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GeoWell

Innovative materials and designs for long-life high-temperature geothermal wells

Deliverable D6.2

A roadmap for transferring well integrity risk assessment from oil and gas to geothermal

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Executive summary

As part of the activities in work package 6 of the GeoWell project, the aim of deliverable 6.2 is to present the current status of risk assessment methods in the petroleum industry based on a literature review and compare it with the status of risk assessments in the geothermal industry. Moreover, D6.2 also provides discussions on the applicability of risk assessment methods used in the petroleum industry for the geothermal industry. Moreover, the collected (raw) data of the survey together with analysis of data is presented in this report.

In parallel to this work, deliverable 6.1 has been performed, aiming at mapping the status of risk assessment used in the geothermal industry. In both deliverable 6.1 and 6.2, a literature review and a risk assessment survey have been conducted. The results from both the review and the survey should be interpreted as indicative, not conclusive evidence, due to a limited portion of publications reviewed and limited responses to the survey.

The main findings can be summarized as follow:

- There has been an increasing number of tools and techniques used, both from the petroleum industry itself and other industries. Risk assessment is today an important part of the oil and gas industry. Besides the methods aimed at performing common risk assessment activities, the petroleum industry today also has a strong focus on well integrity, and in particular on so-called well integrity management systems (WIMS).
- Based on the survey, the overall impression is that geothermal and petroleum industries are similar when it comes to supporting tools for performing risk assessment. The methods frequently used in the petroleum industry are also the more frequently used methods in the geothermal industry. However, every method is used more frequently in the petroleum industry than they are in the geothermal industry. In general, the petroleum industry uses a wider range of methods.
- In terms of types of risks assessed, both industries have a strong focus on health and safety, environmental risk and project/financial risk. However, a significant difference can be seen for barrier reliability, where there is a considerable focus in the petroleum industry, but not in the geothermal industry. A similar, but smaller difference can also be observed concerning pressure/well control. The geothermal industry, on the other hand, has a greater focus on geological risk and geological event risk.
- Main differences between the geothermal and petroleum industry, relate to the maturity and profitability of the petroleum industry resulting in access to large amounts of data. Learning from the petroleum industry what types of data are useful, and how these can be compiled and utilized, can enable the use of such methods in the geothermal industry in the future.
- Regarding regulations, the petroleum industry is highly regulated, and has specific standards, such as NORSOK D-010, which concern the well integrity of oil and gas wells. For geothermal wells, on the other hand, there are few regulations related to/supporting risk assessment.
- There is a learning potential regarding the use of risk assessment methods, in which lessons learned from the more mature petroleum industry could be transferred to the geothermal industry, by focusing on the underlying reasons for why these methods

have found success in the petroleum industry (or lack thereof), and by identifying their relevance for the geothermal industry.

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Abbreviations

API	American Petroleum Institute
CBA	Cost/benefit analysis
CCS	Carbon capture and storage
CO_2	Carbon dioxide
ERA	Environmental risk assessment
ETA	Event tree analysis
EU	European Union
FEP	Features, events and processes
FMEA	Failure mode and effects analysis
FMECA	Failure mode, effects and criticality analysis
FTA	Fault tree analysis
GEA	Geothermal Energy Association
GRC	Geothermal Resource Council
HACCP	Hazard analysis and critical control points
HAZID	Hazard identification
HAZOP	Hazard and operability studies
HIRAC	Hazard identification risk assessment and controls
HRA	Human reliability analysis
HSE	Health, safety and environment
IAEA	International Atomic Energy Agency
IEA GHG	International Energy Agency Greenhouse Gas R&D Programme
IGA	International Geothermal Association
ISO	International Organization for Standardization
LOPA	Layer of protection analysis
MCDA	Multi-criteria decision analysis
NCS	Norwegian Continental Shelf
NJRISE	North Japan Research Institute for Sustainable Energy
NORSOK	the competitive standing of the Norwegian offshore sector (Norsk sokkels konkurranseposisjon, standards that are developed by the Norwegian petroleum industry)
OSTI	Office of Scientific and Technical Information
PHA	Preliminary hazard analysis
PSA	Petroleum Safety Authority
PRA	Probabilistic risk assessment
QRA	Quantitative risk assessment
RAMS	Reliability, availability, maintainability and safety

