broadly acceptable

4. Risk treatment

Risk treatment involves decisions on how risks will be mitigated. During evaluation, different levels of risks are determined and in managing them, risk treatment selects the appropriate solutions. The risks that are considered unacceptably high will require immediate mitigation, while those considered to be medium risks should be treated when considered reasonable within the framework of project costs, other risks and company objectives. Risks that are sufficiently low and are considered of minor effect on the project can be retained (Scarlett et al., 2011). Most common strategies for risk response are:

i. Avoiding the risk,
ii. Reducing (mitigating) the risk,
iii. Transferring (sharing) the risk
iv. Retaining (accepting) the risk.

5. Monitoring and review

The risk management process requires continuous monitoring and reviewing to ensure that the risk management process is effective and to identify any new risks that arise from either the mitigations or the changing project environment. Identified risks can be tracked and closed risks can be eliminated from the risk assessment and project (PMBOK, 2013). One tool that is used for risk monitoring and review is a risk register.

Risk register

A risk register is a tool for recording all the risks encountered in the project and the entire risk management process in an auditable and sustainable way. Risk registers can be customized for every project and there is no one register that fits all applications. An example of a drilling risk register is shown in Table 7.

The first column is for risk identification, followed by consequences. The probability and impact of occurrence in this example were based on opinions of industry experts. In some cases, the cost of the risk is indicated if available. The risk ranking is given by the combination of the probability and impact (multiplying the two ranking numbers). It is the same as used in risk matrix to show where the risks lie and to identify whether to mitigate, avoid, accept or transfer.

In the next column, the risk mitigations actions that are in place are recorded, as determined by the risk assessment team. This is followed by the cost of these mitigations if available. After mitigation a new probability and impact are assigned. These are usually lower as the mitigation measures are expected to have reduced the risk probability but not so much the consequence.

TABLE 7: Drilling risk register

Risk ID	Risk	Consequence	Probability %	Impact %	Risk ranking %	Cost of risk if it occurs (USD)	Risk response	Mitigation	Cost of mitigation (USD)	Probability after mitigation %	Impact after mitigation %	Risk ranking %	comments
1	Loss circulation	poor hole cleaning resulting in stuck pipe	81	50	41	830,000	Mitigate	Introduce loss circulation materials Plug Loss zones	100,000	71	40	28	drill blind and plug below loss zone if severe.
2	Stuck pipe	Lost drilling time. Could result in fishing operations	83	70	58	310,000	Avoid	Use drilling jar. Minimize time in hole without circulation	100,000	58	45	26	

3. RISK MANAGEMENT IN THE DRILLING PROCESS

Drilling risks could result in project delay, project cost overrun, temporary abandonment or permanent loss of well, loss of revenue, physical damage to equipment, physical harm to personnel, loss of reputation and business as well as other factors. There is therefore a great need to incorporate the risk management concepts into drilling projects in order to mitigate or eliminate risk consequence and enhance the performance of project.

In this chapter, risk management, is explained in the drilling context. The scope of this risk analysis ranges from the spud-in time to the time the rig is released. It also includes components of risks of financing, policy and political because these risks affect the project from the start and progress of drilling.

3.1. Risks in the geothermal drilling process

Drilling success can be viewed in terms of timely completion of a fit-for-use well, in a safe manner, using the available technology while minimising the overall cost (Okwiri, 2013). This is not always the case, as several factors and events arise that may push the drilling project off of the critical path. Effects of these events range from non-productive time to catastrophic wellbore failure or even loss of well control (Pritchard, 2011). The consequences of these risks are undesirable and could have implications on project completion, economic performance, professional reputation, environment and safety. Managing risk effectively in drilling is consequently central in ensuring safe and timely delivery of geothermal project within budget. This involves understanding and deliberately applying specific risk-mitigation strategies. Risk management is therefore an important aspect of any geothermal drilling project.

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 management in drilling should be updated for each well since each well is considered a different project. The lessons learned from one well can be inputs for the risk management process of the next well.

As discussed in section 2.3.2., risk assessment starts with risk identification. Risk identification in the drilling project should start during feasibility phase, but can be done any time in the life cycle as risks arise during the well construction. Drilling risks were identified from previous work found in literature. The list was narrowed down to 64 risks for the purpose of this thesis. These risks were categorized into 6 main risk categories as shown in Table 8 below. The list may not be exhaustive but most of the common risks have been captured.

3.1.1. Technical risks

A majority of risks affecting geothermal drilling projects are technical risks. They are commonly related to the geological formation or equipment and material supply and delivery. When one risk occurs in this category there is usually a ripple effect that increases the chance of other risks to occur if not adequately handled. Take for example a risk such as lost circulation. Lost circulation creates a condition where hole cleaning is compromised resulting in stuck pipe. High torques applied in efforts to unstick the pipe have a potential of causing a twist off leading to fishing operations. When fishing operations fails, decisions must be made to plug and abandon the well or to plug and side track. Other technical issues are a result of resource characteristics such as fluid chemistry and reservoir conditions such as permeability, pressure and temperatures; but they impact more the success of the well for production rather than the drilling process. This thesis does not go into details on the issues that occur during production. Technical risks were further divided into six categories which are described below.

i. Geological risks
ii. Casing and cementing
iii. Equipment and tools challenges
iv. Drilling materials and consumables
v. Force majeure
vi. Well success

TABLE 8: Drilling risks in literature

	(Habtemariam, 2012)	(Finger & Blankenship, 2010)	(Makuk, 2013)	(Lavrov, 2016)	(Culver, 1997)	(Tunio, Tunio, Ghirano, & Irawan, 2011)	(Jones, 2011)	(Vollmar, Wittig, & Bracke, 2013)	(Noorollahi, 1999)	(Mannvit hf, 2013)	(Franco & Arévalo, 2011)	(IFC, 2007)	(Deloitte L. L. P, 2008)	(Ngugi, 2014)
TECHNICAL RISKS	X	X	X	X	X	X		X						X
HEALTH, SAFETY, & ENVIRONMENT									x	X	X	X		X
FINANCIAL RISK													X	X
LEGAL RISK														
ORGANISATION RISK							X							
POLICY AND POLITICAL RISK														X

i. 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:

a) Loss of circulation
b) Wellbore instability- collapsing formation
c) Stuck pipe
d) Hard and soft formation
e) High pressures and temperatures
f) Magma or intrusions in deep wells

a) *Loss of circulation:* Loss of circulation during drilling is mainly caused by highly fractured formations in geothermal reservoirs. These factors are sought after in the productive interval of the wells but they also cause the greatest challenges during drilling. Improper drilling practices may also lead to induced fractures aggravating lost circulation problems. If not managed, lost circulation can cause other problems in the wellbore (Okwiri, 2013). Lost circulation can be expensive. It results in loss of expensive drilling fluids (mud, drilling soap) and requires the purchase and introduction of circulation materials to prevent the loss. In extreme cases loss zones must be plugged by a cement plug which is very expensive. A large portion of drilling time can be lost while trying to mitigate lost circulation and this is quantified in terms of time spent setting cement plugs and the several hours that the crew has to wait for the cement to harden before commencing drilling.

Lost circulation also poses a challenge when cementing casing as it takes a greater volume of cement slurry to fill up a wellbore that has loss zones and the cement may fail to reach the surface. This leads to several back fills as it is not easy to calculate cement requirement for the well. For this reason, when loss of circulation has been encountered during drilling, the actual cement requirement quite often exceeds 100% over the theoretical annulus volume.

Lost circulation easily results in other challenges including stuck pipe. This is caused by the fact the cuttings are not being evacuated from the well, increasing the chance of the cuttings settling down on the string resulting in mechanical sticking

b) Wellbore instability- collapsing formation: Wellbore instability refers to the failure in the structural integrity of the open hole, resulting in a well that cannot retain its gauge size and form. As a result of the stress state within the boreholes, formation instability results in borehole widening through caving and collapsing or contracting through formation swelling and slouching (Awili, 2014). The cavings results in fillings inside the hole which if not well cleared will result in stuck pipe. The solution to this can be a good drilling fluid design and isolation of potential problem zone.

c) Stuck pipe- Stuck pipe is usually a result of other formation challenges and the second largest cause of non-productive time in most drilling projects after lost circulation. Stuck pipe occurs through either differential sticking or mechanical sticking.

d) Hard and soft formation: Geothermal formations are characterized by layers of hard and soft formations. These result in different rates of penetration that have different effects on the wellbore, drilling time and drilling costs. Hard formations drastically reduce drilling rates and hence increase the drilling time. Soft formations, on the other hand, result in faster drilling rates and pose a threat to wellbore stability as the soft formations are not always stable and wash out easily.

e) High pressures and temperatures: Geothermal drilling involves drilling in high temperature and pressure environments. The drilling program is designed with this in mind and materials and equipment are selected to withstand these conditions. Drilling fluid is pumped into the wellbore to provide the needed cooling and lubrication for the drilling bits. Even so there is a possibility of high temperature degrading the equipment, especially downhole equipment with elastomers and seals such as drilling bits, logging tools and drilling jars. High temperature can also degrade the drilling mud and cement quality which can result in problems developing later in the life of the well. High temperatures and pressures may result in blow outs and kicks that could cause harm to the drilling personnel and surface equipment, well control procedures should be in place that reduce this risk.

f) Magma intrusions in deep wells: It is uncommon for deep geothermal wells to reach magma. In 2009, however, the Iceland Deep Drilling Project research well IDDP-1 – which was intended to be drilled to depths of 4-5 km – had instead to be completed at only 2.1 km because magma was encountered (Friðleifsson et. al. 2015). In one of the wells drilled in Menengai, Kenya chilled fresh glass was encountered at a depth of 2,174 m, indicating a possible a very recent intrusion that was chilled by the drilling fluid (Mibei, 2012). Drilling into magma increases chances of encountering unusually high temperatures due to high heat flow influx from the magmatic intrusion, sudden sticking with no prior signatures of sticking and damage to downhole equipment.

ii. 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. These consequences could render a well unproductive due to casing collapse meaning loss of investments. Some of the casing and cementing challenges in this study are described below:

a) Casing wear during drilling
b) Casing off-set (decentralized)
c) Parted casing
d) Water or mud pockets resulting in collapsed casing
e) Cold inflows- poor cementing
f) Difficult cementing jobs due to loss zones
g) Cement hardening inside casing

a) Casing wear during drilling: A vertical well may not always be vertical due to the whirring action of the bit resulting in doglegs. The doglegs increase contact between the drill pipe and its tool joint with the casing inside diameter. Drill pipe tool joint are usually coated to reduce wear, but this coating also harms the casing. The most abrasive materials used for the coating is tungsten carbide. Though the use of it has greatly reduced since high-tech hard banding materials have been developed for drill pipes. The other cause of casing wear could be attributed to drilling on hard formation. This results in low rate of penetration (ROP) which increases contact time between casing and drill pipe tool joint and higher revolution per minute (RPM) increasing the abrasion effect.

b) Casing off-set (decentralized): Centraliser are usually included on the outside of the casing while running-in casing, at least on every casing joint. This is to offset the casing such that the space between the outside diameter of the casing and the wellbore diameter remains constant throughout the length of the casing. There is no certain way of confirming that the centralisers remain in place during cementing. From talks with industrial experts there have been cases where several meters of casings were excavated and the profiles showed that the centralisers had slipped and casing lied upon casing.

c) Parted casing: This failure usually manifests at the connection. This could be caused by a manufacturing defect resulting in weaker casing threads. Others causes could be due to the operations during drilling such as working a stuck casing and bumping the cement plug too hard (Khaemba, 2014).

d) Water or mud pockets resulting in collapsed casing: During cementing, challenges may occur resulting in failure to fill the entire wellbore with cement. This can lead to trapping of drilling mud or water between the casing and the cement as remedial cement jobs are carried out. If this occur there is an increased chance of the trapped fluids expanding during the heating u of the well resulting in casing collapse.

e) Cold inflows: A cold inflow to the well can be incurred due to setting the casing too high and therefore failure to seal all the cold feed zone. This is a serious issue that can result in the quenching of the well.

f) Difficult cementing jobs due to loss zones: Loss zones are a problem for geothermal drilling. When cementing, loss zone results in several back fill jobs. This increases the cost of the well in terms of the amount of cement used and the time spent on the back fill jobs. Each and every backfill job requires a period of eight hours for cement to set, before the next job can resume.

g) Cement hardening inside casing: Cement additives such as cement retarders are used to prevent the cement from drying too fast. In some instances, due to high temperature, cement pumping rates and cement design, cement may harden too fast and therefore dry inside the casing. This could be due to slow pumping and high temperatures inside the wellbore. This sets back drilling as it creates extra columns of cement to be drilled out.

iii. 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. Four major equipment failure have been looked at in this project:

a) Drill pipe failures
b) BOP failure
c) Loss of tools- BHA, logging tools, drilling tools
d) Machine failures

iv. Drilling material and consumables

Drilling consumables and materials are needed for the daily operations of the drilling rig and drilling activities. To ensure that the project is not interrupted their supply should be planned for and be delivered ton site as need.

a) Long lead times of material delivery
b) Bureaucracy in the tendering process
c) Failure to allocate risks properly in the contract
d) Poor materials quality

v. Force majeure

These are unavoidable catastrophes that interrupt the expected course of events and restrict participants from fulfilling their obligations. They include, for example:

a) Extreme weather conditions
b) War and country insecurities
c) Earthquakes

vi. 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, such as reinjection wells with good injectivity. The report further lists reasons for the wells not being successful and these include: unforeseen mechanical problems during drilling resulting in partly filled or bridged well, inadequate temperature and low reservoir pressures, low productivity index, unacceptable chemical problems and wells that do not reach the reservoir.

a) Plugged and abandoned well
b) Suspended well - not completed:
c) Non-productive well:

A) Plugged and abandoned well: Many wells plugged and abandoned during the drilling process had encountered geological and drilling challenges that made it difficult for the drilling to continue. These challenges could be a loss zone that could not be healed and resulted in an unstable well that could not stop collapsing on itself, a stuck pipe that could not be freed, anything left in the wellbore (fish) that was so buried that it was not possible to remove anymore, or high temperatures that couldn't be contained and resulted in loss of well control.