RCM	Reliability centred maintenance
SIF	Safety integrity function
SIL	Safety integrity level
SPE	Society of Petroleum Engineers
SWIFT	Structured what-if technique
US DOE	United States Department of Energy
WIMS	Well integrity management systems
WP	Work package

1 Introduction

In order to accelerate the development of geothermal resources for power generation in Europe and worldwide in a cost effective and environmentally friendly way, the GeoWell project has received funding from the European Union (EU) [1]. This collaborative research project (2016-2019) aims at developing reliable, cost effective and environmentally safe technologies for design, completion and monitoring of high-temperature geothermal wells.

As part of the GeoWell project, work package six (WP6) entitled "risk assessment for geothermal wells" has the overall objective to develop risk and reliability analysis tools for risk assessment in both high enthalpy wells and extreme temperature wells in volcanic areas. This WP has the following secondary objectives:

- Raise the standard of risk analysis tools for geothermal wells to a standard that is comparable to that of oil and gas wells;
- propose a risk management framework that can be used for any deep geothermal wells; and
- Evaluate and manage risk related to the introduction of new materials and tools developed in other work packages within the GeoWell project.

In order to achieve all the WP6 objectives, existing experiences laid down in the vast volume of knowledge and methodologies developed in the petroleum industry will be employed. Accordingly, the foundations for the development of new risk analysis tools and a framework for risk assessments in the geothermal industry, more specifically for the needs of high-temperature geothermal wells will be established.

Deliverable 6.2 aims to map different risk assessment methods that are currently practiced in petroleum wells and also to discuss the applicability of relevant methods for geothermal wells. For this purpose, the "GeoWell risk assessment survey" has been prepared and sent to stakeholders dealing with risk assessment in both geothermal and petroleum industries. D6.2 presents the findings of the survey and analysis of the responses in addition to recent advancement in risk assessment in the petroleum industry based on the literature. The applicability of risk assessment methods used in the petroleum sector for the geothermal industry is addressed taking into account the significant differences between geothermal and petroleum wells.

Note that deliverable 6.2 and 6.1 are complementary to each other. Although the analysis of the survey's results as well as information from the literature are different in the two deliverables, these deliverables share some common topics including an introduction to well integrity and risk assessment as well as the GeoWell risk assessment survey. The main purpose for presenting common topics in both deliverables is to enable both reports to stand independently and to provide the necessary background information that readers might need to receive the main messages of each report.

1.1 Scope

The life cycle of an oil and gas well is shown in Figure 1-1.

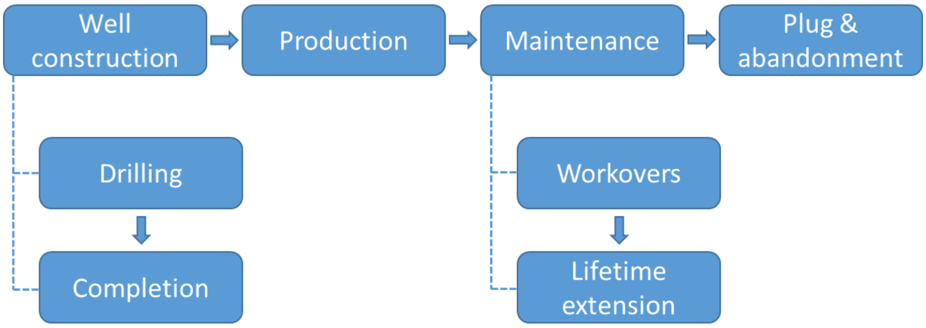

Figure 1-1. Different phases in the life cycle of a well.

Risk assessment is performed for both the initial execution of the job and the long-term consequences of the activity for every life cycle phase. However, this deliverable mainly focuses on methods for performing risk assessment during the well construction, production and maintenance phases.

One may distinguish between technical and non-technical risk assessments. Although WP6 of the GeoWell project addresses only technical risk assessment, to have a good overview, financial/economic risks and risks connected to personnel's health and safety are also covered in D6.2.

1.2 Outline of the report

Section 2 presents a brief introduction to well integrity. Section 3 introduces risk assessment, general risk assessment frameworks, regulations and guidelines influencing the risk assessment process and existing risk assessment methods and techniques.

Section 4 presents the objectives, methodology, criteria, preparatory requirements and post survey evaluations of the risk assessment survey. Section 5 provides the status of risk assessment methods in the petroleum industry based on the literature. This section also presents results of the risk assessment survey and a comprehensive comparison between petroleum and geothermal industries with respect to risk assessment methods. In addition, Section 5 addresses transferability of risk assessment methods from the petroleum industry to a geothermal context. Section 6 provides the concluding remarks of this deliverable, while Section 7 presents future activities within WP6. Appendices I and II provide the questions in the risk assessment questionnaire and its assembled raw data, respectively.

2 Introduction to well integrity

Wells can be classified into two main categories; i) exploration wells, with the aim to characterize potential reservoirs for future development and production, and ii) production or injection wells that either extract the resources from the reservoir or inject water or gas for pressure support.

The term "well integrity" has different definitions. Two of the most commonly used and accepted definitions are found in standards NORSOK D-010 and ISO TS 16530-2:

NORSOK D-010: "Application of technical, operational and organizational solutions to reduce risk of uncontrolled release of formation fluids throughout the life cycle of a well" [2].

ISO TS 16530-2: "Containment and the prevention of the escape of fluids (i.e. liquids or gases) to subterranean formations or surface" [3].

NORSOK D-010 is developed by the Norwegian petroleum industry and has a focus on well barrier elements, and the integrity of these shall be verified by pressure testing or by other specified methods. The standard requires at least one primary and one secondary barrier. It also requires the risk assessment of well integrity failure or well control incident. Risk assessments of well integrity shall consider:

a) Cause of degradation;
b) potential for escalation;
c) reliability and failure modes of primary well barrier elements;
d) availability and reliability of secondary well barrier elements, and
e) outline plan to restore or replace degraded well barriers.

As mentioned earlier in Section 1, the life cycle of the well is from the construction phase to final abandonment (i.e. including drilling and completion, production, workovers and lifetime extension, and plug and abandonment). NORSOK D-010 also specifies a well integrity management system, which comprises the following elements: organization, design, operational procedures, data system and analysis.

ISO TS 16530-2 applies to all wells that are utilized by the oil and gas industry, regardless of age, type or location. It considers only the operational phase (i.e. no well construction, workover/lifetime extension nor abandonment), and similarly requires addressing risk assessment aspects of well integrity. While NORSOK is more barrier-focused, ISO TS 16530-2 lists considerations such as:

- Location;
- outflow potential;
- well effluent (i.e. fluid components);
- external environment, and
- redundant systems.

There are generally four ways in which a leakage may occur from the well to the environment; 1) through the downhole completion tubing, 2) through the downhole completion annulus, 3) through the cement between the annuli or 4) outside and around the well casing system.

3 Introduction to risk assessment

This section aims to present definitions of risk-related keywords that are often used throughout this document. Moreover, risk assessment and its underlying activities as part of generic risk management frameworks are described. This section also presents the available regulations and standards that govern risk assessments to be performed within petroleum industries. Finally, different risk assessment methods/techniques that have been touched upon by the Geowell risk assessment survey are briefly introduced.

3.1 Important risk-related definitions

The following important key words/phrases are frequently used throughout this report, based on ISO 31000:2009 [4]:

- **Risk** – Effect of uncertainty on objectives. An effect is a deviation from the expected – positive or negative. Objectives can relate to different aspects including strategy, organization, project, product and process. Risk is often characterized by reference to potential events and consequences, or a combination of these. Risk is often expressed in terms of a combination of the consequences of an event (including changes in circumstances) and the associated likelihood of occurrence. Uncertainty is the state, even partial, of deficiency of information related to, understanding or knowledge of an event, its consequence, or likelihood.
- **Risk assessment** – The overall process of risk identification, risk analysis and risk evaluation.
- **Risk identification** – Process of finding, recognizing and describing risks. Risk identification involves the identification of risk sources, events, their causes and their potential consequences. Risk identification can involve historical data, theoretical analysis, informed and expert opinions, and stakeholder's needs.
- **Risk analysis** – Process of comprehending the nature of risk and determining the level of risk. Risk analysis involves developing an understanding of the risk and provides an input to risk evaluation, to decisions on whether risks need to be treated, and on the most appropriate risk treatment strategies and methods. It also involves consideration of the causes and sources of risk together with their positive and negative consequences, and the likelihood that those consequences can occur.
- **Risk evaluation** – Process of comparing the results of risk analysis with risk criteria to determine whether the risk and/or its magnitude or likelihood is acceptable or tolerable. Risk evaluation involves comparing the level of risk found during the analysis process with risk criteria established when the context of the risk assessment was considered. The aim here is to assist in making decisions about which risks need treatment and the priority for treatment implementation.