There is no rule of thumb as to when a problematic well that clearly show no signs of progress should be terminated. Sometimes the decision to abandon a well comes when it is understood that the cost of salvaging it is more than the cost of what will be lost by abandonment. For example, if the cost of drilling a geothermal well is approximately 5 million U.S. dollars (MUSD). This translates to average overall costs of over 83,000 USD daily operating cost for a well projected to take 60 days. About half of this cost is the day rate for the rig. If fishing operations are carried out for 7 days without success the cost will increase by over 290,000 USD. At 2 weeks, it will be already over 0.5 MUSD and in a month it will be over 1 MUSD.

b) Suspended well - not completed: A well may be suspended for the same reasons it will be abandoned, though the intention here is to come back and complete it later. When drilling with a smaller rig and challenges such as stuck pipe or fishing are encountered, the rig might not have the needed capacity to perform such jobs. Such a well is usually temporarily abandoned and the rig moved, to allow a larger rig with the adequate capacity and tools to move in and complete the job. These costs may be due to changed rig rates, rig move costs and increased labour costs for a larger crew to operate the bigger rig. It is also of essence when dealing with fishing and stuck pipe, that the longer the fish stays in hole the chances of it being buried increase making the job even more difficult.

c) Non-productive well: Every drilling crew aims to deliver a fit-for-use well. Sometimes, however, this does not occur: even wells completed to specifications can fail to produce or serve the intended purpose. The main reasons are low enthalpy, low injectivity, harsh fluid chemistry, cyclic pressures, or dry wells. A few of the causes usually go back to the feasibility phase of the project, where the well is designed. When a well is designed with the production casing shoe depth not deep enough for cold zones below 200°C to be adequately isolated, that could result in difficulty in stimulating the well to flow or unexpected quenching of the well. Production casings that are set too deep may close off the major productive zones. Materials used to prevent circulation loss may permanently block the productive zones so they are seldom used in drilling the open hole section.

3.1.2 Health, safety and environment (HSE)

HSE risks, refers to those risks that affect the personnel, property and the environment of operation. HSE is an important issue for the geothermal drilling industry as it faces several hazards which have the potential to cause injury or harm for people, property and the environment. Furthermore, when these risks occur, they could result in litigation and damaged reputation for the companies. A lot of risk assessment and management in the drilling industry has focused on HSE risks and high standards have always been set for working at the drilling site. For example, part of the requirement for rig works is usually a certificate in health safety and environment. In addition, there are regulations in place concerned with risks in this area. Eight HSE risks were identified and are as described below:

i. Toxic gases (CO_2, H_2S released from the well)
ii. Noise
iii. Equipment and personnel safety
iv. Working environment
v. Leakage or collapse of brine pond
vi. Improper disposal of drilling cuttings
vii. Air pollution due to using diesel generator
viii. Thermal and chemical pollution

i. Toxic gases (CO_2, H_2S released from the well)

During drilling gases are encountered within the wellbore and can be release to the surface. This is not common though during drilling as these gases are dissolved by the drilling fluid. These gases can also be produced from leakages in adjacent wells previously drilled in the same well pad. There are several gases associated with geothermal drilling. Most of these gases are usually in small doses and may not have significant effect with the exception of carbon dioxide (CO_2) and hydrogen sulphide (H_2S).

H_2S: Hydrogen sulphide is an extremely poisonous gas, with a characteristic rotten egg smell at lower concentrations, but odourless at higher concentration and hence lethal. The detection and monitoring of H_2S is vital at all drilling sites. The effects of H_2S at various concentration is as given in Table 9 below (Danielsson, et al, 2009). These effects will however depend on the length of exposure, frequency and intensity.

TABLE 9: Effects of H_2S at deferent concentration

Exposure (ppm)	Effect
0.001-0.13	Odour threshold (highly variable)
1 - 5	Moderately offensive odour, possibly nausea, or headaches with prolonged exposure
20-50	Nose, throat and lung irritation, loss of sense of smell,
100 -200	Severe nose, throat and lung irritation, ability to smell odour completely disappears
250-500	Pulmonary oedema, headache, nausea, dizziness
500	Unconsciousness, loss of memory, death within 4-8 hours of exposure
500-1000	Respiratory paralysis, irregular heartbeat, collapse, and death.

CO_2: Carbon dioxide, is an odourless gas with and acidic taste. Even though less lethal than H_2S, longer exposure to it could be fatal. According to Noorollahi (1999), in concentrations of 500,000 ppm, meaning 5% of CO_2 in air, can produce shortness of breath, dizziness, mental confusion, headache and possible loss of consciousness. It becomes fatal at 10% concentrations, where the patient loses consciousness and could potentially die if exposure continues.

ii. Noise

Drilling operations usually results in high noise levels especially when using diesel generators for power production and air drilling unit during underbalance drilling. Several other equipment produces noise at lower levels. Noise from a drilling rig affects a wider group beyond the drilling crew. This is so because, drilling sometimes takes place in close proximity with the populated areas and in some case takes place in protected areas such as game reserves and national parks. In advanced fields, where power plant has been built and drilling is done to increase steam flow rates, there are usually personnel working in these plants. Noise during drilling is therefore a concern not only to the drilling personnel, but also to the local community, other personnel in the power plant and wildlife.

iii. Equipment and personnel safety

Several heavy equipment and materials are involved in any drilling project. The activities carried out during drilling, mobilization and demobilization, results in hazardous working conditions for personnel and equipment. During drilling, personnel are exposed to massive moving parts, exposure to falling objects from overhead works. During mobilization and demobilization, there is an increased vehicle movement in and out of site and personnel and equipment are exposed to hazards such as to terrain and ground conditions, or climate and weather. Lack of experience, inadequate training, equipment in poor repair, misuse of equipment and poor communication are some of the issues that can greatly increase chance if accidents in the in drill site. Adherence to safe work practices by all parties is important.

iv. Working environment

Geothermal drilling is usually conducted 24 hours a day 7 days a week. With crew working on 12 hr shifts. Most areas of drilling are remote areas far from civilization. In some instances, the drilling personnel are exposed to wild animals. Some job such as the derrick job requires working at heights of up to 40m in a rather open structure. Weather elements are harsh sometimes. All these makes drilling among the more dangerous jobs.

v. Leakage or collapse of brine pond

The brine pond is a pit dug next to the drill pad and used to hold drilling fluid and formation fluid coming to the surface from the wellbore during drilling. This is for the purposes of cooling the fluid to reuse it for drilling or in some cases to hold the fluid when the mud tanks are in use. The formation fluid usually contains dissolved inorganic salt, if not properly contained may percolate into the ground and contaminate ground water. For this reason, the pond is usually lined by a pond liner (thick polythene).

vi. Improper disposal of drilling cuttings

Drill cuttings are grounded rocks from the wellbore usually mixed with drilling fluid. The drilling fluid used in geothermal is bentonite, a naturally occurring clay. Though not poisonous, drill cuttings form the largest amount of waste from drilling and should be disposed correctly

vii. Air pollution due to using diesel generator

Drilling operations mostly occur in remote locations where electricity is not available yet. Therefore, power requirement for the drilling rig is usually produced by diesel generators. Several generators are required for drilling purposes. Commonly, rigs are equipped with four 3512C caterpillar engines. Where 2 are run for most operations while the other two are on standby. Since the drilling operations are run 24 hours, the generators are switched over after a predetermined time for routine maintenance. For air drilling rigs are usually equipped with three to four air compressors, a couple of boosters and an air dryer. The cementing unit comes with its own compressors. Considering all this equipment are run on diesels engines, the amount of emissions is significant. Some of the air pollutants from these generators include sulphur oxides, nitrogen oxides, carbon dioxide and particulate matter.

viii. Thermal and chemical pollution

A lot of formation fluid come to the surface from the wellbore. This fluid is usually at elevated temperatures and contains dissolved substances. The thermal and chemical properties of this fluids have the potential to harm the environment. Especially the flora and fauna.

3.1.3. 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. Because of this many drilling projects experience cost overruns. Eight items were identified for this risk category which include:

i. High cost of drilling
ii. Bankruptcy of project partner
iii. Interest and exchange rate fluctuation
iv. Reduction in annual budget allocation by government
v. Delayed disbursement of funds from financiers
vi. Price instability of fuel and steel
vii. Low credibility of shareholders and lenders
viii. Changes in bank formalities and regulations

i. High cost of drilling

According to Fjose et al. (2014), the cost of drilling a geothermal well can be obtained using Equation 1 below. It shows that drilling time is the most essential component of drilling costs and therefore to minimize drilling cost drilling time is of high priority.

$$Well\ cost = (rig\ rate + other\ time\ related\ cost + logistic\ cost) * time + (consumables + other) \qquad Eq.\ 1$$

ii. Bankruptcy of project partner

The high cost of drilling and the long duration before geothermal projects start earning returns on investment, coupled with risk of drilling success, can put great pressure on project financiers and partners. When project partners and financiers go bankrupt or are financially stretched, funding can be cut or reduced for the project and planned wells may not be drilled. An operator may be forced to seek alternative financing.

iii. Interest and exchange rate fluctuation

The currency at work in any drilling project is usually the U.S. dollar. This is because most of the drilling equipment, consumables and personnel are sourced internationally. Because the dollar is a more stable currency, its use protects the owner, contractor and lender. The interest rates for geothermal drilling are high due to the resource and success risk of the drilling projects.

iv. Reduction in annual budget allocation by government

Investor appetite for risk in geothermal projects is usually low in the beginning of the project, that is the exploration and the drilling phase, when the risk is generally high. Therefore, most geothermal drilling projects are financed by the government or loans guaranteed by government. Depending on the priorities of the government in power, drilling project finance may be reduced or altogether stopped.

v. Delayed disbursement of funds from financiers

Lengthy and complex financial review processes could result in delays in disbursement of drilling project funds. Other causes may be the failure of project owner to provide the required project counter funds and inconsistencies in project documents.

vi. Price instability of fuel and steel

Geothermal wells are drilled to depths of 2-3 km. High temperature wells are designed to have at least 3 cemented strings of steel casings. This is a lot of steel and any changes in price have a possibility of impacting drilling cost. For drilling operations using diesel generator for power generation, the fuel consumption goes can be up to 6000 litres a day. Fuel prices therefore have an impact on the drilling costs. On the other hand, low fuel prices globally make oil companies unwilling to drill oil. This mean that there are more rigs available for hire for geothermal drilling, at lower day rates.

vii. Credibility of shareholders and lenders

When banks are not an option, non-bank providers of loan and even equity financing may be available. These include private equity, sovereign wealth funds, large pension funds and insurance companies. While these institutions provide opportunities for the drilling project, there is minimal regulation and transparency in their dealings which can presents heightened risk (Mitchell et al. 2015). Shareholders and lenders may face expropriation and default risks, but the project owners are affected by the consequential higher interest rates and loan limits imposed (Hermalin et al., 1999).

viii. Changes in bank formalities and regulations

A high cost project such as geothermal drilling is always affected by bank lending behaviours, such as interest rate changes, where banks are the major source of productive capital. Bank lending and interest rate changes could result in increased project cost. Sometimes these may result in time consuming legal procedure at the expense of the project.

3.1.4 Legal risk

There are several aspects of legal risk that could affect geothermal drilling. This thesis though looks at two risks that may result from contract management.

i. Breach of contract by project partner
ii. Improper verification of contract documents

i. Breach of contract by project partner

A drilling contract may or may not include provisions on how to handle breaches of contract. Even where such clauses are included, they may be the subject of extensive and expensive litigation. Other issues may arise that are not provided for in the contract, these may result in court battles that will drag on and delay drilling projects.

ii. Improper verification of contract documents

A drilling contract is the key document in any drilling operation. A contract may be drafted for every new well, or it may cover a group of wells. When subsequent wells are desired, a new contract may be drafted, or a previous contract may be adopted. There may be changes to the contracts as the operations proceed, depending on what the parties negotiate for. It is therefore not appropriate to assume that all drilling contracts are standard ones (Jones, 2011). This may lead to disputes and litigation.

3.1.5 Organisation risk

Organisations face varied risks in a constantly changing environment. These risks have more global effect and are not only affecting the drilling project at hand but go beyond and affect the entire establishment and can extend beyond the life cycle of the drilling project. Two risk categories were looked at in this area:

i. Human resources
ii. Management risk

i. Human resources:

The human resource requirement of the drilling industry differs from most other industries due to its nature, the importance of safety, the stakeholders and a multi skilled workforce requirement. Human resource capital is therefore a critical investment to operate evolving technologies and to remain productive and competitive (ILO, 2012). Some of the risks identified in this area include:

a) Inexperienced and less knowledgeable personnel
b) Workforce stress due to inadequate staffing
c) Work schedule and cyclic nature of drilling
d) Unmotivated personnel
e) Deficiencies in organisational culture

ii. 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 are described in more detail below. These include:

a) Change of organisation ownership or management
b) Inadequate well planning and budgeting
c) Inadequate management of drilling contracts
d) Unclear contract specification
e) Changes on scope of contract
f) Stakeholders not consulted and/or kept informed about contract performance
g) Unclear lines of communication- owner, contractor and operators

a) Change of organisation ownership or management: Organisations may be reorganized for various reasons and it is important to minimize disruptive impacts while maximizing business value. Change can be instituted to improve drilling performance, to ensure regulatory compliance, or to pursue new technology to reduce well time delivery. Whatever the reason it is important to effectively manage change: this reduces the chance of confusion, resistance and negative effects of killing employee morale, all of which can undermine performance.

b) Inadequate well planning and budgeting: Many wells are drilled within budget and schedule, while others overrun the budget and schedule. Drilling projects have a way of going off the critical path and these activities off the critical path are usually not accounted for when planning. Adequate project definition and planning helps to reduce the chances of deficiencies in the procurement process, logistics and contracting and of which could lead to long delays resulting in increased well or project costs. Drilling and service contracts and the scopes of work should cover every eventuality relating to the well.

c) Inadequate management of drilling contracts: A drilling contract is one of the most significant contracts an operator will enter into (Jones, 2011). It provides a basis for carrying out drilling project. Such contracts should spell out terms of engagement and duties and responsibilities of each party involved. Inadequate contract management could result in significant operational and financial consequences for both the operator and contractor (Marietta & White, 2015). It will fail to allocate risks properly in the contract which may be unfair to one party. It is important to ensure that drilling contracts are not silent or vague on critical issues in order to avoid conflict should circumstances arise that necessitate contract interpretation.

d) Unclear contract specification: Drilling contracts are meant to allocate responsibilities for both jobs and risks before incidents occur (Jones, 2011). Due to the detailed nature of drilling contracts and costly nature of drilling, it is important to be exhaustive and clear in contracts to avoid conflicts later on in the project.

e) Changes on scope of contract: During drilling, a well may encounter challenges that require a side track. This changes the initial well plan and program from a vertical well to a directional well, which may set the whole project several days back. A question that may arise is whether the directional section constitutes a new well (Marietta & White, 2015).

f) Stakeholders not consulted and/or kept informed about contract performance: A stakeholder is anyone who can affect or is affected by the actions of a corporation (including an organisation, company, or business). The idea of the stakeholder was first formulated in 1963 at the Stanford Research Institute and defined as "those groups without whose support the organisation would cease to exist" (Freeman & Reed 1983). There are typically several stakeholders involved in any geothermal project, from the local communities to the national government: each can be affected by or affect the project in a different way. For example, the local community is an important stakeholder who needs to co-exist with the project. Their support for the project is as important as the support the project gives to the community.

g) Unclear lines of communication- owner, contractor and operators: As described above, many different groups are involved in the creation of a well. Clear lines of command and allocation of responsibilities are required. Everyone involved must have the information he needs to complete his tasks. Reporting lines should also be clear to ensure the right information reached the right people so that solutions and project can be executed from a point of knowledge and information. It is also important to know what data may be confidential and whom it is meant for, to avoid needless disputes over proprietary information.

3.1.6 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:

i. Cost increase due to changes of Government policies
ii. Loss incurred due to corruption and bribery
iii. Low/inadequate budgetary allocation
iv. Procurement policy (e.g. long tendering process)
v. Loss due to bureaucracy and late approvals

3.2 Survey questionnaire

Part of the methods was to send out a questionnaire to personnel in the drilling industry, where they were asked to evaluate the 64 risks that were identified by the literature review, in terms of quantifying the probability of occurrence and the impact to the drilling project. The online survey tool “QuestionPro” was used to conduct the survey (http://www.questionpro.com/). The responses were anonymous. An initial pilot study was conducted and five online surveys were sent out to determine the ease of use, clarity of the online questionnaire, to add more risks items and provide additional information where needed. The changes recommended were incorporated before the final questionnaire was sent out to 50 individuals in the industry. Nineteen responses were received. That is a 38% response rate. The groups targeted were

i. Drilling engineers
ii. Supervisors of drilling projects
iii. Project managers
iv. Drillers

3.2.1 Survey structure

A brief introduction to the objectives of the questionnaire was included on the forms: "Given the capital intensive and high risk nature of geothermal drilling operations, drilling risk analysis is not a common practice. Drilling projects are faced with numerous drilling challenges and uncertainties which result in schedule overruns and drive the cost of these projects up. When these troubles and uncertainties are encountered, meetings are usually called to resolve the problem at hand and resolutions are made to select any solution available for that kind of problem or at least reduce the impact of non-productive time as a result of those problems." Then further explained that the survey intended to obtain the perception of risk in the industry in terms of probability of occurrence and impact.

The survey consisted of two sections with the first collecting general information about the respondent such as country, years of experience and title. The participants were also asked 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: first to indicate their perception for how probable the risk was to occur and second how severe the impact would be if it did. The intention of the survey was to appreciate the professional's opinions and judgments in determining the relative significance of each risk category. Particulars of assessment of the risks, made in the survey are shown in Table 9. The detailed questionnaire structure is found in appendix A.

3.2.2 Risk measurement and scale

For risk measurement and scale, a multi attribute Likert scale of 1-5 was used. Published in a report in 1932 by Rensis Likert, a Likert scale is a type of psychometric response scale widely used in questionnaires to find out respondent's preferences or degree of agreement with a statement or set of statements (Bertram, 2007). In this thesis, respondents were required to rank the probability and impact of the given risk on a scale of 1 to 5. The scale is shown in Table 10 and the risk components in Table 11.

TABLE 10: 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

3.2.3 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 was the one described in (PMBOK, 2013); this is a common way to determine risk significance combining risk probability and impact values by multiplying them together. (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 2.

$$S_j^i = \alpha_j^i \beta_j^i \qquad \textit{Eq. 2}$$

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 3 below.

$$RS^i = \frac{\sum_{i=1}^{n} S_j^i}{n} \qquad \textit{Eq. 3}$$

Where

RS^i = Risk index for risk i

n = Number of respondents

Once the risk index score has been obtained, one has to 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.

TABLE 11: Risk breakdown structure

DRILLING RISKS	TECHNICAL RISKS	Geological	Loss of circulation Wellbore instability- collapsing formation Stuck pipe - clays, formation collapse, dog legs Soft and hard formation High pressures and temperatures Magma or intrusions in deep wells
		Casing and cementing	Casing wear during drilling Casing off-set (decentralized Parted casing Collapsed casing due to poor cement job. Cold inflows- poor cementing Difficult cementing jobs due to loss zones Cement hardening inside casing
		Equipment and tools challenges	Drill string failures- buckling, fatigue BOP failure Loss of tools- BHA, logging tools, drilling tools Machine and Equipment failures
		Drilling material and consumables	Long lead times of material delivery Bureaucracy in the tendering process Failure to allocate risks properly in the contract Material quality
		Force majeure	Extreme Weather conditions War and country insecurities Earthquakes
		Well success	Suspended well Abandoned/plugged well Non-productive well
	HEALTH, SAFETY, & ENVIRONMENT	Health, safety, & environment	Toxic gases Noise Personnel safety Working environment Leakage or collapse of brine pond Improper disposal of drilling cuttings Air pollution due to using diesel generator Thermal and chemical pollution Induced seismicity
	FINANCIAL RISK	Financial risk	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 Low credibility of shareholders and lenders Changes in Bank formalities and regulations Insurance risk
	LEGAL RISK	Legal risk	Breach of contract by project partner Improper verification of contract documents
	ORGANISATIONS RISKS	Management	Change of ownership or top management Inadequate well planning and budgeting Inadequate management of drilling contracts Unclear contract specification Changes on scope of contract Stakeholders not involved Organizational culture Unclear lines of communication
		Human resource	Inexperienced and less knowledgeable personnel Workforce stress due to inadequate staffing Work schedule and cyclic nature of drilling Personnel not motivated Organizational culture
	POLICY AND POLITICAL RISK	Policy and political risk	Cost increase due to changes of Government policies Loss incurred due to corruption and bribery Budgetary allocation Procurement policy Corruption Loss due to bureaucracy for late approvals

3.3 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 risk on cost risk 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. Risk assessment software has seen great improvement in recent years and become an integral part of the risk assessment process (Ristvej & Lovecek, 2011). Today, there are a number of risk management software packages available in the market, as well as others developed in-house, able to performing probabilistic well cost estimation and/or Monte Carlo simulations. Most in-house software tools involve the use of spreadsheets, which also forms the basis of commercial software tools with inbuilt Monte Carlo simulation. The last part of the thesis was to carry out an integrated cost and schedule risk analysis using a risk management software RiskyProject, created by Intaver Institute (Intaver Institute, 2012). RiskyProject takes into consideration the existence of numerous project uncertainties including task duration, start and finish times, quality, safety, technology costs and resources uncertainties.

Software – RiskyProject

RiskyProject is a project risk management software package created by Intaver Institute Canada. It is created to perform integrated cost and schedule risk analysis. The software is capable of analysing project schedules with risks and uncertainties, calculate the probability of the project being completed within schedule and budget and prioritise project risk (Intaver Institute, 2012). RiskyProject has an inbuilt project schedule, risk register and a Monte Carlo simulation as the main tools for analysis. It is therefore able to perform both qualitative and quantitative risk analysis. The software only allows up to 600 iterations. The input requirements for this tool include:

1. Project schedule,
    a. All jobs scheduled
    b. Resources loaded
    c. Unbiased estimates of durations
2. Cost estimate
    a. Resource cost
    b. Fixed cost
3. Risk data
    a. Risk list
    b. Probability and impact parameter data collected
    c. Risk weighting
    d. Risk and mitigation costs

For the schedule and cost inputs a distribution type can be selected. RiskyProject provides several distribution types to be selected from, including triangular, uniform, logarithmic, beta etc. For this project, the RiskyProject triangular distribution was selected for both the cost and schedule.

3.3.1 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 for this thesis, Microsoft Project was used.

Microsoft Project is a project time management tool that allows for the process of planning and controlling of the amount of time needed to perform and complete a given task or activity within a project. To schedule activities, consideration is given to the entire duration of completing the task, earliest or latest date an activity can start without affecting other activities and project completion. The process to accomplish an effective project time management and hence schedule is as follows:

i. Activity definition
ii. Activity sequencing
iii. Activity resource estimating
iv. Activity duration estimating
v. Schedule development
vi. Schedule control

i. Activity definition

This involves listing all the tasks that must be accomplished in order to deliver the project results. The sample project used was a vertical well drilled to 3,000m in 1,440 hrs. The project was divided into 7 sections and each section defined as:

- 26" section
- 20" casing
- 17½" section
- 13⅜" casing
- 12¼" section
- 9⅝" casing
- 8½" section

These activities were further divided into subtasks for easier allocation of resources and budget. Most of the sub tasks were repeat tasks in all the sections: for example, with the 26" section, 17½" section, 12¼" section, 8½" section, the sub tasks for each included:

- Drilling ahead
- Drilling out cement
- Inclination survey
- Pulling out of hole (POOH) to change bottom hole assembly BHA

Other tasks that appear in only some activities include

- Nipping up/down of blow of preventer (BOP)
- Installation of control head flange (CHF)
- Installation of flow line.
- Testing of BOP
- Running in liners
- Breaking stands to singles and laying them down.
- Well logging
- Installing master valve.