3.2 General risk management frameworks

According to ISO 31000:2009 [4], risk management refers to "coordinated activities to direct and control an organization with regard to risk". Risk assessment is one part of a risk management process, and is in the same standard defined as "the overall process of risk identification, risk analysis and risk evaluation".

Typically, other parts of the risk management framework include establishing the context, risk treatment, communication and consulting, and monitoring and review, as shown in Figure 3-1.

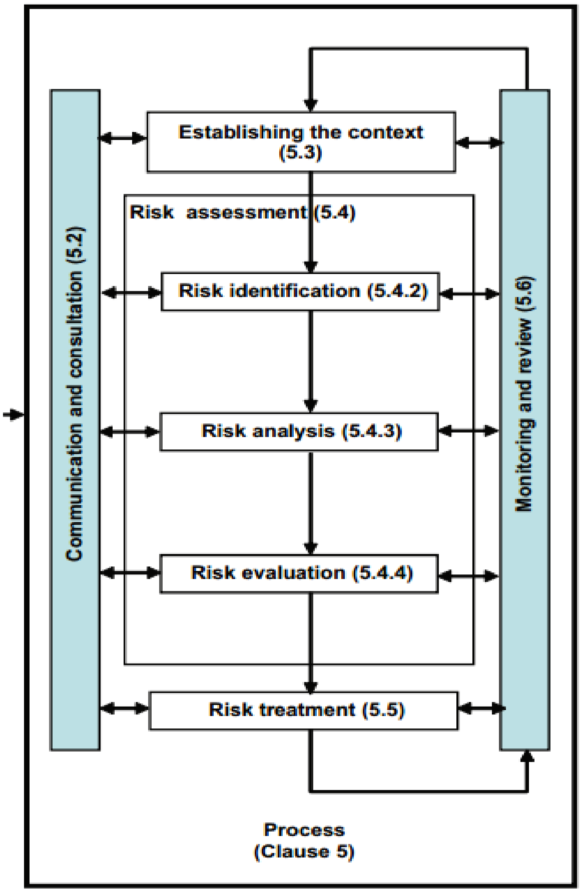

Figure 3-1. A general framework for risk management as presented in ISO 31000:2009.

The ISO framework for risk assessment and risk management is generic and high-level, and does not give detailed guidelines on what tool or methods should be used to achieve the overall objectives. Naturally, the specific implementations of risk assessment frameworks will vary in accordance with the area of application. The nature of the risk and its associated uncertainty will be different when considering areas or industries such as petroleum, nuclear energy, space aviation, societal security or natural disasters. The actual implementation of the risk assessment and management framework will also vary with the types of risk that are in focus of the assessment. Such categories include project- and financial risks, geological risks, barrier risks, health and safety risks, environmental risks or pressure- and wellbore risks, and are quite different from one another.

Examples of other high-level standards or guidelines for risk assessment and management include OCEG "Red Book" 3.0 GRC Capability Model[1], BS 31100:2011 Risk Management: Code of practice and guidance for the implementation of BS ISO 31000[2], COSO:2004 Enterprise Risk Management – Integrated Framework[3], FERMA:2002 A Risk Management Standard and Solvency II[4].