The casing section activities, that is the 20" casing, 13⅜" casings, 9⅝" casing, were broken down into the following sub activities:

- Request and avail casings to site
- Preparing casings and tools
- Rigging up casing tools
- Running casing
- Cementing casing
- Wait on cement

ii. Activity sequencing

This process involves organising the tasks into the order in which they should be undertaken. The activities are studied to determine how the activities are related to each other. Microsoft Project uses activity-on-node (AON) technique to do sequencing and it involves four types of dependencies or precedence relationships as described in PMBOK (2013):

a) Finish-to-start. The start of the successor activity depends upon the completion of the predecessor activity.
b) Finish-to-finish. The completion of the successor activity depends upon the completion of the predecessor activity.
c) Start-to-start. The start of the successor activity depends upon the initiation of the predecessor activity.
d) Start-to-finish. The completion of the successor activity depends upon the start of the predecessor activity.

iii. Activity resource estimating

Part of the planning will require the estimation of the type and quantities of resources required to perform each schedule activity. These resources include human resources, equipment, material and consumables required to perform each activity. In this thesis though, the resource scheduling was conducted in the software RiskyProject.

iv. Activity duration estimating

Each task needs to be allocated a realistic work period for its completion. This can be determined from historical data of similar tasks in the past or professionals with technical knowledge or experience.

v. Schedule development

Once all the above information is in place, the project schedule is developed. This is an iterative process that involves determining the planned start and finish dates for project activities and reviewing and revising duration estimates and resource estimates as need arises and the project progresses.

vi. Schedule control

Schedule control forms the last part of the project time management. It involves controlling changes to the project schedule. This is not part of this thesis.

3.3.2 Cost estimates

a) 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 services are drilling supervision, maintenance engineering, site geologist, geological services, reservoir engineering, planning and logistics, drill stem inspection and logging services.

The cost information is summarised in Table 12. 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 5.

	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 5: Resources and costs

TABLE 12: Daily operating cost

Daily operating costs for 60 days	Operating Cost		
	Total Cost/Well	Per Day	Per hr.
	(USD)	(USD)	(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**

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.

b) Fixed cost

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 including the fuel used in 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 13 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 6.

3.3.4 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). In this project a risk register was uploaded in the risk management tool as this allowed for assigning the individual risks to activities.

Risk items identified in the literature were used as inputs for this section. The risk probabilities and impact factors resulting from the survey were used. Once all the risk data had been loaded, the risks were assigned to drilling activities. To complete the risk register mitigation and response plans were developed and assigned to the risks. Figure 7 is a screen shot of the populated risk register from RiskyProject.

	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 7: Cost view in RiskyProject

						Pre-Mitigation			
	Risk Name	Open...	Risk/Issue	Threat/O...	Risk Assigned To	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 6: Part of the risk register from RiskyProject

TABLE 13: Cost estimation (USD)

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

a) Risk list

Risk items identified in the literature were used as inputs for this section. 64 risks were uploaded and there mitigations determined and loaded in the software.

b) Probability and impact parameter data

The risk probabilities and impact factors used were as determined by the industrial expert from the online survey.

c) Risk weighting

Risk weighting was required in order to assign the relative importance of the risk categories risk. 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. Looking at the questionnaire output, the respondents answered using previous experiences. These experiences were different for both the Kenyan group and the Icelandic group. 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. Having this input in the RiskyProject software allows for risk probabilities and impact values that are more objective.

The relative importance ranking obtained from the survey was used for this purpose. A pairwise comparison was done using the information in Table 14. The final result of the pairwise comparison is shown in Table 15. 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.

d) Risk and mitigation costs.

To fully analyse the effects of each risk on project cost, the software required the input of each risk's expected cost. This would be any additional cost incurred as a result of the encountering the risk and the cost of the mitigation measures for returning the project to normal. This data was not available therefore no cost was added to the risks, limiting the ability to see how much the risks would affect the drilling costs.

3.4 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 a 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. The software RiskyProject was used for simulation.

TABLE 14: 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

TABLE 15: 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	i	1	0.33	0.33	5	3	3	7
Financial and cost risk		3	1	0.33	7	5	3	9
Health, safety and environment		3	3	1	9	7	5	9
Legal risk		0.2	0.14	0.11	1	0.33	0.20	3
Policy and political risk		0.33	0.2	0.14	3	1	0.33	5
Technical risks		0.33	0.33	0.2	5	3	1	7
Organizational risk		0.14	0.11	0.11	0.33	0.2	0.14	1
Column Sum		**8.01**	**5.12**	**2.23**	**30.33**	**19.53**	**12.67**	**41**
Normalized matrix to determine the weight for each risk category.								
Schedule and scope	15.2%	0.12	0.07	0.15	0.16	0.15	0.24	0.17
Financial and cost risk	23.7%	0.37	0.20	0.15	0.23	0.26	0.24	0.22
Health, safety and environment	38.3%	0.37	0.59	0.45	0.30	0.36	0.39	0.22
Legal risk	3.5%	0.03	0.03	0.05	0.03	0.02	0.02	0.07
Policy and political risk	6.3%	0.04	0.04	0.06	0.10	0.05	0.03	0.12
Technical risks	10.9%	0.04	0.07	0.09	0.16	0.15	0.08	0.17
Organizational risk	2.1%	0.02	0.02	0.05	0.01	0.01	0.01	0.02
	100.0%							

4. RESULTS

The focus of this thesis has been on determining the risks that are affecting geothermal projects and conducting a risk assessment to quantify them. It further carries out an integrated cost and schedule modelling of cost and schedule risk involved in the drilling process. The results of the study from questionnaire and the RiskyProject software are presented in this chapter.

4.1 Questionnaire results

The questionnaire was in two parts: the first was a demographic survey, followed by the risk probability and impact ranking in the second part. 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.

4.1.2 Demographic survey

The first three questions were general questions about the respondents. The following are the results.

Country of respondent project: First question asked about the country of the project or operation of the respondents. 18 responses were received, 5 of them from Iceland, 13 from Kenya and one respondent did not respond to this question but went ahead and completed the survey. This is shown in Table 16 and Figure 8.

TABLE 16: Respondent by country

Country	Percentage (%)	Count (N)
Iceland	28	5
Kenya	72	13
Total	100.00	18

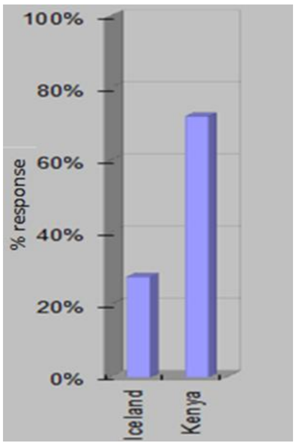

FIGURE 8: Respondent by country

Years of experience: The respondents were requested to indicate how many years they have worked in the drilling industry. Seven of them had been in the industry for less than 5 years; eight respondents had been in the industry between 6 to 10 years. The cohorts between 10 and 20 years and 20 and 30 years had only one respondent each and two respondents had been in the industry more than 30 years. This is shown in Table 17 and Figure 9.

TABLE 17: Respondent by years of experience

Years	Percentage (%)	Count (N)
1 to 5	37	7
6 to 10	42	8
10 to 20	5	1
20 to 30	5	1
More than 30	11	2
Total	100	19

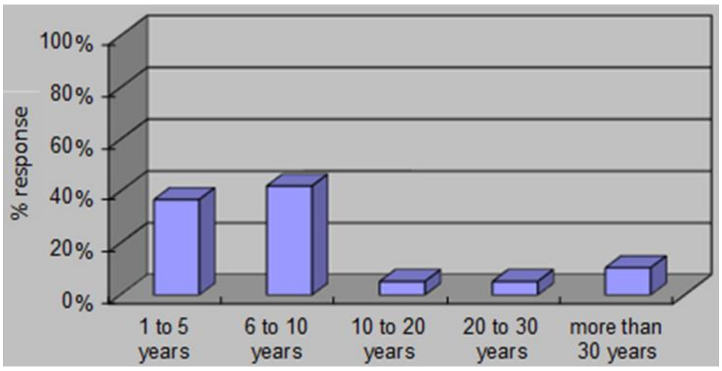

FIGURE 9: Respondent by years of experience

Position of respondent: The third question sought to find out the position of the respondent within the drilling industry. Of the 19 respondents who returned the survey, 4 indicated that project manager best described their title, 10 were drilling engineers, 3 were rig maintenance engineers and 2 were supervisors as shown in Table 18 and Figure 10.

TABLE 18: Respondent by position held

Title	Percentage (%)	Count (N)
Project Manager	21	4
Drilling engineer	53	10
Rig maintenance engineer	16	3
Supervisor	10	2
Total	100	19

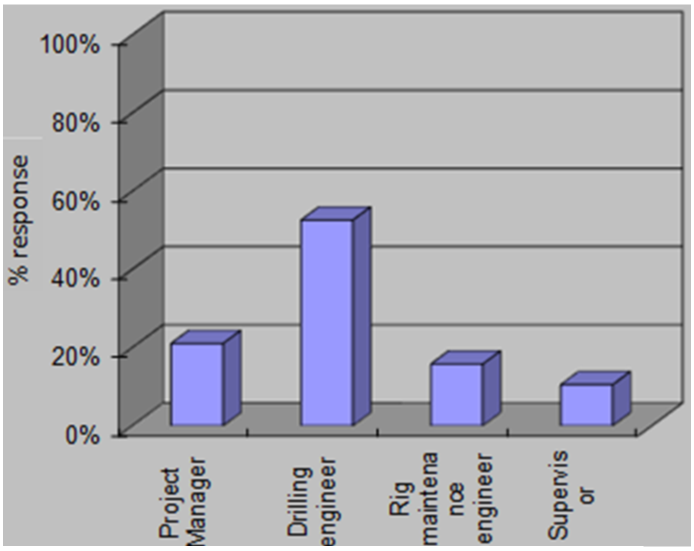

FIGURE 10: Respondent by position held

The next three questions were general questions about the respondents' general experience with risk management assessments. They yielded the following results:

Risk management system: The fourth question was about the risk management system in place in the projects the respondents were working on. The respondents were asked if they were using any risk management tools currently in their projects. Seven indicated that they had some in place while 11 indicated that there was none in place. One respondent said other. The results are as shown in Table19 and Figure 11.

TABLE 19: Using risk management systems

Answer	Percentage (%)	Count (N)
Yes	37	7
No	58	11
Other	5	1
Total	100	19

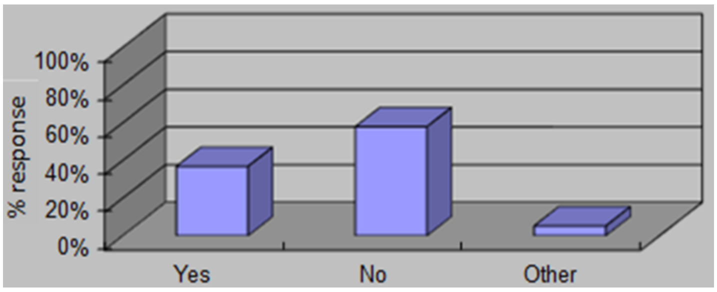

FIGURE 11: Using risk management systems

List of tools used: If the response to the previous question was a yes, then the respondents were to indicate which tool they were using**.** The responses are as listed below.

1. Modified from petroleum drilling company
2. Risk matrix
3. Both commercial and internal
4. Risk mitigation fund (from African Development Bank) and insurance of equipment
5. OSHA
6. Job safety analysis

Impact of drilling risks on the project: The respondents were also asked to indicate how much they perceived drilling risks to impact on the project cost, schedule and well completion. As shown in Figure 12, the respondents considered risks to more greatly impact drilling cost than schedule and well completion at 36.98% , 31.6% and 26.92% respectively.