The petroleum industry has several standards for risk assessment and management . On the Norwegian Continental Shelf (NCS), the NORSOK Z-013 [5] standard is widely used, which

[1] http://www.oceg.org/resources/red-book-3/
[2] http://shop.bsigroup.com/ProductDetail/?pid=000000000030228064
[3] http://www.coso.org/documents/coso_erm_executivesummary.pdf
[4] http://www.ferma.eu/app/uploads/2011/11/a-risk-management-standard-english-version.pdf

has been developed by the petroleum industry. This standard is focused on a quantitative risk assessment (QRA), as shown in Figure 3-2.

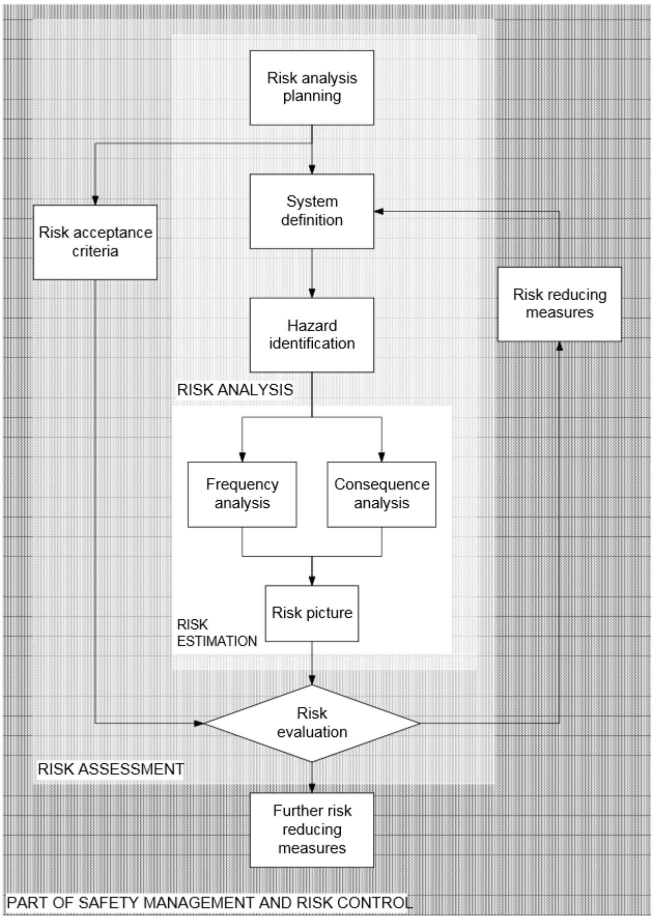

Figure 3-2. Risk assessment and management framework with a quantitative focus, as presented in NORSOK Z-013.

In quantitative risk assessments, the probability and consequence dimensions of risk are expressed in quantitative terms, using for example risk matrices, historical data or probability distributions, whereas in a qualitative assessment, a descriptive approach is used to express risk. The use of these two approaches may be by design, due to a lack of available data required to use quantitative models, or due to the complex nature of the risk or its inherent uncertainty.

Other examples of high-level risk assessment frameworks from the industry include those from the International Atomic Energy Agency (IAEA) for the nuclear industry [6] and from the International Energy Agency Greenhouse Gas R&D Programme (IEA GHG) [7] for CO_2 storage projects, as shown in Figure 3-3.