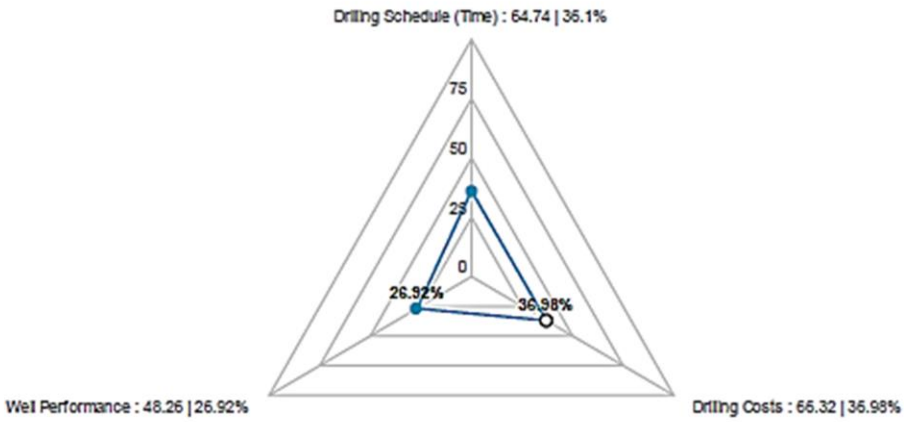

FIGURE 12: Impact of drilling risks on drilling schedule, cost and well completion

4.1.3 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 20 shows the ranking of top 10 risk of all the respondents. Table 21 shows the ranking of the Icelandic respondents and Table 22 shows the results of the Kenyan respondents. The full results are shown in the Table 23.

TABLE 20: Top risks as ranked by all respondents

Toxic gases (CO_2 H_2S) released from the well	12.53
High cost of drilling	12.40
Loss of circulation	11.73
Stuck pipe	11.33
Procurement policy (e.g. long tendering process)	11.20
Reduction in annual budget allocation by government	11.00
Wellbore instability- collapsing formation	10.87
High noise levels	10.87
High pressures and temperatures	10.60
Long lead times of material delivery	10.27

TABLE 21: Top risks as ranked 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	13.00
Magma or intrusions in deep wells	13.00
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 22: Top risks as ranked by Kenyan respondents

High cost of drilling	12.75
Toxic gases (CO_2 H_2S) released from the well	12.00
Loss of circulation	11.50
Wellbore instability- collapsing formation	11.50
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	10.00

TABLE 21: 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

4.2 Integrated cost and schedule results

This section illustrates how an integrated schedule and cost risk management system works using data of a sample drilling project. The specific cost data was not available and average industrial values were used instead.

4.2.1 Drilling schedule and cost

The first stage in the system starts by creating a project baseline schedule in Microsoft project as was described in section 3.3.1. The project was a 3,000m deep vertical well that was drilled for 60 days starting on 4 February 2016 and concluding on 3 April 2016. The project schedule has two main task groups. The first is the review meeting. There were eight such meetings spread throughout the project duration. The second item was the drilling time plan which was divided into seven sections marking the milestones for the project.

- Review meetings
- Vertical well drilling timeline
  - 26" section
  - 20" casing
  - 17½" section
  - 13⅜" casing
  - 12¼" section
  - 9⅝" casing
  - 8½" section

The seven sections have several detailed activities under them. The well plan is to drill the well in four sections. This well is similar to the well as described in section 2.2.4. The top section of a diameter of 26" was drilled to a depth of 100m from 0m and cased with a 20" casing. The second section of diameter of 17½" was drilled to a depth of 450m and cased by a casing of 13⅜". During the drilling of this section there were two inclination surveys done at intervals of 200 meters. The third section of a diameter of 12¼" was drilled to a depth of 1,200m and cased with a 9⅝" casing. 7 inclination surveys were done in this section at intervals of 200 meters. The final section of a diameter of 8½" was drilled to 3,000m and cased by a slotted liner of 7" diameter. Nine inclination survey were conducted in this section at intervals of 200 meters. All the sections were cemented except for the final section.

Once the well was defined in Microsoft Project, the project was loaded onto RiskyProject. As described in section 3.3. RiskyProject is a project risk management software package created by Intaver Institute Canada. It is created to perform integrated cost and schedule risk analysis and it can analyse project schedules with risks and uncertainties, calculate the probability a project will be within schedule and budget and prioritize project risk (Intaver Institute, 2012). This integrated cost and schedule analysis tool allows for the inclusion of identified project risks to the baseline schedule and cost in order to provide sensitivity information on each activity involved and how they will impact the entire project cost and duration. The system uses Monte Carlo simulation (discussed in 2.3.2) to simulate the cost and schedule outcomes. Monte Carlo simulation requires inputs of three different values: the actual value and the upper and the lower bound values for the distribution. Usually the upper and the lower bound values are not precisely known as they are estimates of future expected values. The resources loaded were calculated based on a day rate as was shown in section 3.3.2, material and consumable costs for the well were also loaded as fixed cost for each section.

4.2.2 Risk register

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 13. 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.

	Risk Name	Open/Cl	Risk/Issue	Threat/Opp	Risk Assigned To	Proba	Impac	Score	Score	Cost (Pre-Mi	Cost (Mitigat	Probab	Impact (Pos
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 101,124	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 130,803	USD 22,084	52.8%	35.0%
11	Difficult cementing jobs due to loss zones	Opened	Risk	Threat	Assigned to 3 tasks/resources	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/resources	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/resources	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/resources	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 13: The resultant risk register from RiskyProject

4.2.3 Risk matrix

Two risk matrices were generated with all the risks in cells corresponding to the likelihood and consequences. The colours as explained in 2.3.2 represent

- Red - High risks
- Orange - Medium risks
- Green - Low risks

Figure 14 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 them or reduce their probability of occurrence. It is usually not possible to eliminate the impact of the risk, though sometimes it is possible to reduce it. 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. If situation does not allow them to be solved immediately timelines should be in place to have the mitigation in place as soon as possible. Only one risk made it to the “low” category. Such risks should be solved when it is considered economically viable to do so, but they require monitoring so that they do not reach the medium or high risk areas.

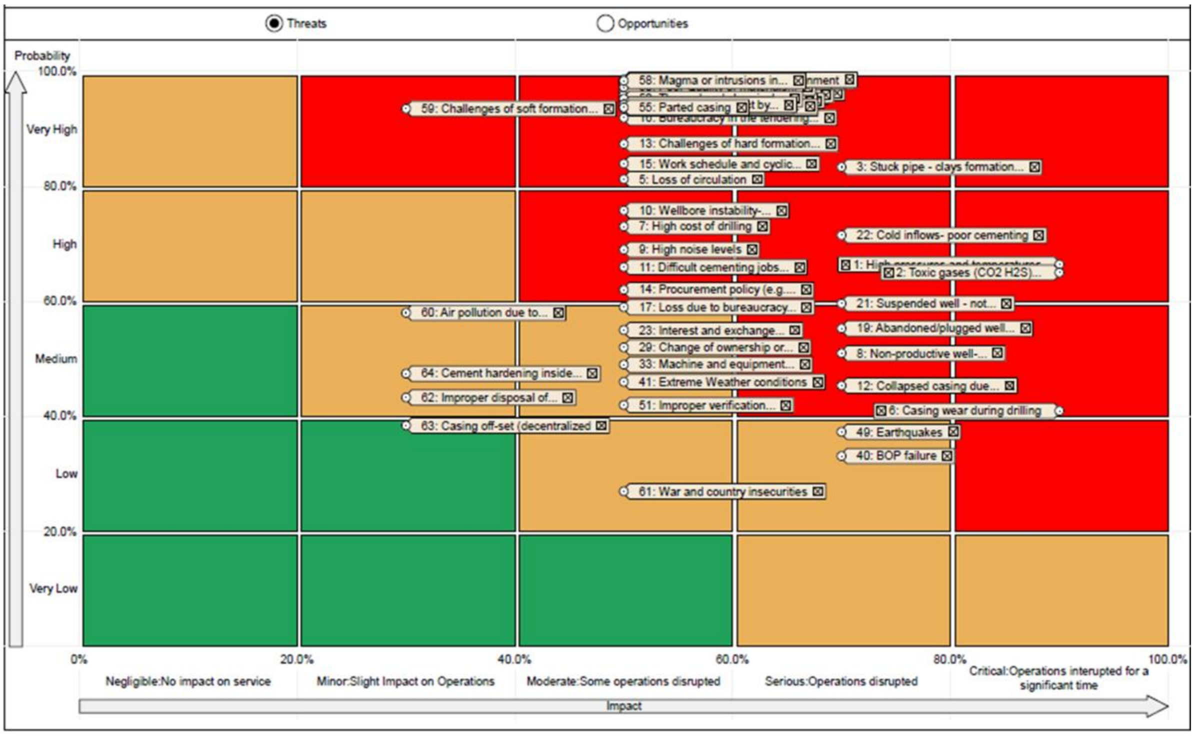

FIGURE 14: Risk matrix without mitigations (see appendix B for a larger version)

Figure 15 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. Initially, the risk of casing offset was the only risk in the low category, after mitigations the risks mostly moved from high and medium to medium and low categories. A few risks still remain in the boundary of the high and medium categories and these are high pressures and temperatures, high cost of drilling, collapsed casing, high noise level and loss of circulation.

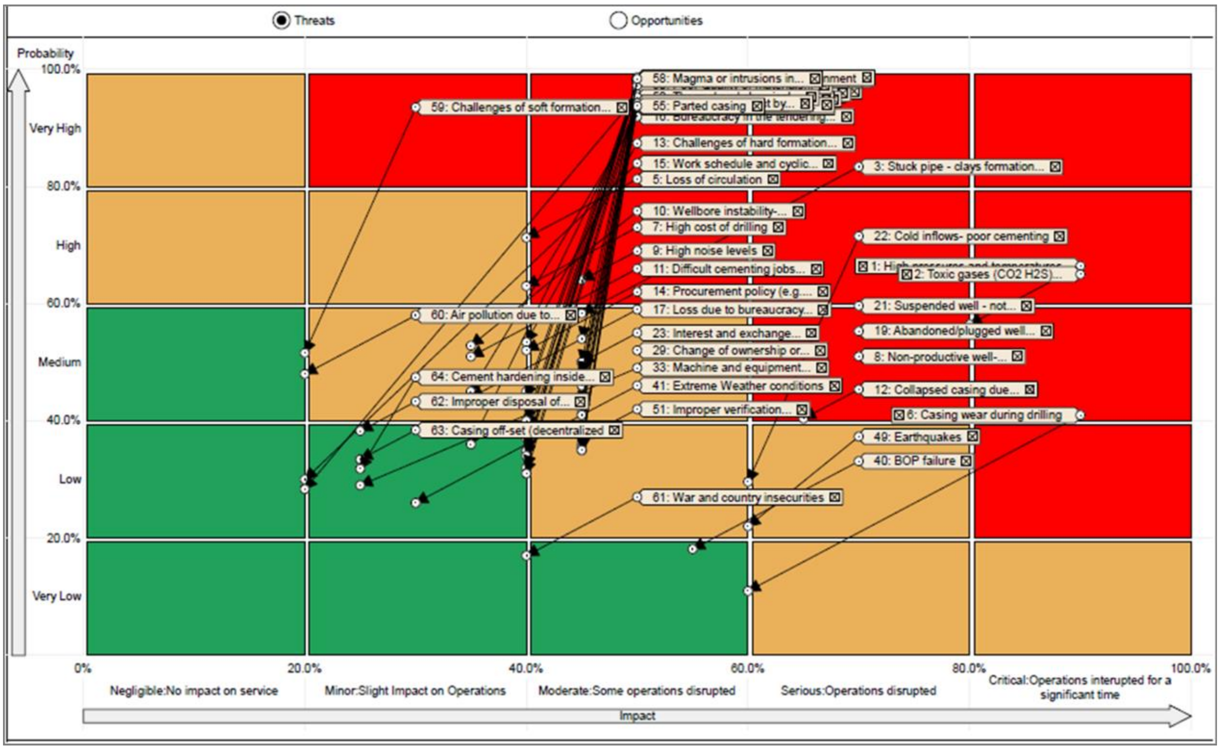

FIGURE 15: Risk matrix with mitigations (see appendix B for a larger version)

4.3 Monte Carlo analysis results

The integrated cost and schedule analysis tool allows for the inclusion of the identified project risks to the baseline schedule and cost in order to provide sensitivity information of each activity involved and indications of how they will impact the entire project cost and duration. Once all the inputs and probabilistic parameters had been uploaded in the analysis tool, it was ready to configure and run the simulation. Figure 16 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.

RiskyProject runs a maximum of 600 iterations and stops when more iterations are not going to change the results significantly. 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 below in Figures 17-21.

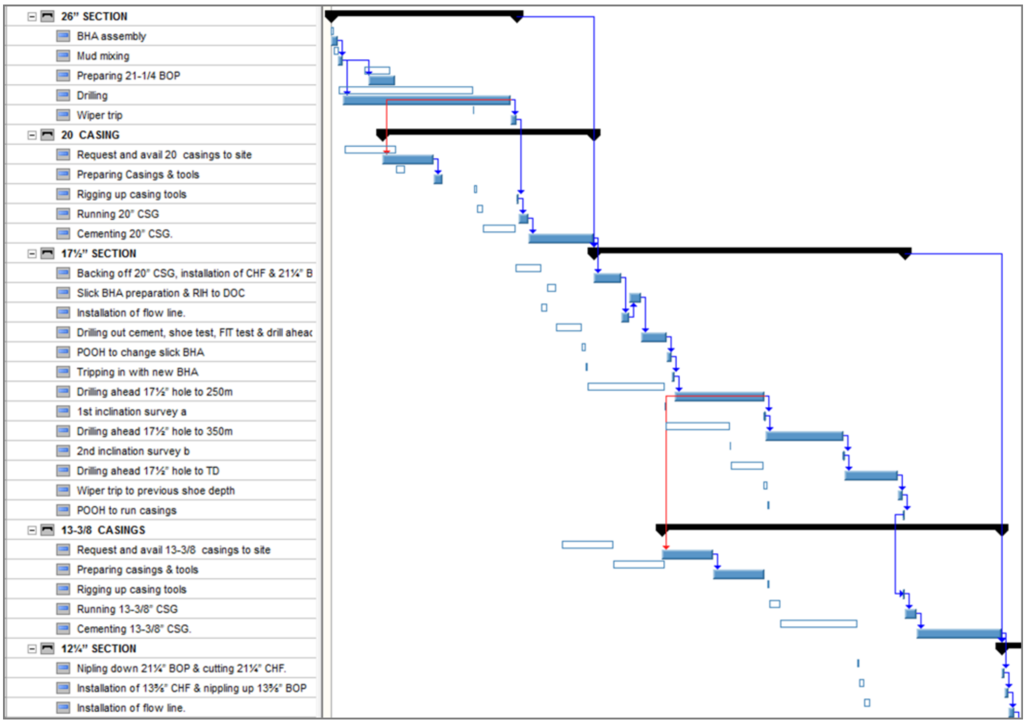

FIGURE 16: Drilling timeline after simulation

Figure 17 shows the probability distribution and cumulative distribution of the drilling cost. The most likely cost of the project (which is also the mean) is calculated to be 6,678,425 USD, indicated by the mark on the graph. It differs from the determined base schedule which was 6,070,120 as calculated in section 3.3.1. The range of the distribution falls between 5,871,069 USD and 7,271,681 USD giving a range of 1,400,613 USD. This shows that depending on risk or risk mitigation there will be an increase or decrease of approximately 15% of the project cost. Corresponding percentiles values are shown below in Table 22. 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 95% chance of costing below 7,056,467 USD.

Figure 18 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 also given by the mean which 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 23 shows the corresponding percentiles values for the project duration, with P5 value or 5% chance of completion below 1,557 hours and a P95 value or 95% chance of completion below 1,817 hours.

Figure 19 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 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 23 shows the corresponding percentiles values for the project finish dates with P5 value or 5% chance of being finished on or before 9 April 2016 and P95 value or 95% chance of being finished on or before 20 April 2016.

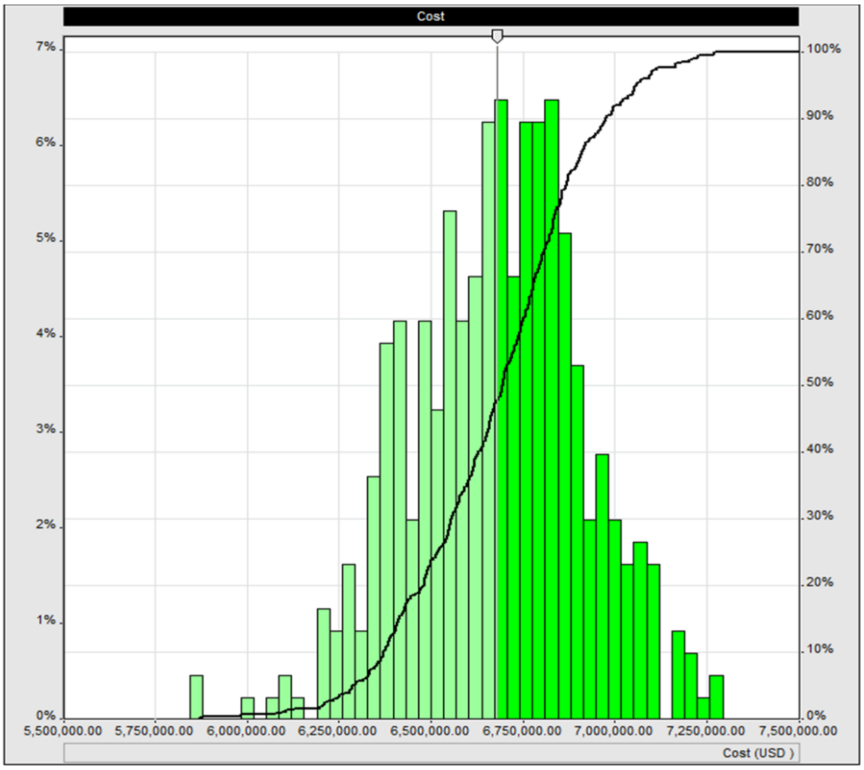

FIGURE 17: Probability and cumulative distribution of the drilling cost.

TABLE 22: Corresponding percentiles values for the project costs

Percentile th	USD
5	6,287,760
10	6,370,918
15	6,413,027
20	6,478,954
25	6,519,058
30	6,554,290
35	6,598,237
40	6,629,252
45	6,661,986
50	6,695,263
55	6,722,963
60	6,752,532
65	6,778,458
70t	6,806,649
75	6,834,620
80	6,865,585
85	6,912,176
90	6,974,266
95	7,056,467

Number of samples	432
Minimum	USD 5,871,069
Mean	USD 6,678,425
Maximum	USD 7,271,681
Range	USD 1,400,613
P1/P99 range	USD 1,115,369
P5/P95 range	USD 768,707
P10/P90 range	USD 603,348
P20/P80 range	USD 386,631
P30/P70 range	USD 252,359
Variance	USD 56,201,026,580
Standard deviation	USD 237,068
Semi Std. Dev	USD 250,849
Skewness	-0.215114
Kurtosis	0.124418

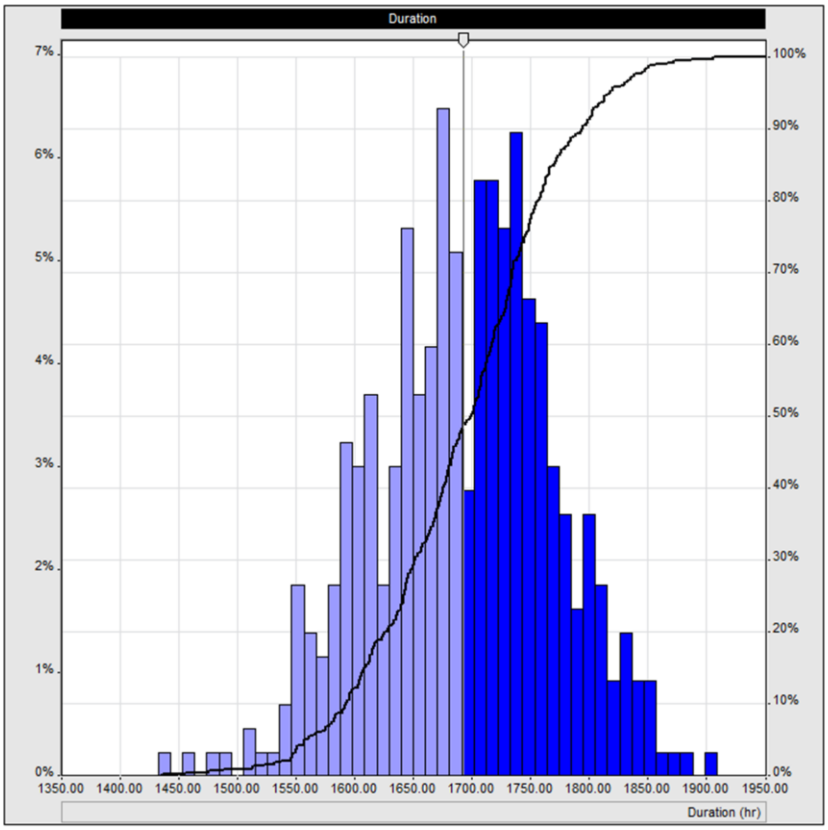

FIGURE 18: Probability and cumulative distribution of drilling duration.

TABLE 23: Corresponding percentiles values for the project duration

Percentile th	hours		
5	1,557	number 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	Standard deviation	77.39 hr.
75	1,746		
80	1,756	Skewness	-0.187572
85	1,770	Kurtosis	-0.014914
90	1,793		
95	1,816		

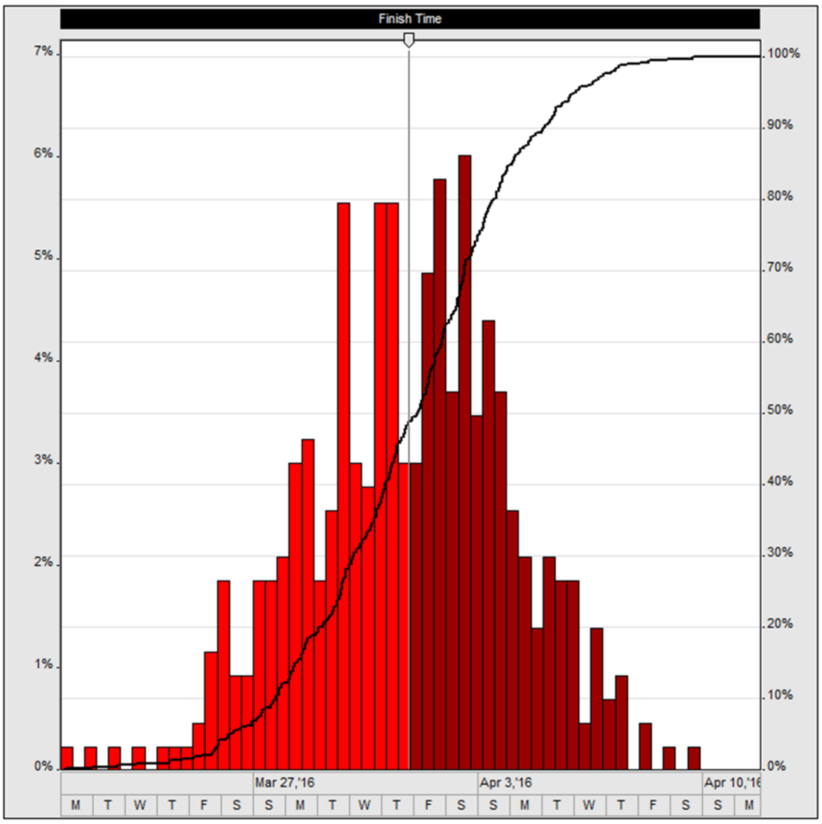

FIGURE 19: Probability and cumulative distribution of the finish time.

TABLE 24: Corresponding percentiles values for the project finish dates

Percentile th	Date		
5	4/9/2016 5:23	Number of samples	432
10	4/10/2016 17:15	Minimum	4/4/2016 4:22
15	4/11/2016 7:45	Mean	4/14/2016 21:01
20	4/12/2016 1:41	Maximum	4/23/2016 17:45
25	4/12/2016 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	Standard deviation	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		

4.4 Sensitivity analysis

RiskyProject only models 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 20 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. This could be because this is the longest open hole section of the well. There are also more trips in this section to change BHA and also to conduct inclination surveys. Several drilling risks are also experienced in this section, such as stuck pipe and chances of encountering high temperature and pressures among others. The task that affects the drilling finish time the least is the breaking up the drill stands.

Task ID	Task Name	Coefficient	Correlation between finish times
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	
15	Task: Drilling	0.22	
75	Task: Drilling ahead 8-1/2" hole to 1850m	0.21	
73	Task: Drilling ahead 8-1/2" hole to 1650m	0.21	
79	Task: Drilling ahead 8-1/2" hole to 2250m	0.21	
52	Task: Drilling ahead 12-1/4" hole to 650m	0.21	
81	Task: Drilling ahead 8-1/2" hole to 2450m	0.20	
34	Task: Drilling ahead 17½" hole to TD	0.19	
56	Task: Drilling ahead 12-1/4" hole to 1200m	0.17	
96	Task: RIH stands POOH breaking the stands	0.16	

FIGURE 20: Sensitivity to finish time of tasks

Following the result shown in Figure 20 above, a sensitivity analysis of the 8½" section was done. This was 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 21. 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).

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

5. SUMMARY AND DISCUSSION

The focus of this thesis has been on determining the risks that affect geothermal projects and conducting a risk assessment to quantify them. It further carries out an integrated cost and schedule modelling of cost and schedule risk involved in the drilling process. The objective of this research was to contribute to the direction of risk management in the drilling projects. This contribution is achieved by the identification, analysing and evaluating risks in the drilling process. There were three research topics based on the objectives of this thesis and they were answered as such.

i. Identify the key risk factors that can interrupt or delay the delivery, or compromise the quality, of a geothermal well in each phase of the drilling project.

This thesis was able to identify 64 risks in the drilling project and these risks were classified into 6 main categories as such

1. Technical risks
2. Health safety and environmental risks
3. Financial risks
4. Legal risks
5. Organisational risks
6. Policy and political risks

The risks were identified through data collection from literature and informal interviews with personnel in the industry. Data collection is the first part of risk assessment and management in any project. To conduct an informed risk assessment on drilling, up-to-date and good quality risk data is important. Historical drilling data of previously drilled wells in the area where the drilling project will take place, coupled with expert judgment of professionals in the drilling industry provide such data.

As risk assessment and management in the drilling industry is not a common practice, there are no structured ways in which risk identification is done to identify drilling risks. The only time risks are identified, especially those expected to be encountered in the formation such as hard formation, or fractured formation is usually a mention in the drilling program. More often the risks are limited to those in the drilling program.

In geothermal drilling, risk management procedures have been largely concentrated in the area of occupational health and safety. This is mostly due to regulatory requirements. In other cases, elements of risk management or tools are implemented in isolation. For instance, one of the questions asked in the questionnaire was if risk management tools were in use in the drilling projects the respondents were working for. They were also asked to indicate which tool they were using. Only 36% responded yes to this question and mentioned the following tools:

1. Modified from petroleum drilling company
2. Risk mitigation fund (from African Development Bank) and insurance of equipment
3. Occupational safety and health administration (OSHA)
4. Job safety analysis
5. Risk matrix
6. Both commercial and internal

From the above list, the risk matrix (item no. 5) has been discussed in the methods section 2.3.2. One respondent just mentioned both commercial and internal tools. Due to the limitation of the survey confidential and non-traceable replies, it was not possible to send a follow up question for clarification on this. The other four are as discussed below.

1. Modified from petroleum drilling

Geothermal drilling borrows a lot from the oil and gas drilling. It is no surprise that risk management tools and procedures for drilling risk management are adapted from there too. Having been in the drilling industry longer, there is more awareness on risk analysis. Some of the advances are in the development of well cost estimation and risk analysis software, used in risk analysis for investment decisions. These developments in oil and gas, provides a good place to start for risk assessment tools for the geothermal industry.

2. Risk mitigation fund (from African Development Bank) and insurance of equipment

The risk mitigation fund is usually put in place to reduce financial investment risk barriers associated with the exploration and appraisal drilling phases. The fund aims to partially compensate an entity public or private for costs incurred in the event of encountering a dry well (Mwangi, 2010). This tool is only applicable on projects in stages of exploration and appraisal drilling, phases which are considered to be most expensive and risky. Production drilling is excluded from this fund. This fund does not cover execution risk related to the drilling phase and only geoscientific criteria are considered to determine success of drilling (Ingimundarson & Tulinius, 2015) It is therefore not sufficient to rely on it alone especially when the project is beyond the exploration and appraisal phases.

3. Occupational safety and health administration (OSHA)

OSHA is a body that enforces laws and promulgates regulations for provision of a safe and healthful workplace to employees by their employers. It was created to develop and enforce workplace safety standards and provide training, outreach, education and compliance assistance. These standards take care of one element of drilling risk which are those risks to safety and health of personnel, arising out of, or in connection with, the activities at work.

4. Job safety analysis

A job safety analysis or a job hazard analysis as a systematic process performed on a specific job or task, to identify risks and determine their control. It allows for developing and documenting safer practices for each job to be undertaken. The main focus of a Job safety analysis is usually the personnel performing the task, the tools available to them and the work environment (Roughton & Crutchfield, 2016). This tool takes care of one element of drilling risk which is the health safety and environment aspect.

ii. Assess the perception of the risk according to industrial practitioners in terms of probability of occurrence and severity.

Response was received from two countries, Kenya and Iceland. Because of the subjectivity of risk assessment, the results obtained showed a difference in how the two groups ranked risk. These differences could be attributed to several factors including: the different geologic formations and prevailing reservoir conditions of the Kenyan and Icelandic drilling sites, available technology and equipment, experience of the drilling personnel, well specification and targets, the project business and physical environments and project funding among others.

Comparing how the professionals in the two countries ranked the risk, the Kenyan group ranked high cost of drilling as the top risk, while it was only the 14th rated by the Icelandic group. Toxic gases (CO_2 and H_2S) released from the well came in 2nd for the Kenyan respondents and tied for 1st place with noise for the Icelandic respondents. Noise was ranked 12th by the Kenyan respondents. Wellbore instability was 4th for the Kenyan respondents while it was ranked 32nd by the Icelandic respondents. Loss of circulation made it to the top 10 risks for both groups at 3rd and 7th position for the Kenyan and Icelandic groups, respectively. Stuck pipe ranked 5th by the Kenyan group and 11th by the Icelandic. Procurement policy resulting in long tendering process ranked 6th among the Kenyan group and 16th in the Icelandic group. Reduction in annual budget allocation for government funded drilling projects was 7th for Kenya and 19th for Iceland. Delayed disbursement of funds from financiers was 8th for Kenya and 43rd for Iceland. Loss due to bureaucracy for late approvals ranked 9th for Kenya but 36th for Iceland. Loss of tools including BHA and logging tools was 10th for Kenya while it ranked 18th for Iceland.

On the other hand, the Icelandic group ranked high pressures and temperatures was ranked 2nd but was ranked 14th by the Kenyan respondents. Inexperienced and less knowledgeable personnel at the 4th position while Kenya ranked it 35th. Hard formation challenges were 5th for Iceland and 22nd for Kenya. Long lead times of material delivery came in 8th for Iceland and 16th for Kenya. Abandoned/plugged well, because of troublesome reservoir characteristics such as cyclic pressure, was ranked 9th for Iceland and 42nd for Kenyan respondents. At 10th place the Iceland group ranked workforce stress due to inadequate staffing, which was 13th for the Kenyan group.

The project environment played a role in risks such as encountering magma and intrusions, which was highly ranked by the Icelandic group at 6th position with 13 points while it was ranked at 54th position by the Kenyan group with a score of 6.3. Iceland lies on an active tectonic area and therefore volcanic activities are still common and magma is at a shallower depth, compared to the Kenyan rift where most of the drilling in Kenya is taking place. The risk of encountering magma is hence greater in Iceland than in Kenya, which may contribute to this factor’s greater perception of risk in Iceland.

Other factors to consider are the organisation of the drilling companies operating in these countries. Kenyan drilling projects are usually conducted by government-owned companies which also own the drilling equipment. The Icelandic drilling projects are owned by the power company and the drilling job is contracted out. This has resulted in the difference of how some of the risks especially financial risks are perceived. For example, the Kenyan respondents’ group ranked high cost of drilling as the highest risk with a score of 12.72. Owning a rig is therefore not a guarantee that the drilling cost will be lower. This group also ranked the risk of reduction of annual funding by government as the 7th highest risk but this was not a high risk for the Icelandic group.

iii. Review an integrated cost and schedule analysis model that can be used to support the risk management process and implement such a tool on a sample drilling project to quantify the impacts of the identified risk factors on the drilling project.

When it comes to cost estimations in drilling projects, in most cases the engineering estimate values are determined for all the project activities and a contingency amount added to it to cover any eventualities. Schedule estimates are done in a similar way to reflect the actual schedule. These estimates can be misleading, as the drilling schedule and cost are influenced by risks and uncertainties that are encountered both within and outside the project. Schedule estimates are often unreliable with likelihood of overrunning or underrunning the budget and schedule. From the sample project, the base cost was determined to be 6,041,320 USD and the schedules was planned for 60 days. These differed from those calculated by the model. In fact, the model produced most likely values of 6,678,425 USD for cost and 70.5 days for the project duration, which were higher than those determined.

Integrated cost and schedule modelling provides a way of evaluating the effect of project schedule variation on the cost of a project - in this case a drilling project. This is made possible by means of assigning resources loaded with cost and a fully populated risk register, on to the scheduled tasks. If the cost of the risk and their mitigation measure can be determined, a clear difference in contingency cost, schedule duration and start and finish dates estimate can be observed.

Risk analysis in the system provided a better ranking of risks compared to the survey results where the probabilities and impact was multiplied to get the scores. Here, the relative weight assigned to each risk category obtained from the pairwise comparison allows for a more objective risk analysis. This is seen in the system-generated risk register where eight out of the ten highest risks ranked were technical risks the other two were HSE risks, while the survey ranking had several categories ranked within the top risks. Two risk matrices were also created. The first matrix showed that most of the risks fell within the high category, but with mitigation the impact and chance of occurrence could be lowered. It was not possible to estimate risk cost values for all the risks and mitigation plans as the risk cost data was not available.

The Monte Carlo simulation results produced a probabilistic output of the expected cost, schedule and expected completion dates. The P50 values which also give the most likely value and were found to be different from the base value determined for the project. Dependence on most likely estimates for drilling projects can easily lead to cost and schedule overruns and in some cases underruns. A second Monte Carlo simulation run on the project without risk did not produce any different results from the one with risks, as there was not enough risk cost data.

Results from the sensitivity analysis showed the sensitivity of various activities on finish time. This can be translated to a drilling cost and time. It was determined that the 8½" section had the largest influence on the drilling finish time. A further analysis showed that the drilling on bottom of this section resulted in most of the increase in the drilling time. 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 is beyond the scope of this study but has been discussed in other research including Miyora (2014).

Drilling project costs are largely determined by the day rate and it is therefore not enough to just have cost estimate and contingency value to cater for eventualities. Analysing the combined effect of risks and uncertainty on both project cost and schedule allows for a better control of the project schedule and budget.

6. 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. As mentioned in Chapter 1, drilling costs account for approximately 40% of geothermal development project. In addition, the drilling phase grapples with several risks that increases this cost and compromises well delivery. 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

An initial risk analysis was conducted through an online survey, based on drilling personnel experience from previous drilled wells in Iceland and in Kenya. This showed that risk assessment is subjective and depends on the drilling project. A further risk assessment conducted using an integrated cost and scheduled risk management tool showed the subjectivity can be removed by the use of risk weighting.

The use of the software RiskyProject to carry out a probabilistic cost estimation shows the potential of such tools to provide valuable information for decision making in the drilling industry. The sensitivity analysis was able to focus on sections that could result in schedule and cost overruns. It was also able to show which activities were prone to increase project duration. Such knowledge of the uncertainties involved in the process forms a basis for clearer decision making, better resource allocation and proper project planning. The risk register and the risk matrices result, showed that if risks (anything that could go wrong) are identified earlier on in the project, and mitigation and control measures applied in time, all the residual risks could be lowered into the medium and low risk zones. Risk assessment methods such as these are easy to use and can be applied to any geothermal drilling project. It is important to remember that each drilling project is unique and therefore there the risk assessment should be tailored to fit the specific project. The uniqueness of each project comes with the type of wells being drilled, the area where the wells are drilled, the drilling project organisation structure, the stakeholders, drilling project objectives, risk perceptions of management and the business environment. Therefor each project should be assessed individually and solutions obtained for each drilling project.

A successful risk management process will require support from the whole organisation: from the top management to every individual taking part in the process, be it the operator, drilling contractor, or service providers and their staff. Correct information including schedule, resources, costs and risks - is crucial for the input to the process if it is to produce unbiased and representative analysis that can be implemented in drilling projects. It would be of great benefit to drilling projects if risk assessment is taken as a crucial part of the projects: not only to fulfil requirements of banks, insurance companies, top management and shareholders but also to implement the findings of prior projects and to improve performance. Knowing that there is a risk management plan in place for the geothermal resource, and also for the process to obtaining the resource, will encourage more response from investors in geothermal drilling projects.

7. RECOMMENDATION AND FUTURE WORK

The findings of this thesis were made with average industrial values. To be able to gain better understanding of how integrated cost and schedule analysis risk management could benefit drilling projects, a suggestion for future research is to perform a similar case study on ongoing drilling projects. Good quality data is important for achieving integrated cost and schedule risk analysis.

It will be also interesting to quantify the cost associated with each risk, and the cost associated with the mitigation measures. This will enable the determination of how much time and money is spent on each risk and inform on the decisions such as to what point or degree should risk reduction efforts be carried out.

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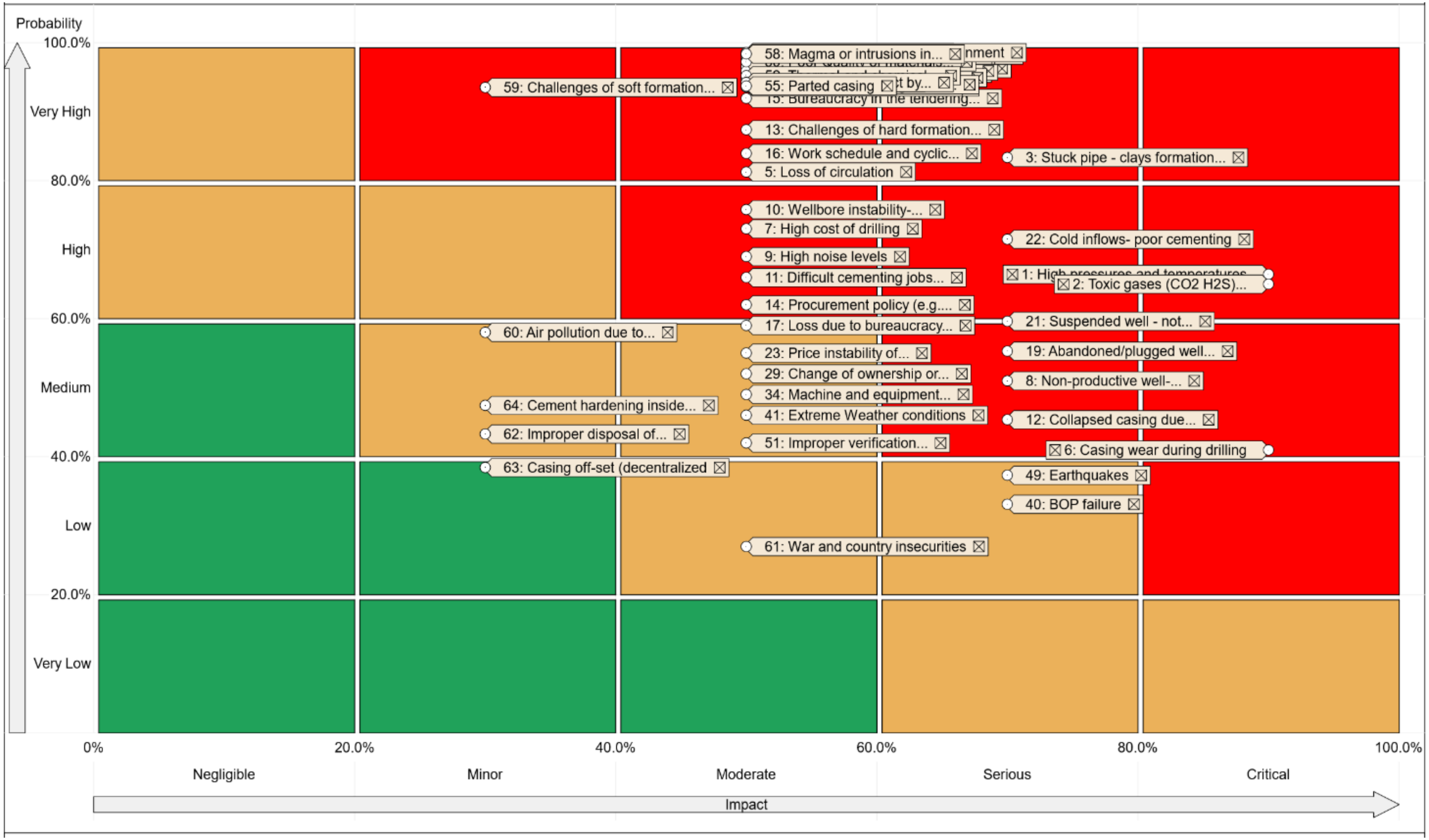
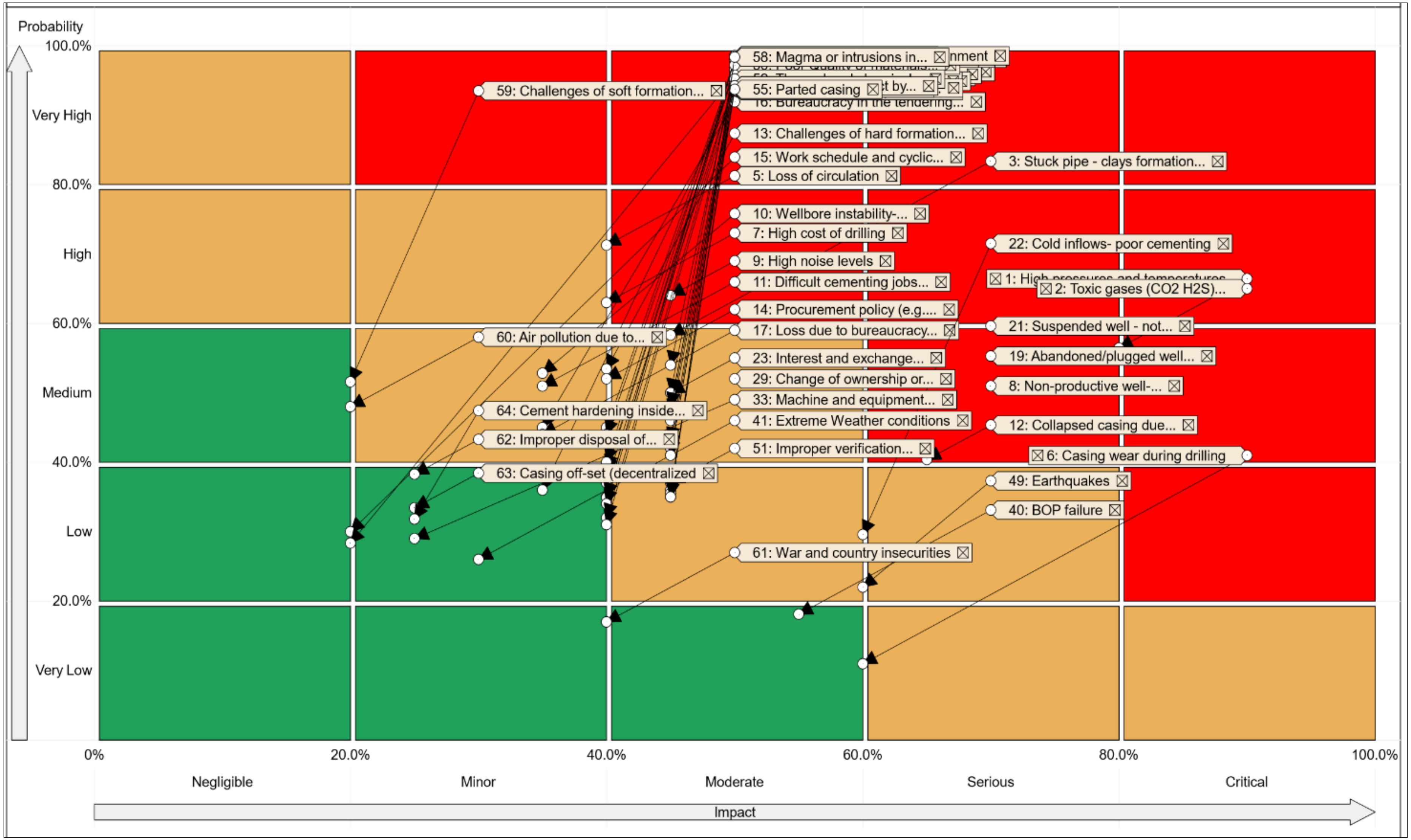
APPENDIX A: Questionnaire

	Risk Item	Probability or chance of risk					Degree of impact or the level of					Risk score
		Unlikely	Very unlikely	Likely	Very likely	Certain	Negligible	Marginal	Serious but tolerable	Major/ Critical	Catastrophic	
		1	2	3	4	5	1	2	3	4	5	
1	**TECHNICAL RISKS**											
	(a) Geological											
	1) Loss of circulation											
	2) Wellbore instability- collapsing formation											
	3) Stuck pipe- clays, formation collapse, dog legs											
	4) Rate of penetration- soft formation and hard formation											
	5) High pressures and temperatures											
	6) Magma or intrusions in deep wells											
	b) Casing and cementing											
	1) Casing wear during drilling											
	2) Casing off-set (decentralized)											
	3) Parted casing											
	4) Bust casing due to poor cement job.											
	5) Cold inflows- poor cementing											
	6) Difficult cementing jobs due to loss zones											
	7) Cement hardening inside casing											
	c) Equipment and tools challenges											
	1) Drill string failures- buckling, fatigue, formation wear											
	2) BOP failure											
	3) Loss of tools- BHA, logging tools, drilling tools											
	4) Machine failures- drill lines, breakdowns											
	d) Drilling material and consumables											
	1) Long lead times of material delivery											
	2) Bureaucracy in the tendering process											
	3) Failure to allocate risks properly in the contract											
	4) Material quality											
	e) Health, safety and Environment											
	1) Toxic gases (CO_2, H_2S released from the well)											
	2) Noise											
	3) equipment and personnel safety											
	4) Working environment											
	5) Leakage or collapse of brine pond											
	6) Improper disposal of drilling cuttings											
	7) Air pollution due to using diesel generator											
	8) Thermal and chemical pollution											
	f) Human resource											
	1) Personnel experience, and knowledge											
	2) Communication- employer, contractor and operators											
	3) Workforce stress due to inadequate staffing											
	4) The cyclic nature of drilling											
	5) Personnel motivation											
	g) Force majeure											
	1) Extreme Weather conditions											
	2) war and country insecurities											
	3) Earthquakes											
	h) Well success											
	1) Suspended well - not completed											
	2) Abandoned/plugged Well - total loss, high pressures											
	3) Non-productive well-low enthalpy, dry, cold, chemistry, pressure											
2	**FINANCIAL RISK**											
	1) High cost of drilling											
	2) Bankruptcy of project partner											
	3) Interest, and exchange rate fluctuation											
	4) Reduction in annual budget allocation by government											
	5) Delayed disbursement of funds from financiers											
	6) high fuel prices											
	7) Low credibility of shareholders and lenders											
	8) Changes in Bank formalities and regulations											
	9) Insurance risk											
3	**LEGAL RISK**											
	1) Breach of contract by project partner											
	2) Improper verification of contract documents											
4	**MANAGEMENT RISK**											
	1) Change of Top management											
	2) Inadequate well planning and budgeting											
	3) Inefficiently skilled and experience resources											
	4) Failure to provide contract deliverables on time, to agreed standards											
	5) Unclear contract specification											
	6) Changes on scope of contract											
	7) Stakeholders not kept informed about contract performance											
	8) Unclear lines of communication											
5	**POLICY AND POLITICAL RISK**											
	1) Cost increase due to changes of Government policies											
	2) Loss incurred due to corruption and bribery											
	3) Budgetary allocation											
	4) Procurement policy											
	5) Loss due to bureaucracy for late approvals											

APPENDIX B: Risk Matrix




Probability
100.0%
Very High
80.0%
High
60.0%
Medium
40.0%
Low
20.0%
Very Low
0%
20.0%
40.0%
60.0%
80.0%
100.0%
Negligible
Minor
Moderate
Serious
Critical
Impact
58: Magma or intrusions in...
55: Parted casing
59: Challenges of soft formation...
13: Challenges of hard formation...
15: Work schedule and cyclic...
5: Loss of circulation
3: Stuck pipe - clays formation...
10: Wellbore instability-...
7: High cost of drilling
22: Cold inflows- poor cementing
9: High noise levels
11: Difficult cementing jobs...
2: Toxic gases (CO2 H2S)...
14: Procurement policy (e.g....
17: Loss due to bureaucracy...
21: Suspended well - not...
60: Air pollution due to...
23: Interest and exchange...
19: Abandoned/plugged well...
29: Change of ownership or...
8: Non-productive well-...
33: Machine and equipment...
64: Cement hardening inside...
41: Extreme Weather conditions
12: Collapsed casing due...
62: Improper disposal of...
51: Improper verification...
6: Casing wear during drilling
63: Casing off-set (decentralized
49: Earthquakes
40: BOP failure
61: War and country insecurities