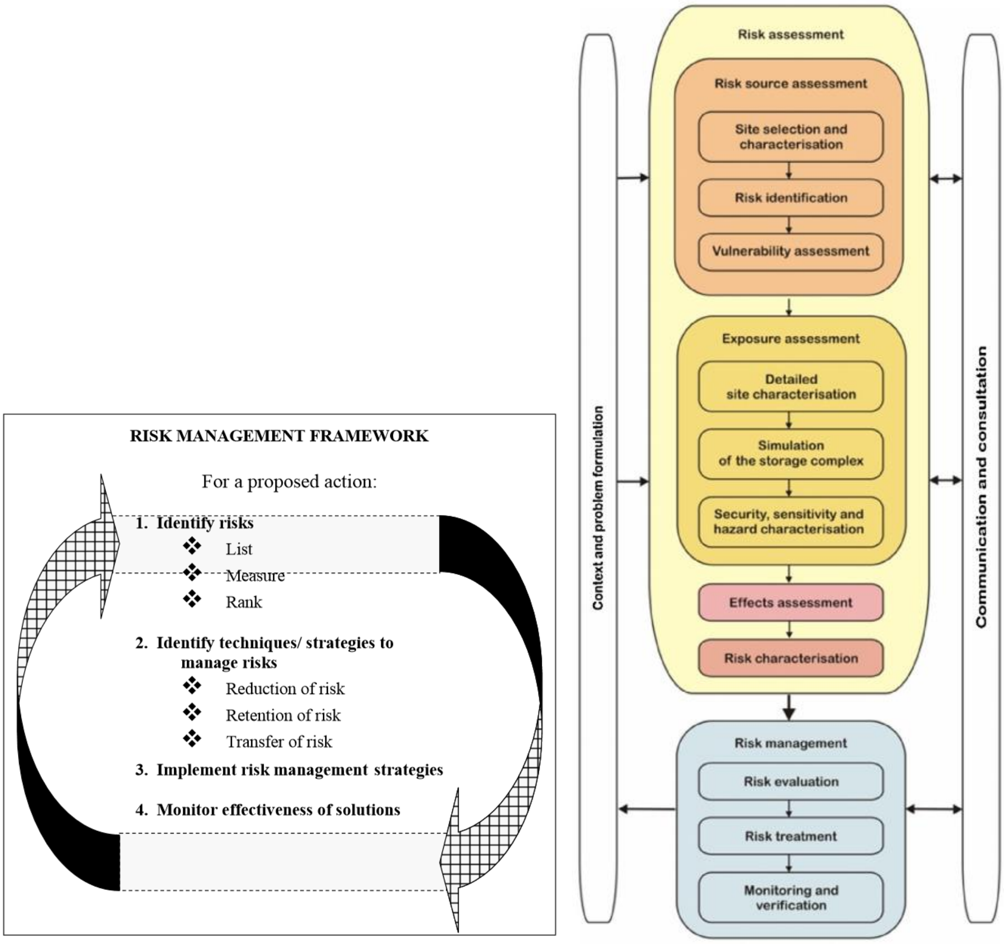

Figure 3-3. Risk assessment frameworks for nuclear industry (left, IAEA 2001) [6] and for CO_2 geological storage (right, IEA GHG 2009) [7].

3.3 Regulations

Generally, most industrial activities involve hazards/risks towards human health, safety or environment, and thus there are laws and regulations requiring risk assessments to be performed. Distinction should be made between directives, standards and guidelines. In the EU, "a directive is a legislative act that sets out a goal that all EU countries must achieve. However, it is up to the individual countries to transfer a directive into their own laws on how to reach these goals" [8]. A standard is a description of a set of activities, and constitutes a particular level in which compliance is to be met. A guideline is of more advisory nature, for example in terms of how to reach compliance with a standard. Developments in regulations over the past decades has seen a gradual shift from prescriptive-based regulation to performance-based regulation, where the management is held responsible for ensuring that appropriate safety systems are in place [9].

In Europe, EU Directive 82/501/EEC[1] (often referred to as the Seveso Directive, and its amended post-Piper Alpha version of 1996, Seveso II) concerns the control of major accident hazards involving dangerous substances. In the United States, 29 CFR 1910.119[2] "Process safety management of highly hazardous chemicals" constitutes similar legislation. Other

[1] http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:31996L0082
[2] https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9760

examples of wide-reaching legislative acts governing risk assessment include; EU Directive 89/392/EEC[1], covering safety aspects for a wide range of machinery, for which the ISO standard ISO 12100:2010[2] was also developed, the UK Health and Safety at Work Act of 1974[3], the UK Offshore Installations (Safety Case) Regulations of 1992[4], and the US Maritime Transportation Security Act of 2004[5].

There are various standards pertaining to different industries. The NORSOK Z-013 standard for Risk and Emergency Preparedness Analysis [5] is used for the petroleum industry. In the nuclear industry the guideline NUREG/CR-2300 concerns the risk assessments for nuclear power plants [10], while in the space industry NASA has developed guides for probabilistic risk assessment (PRA) procedures [11]. The standard EN50126[6] concerns "the specification and demonstration of reliability, availability, maintainability and safety (RAMS)" for railway applications.

On the Norwegian Continental Shelf (NCS), the Petroleum Safety Authority (PSA) for example has requirements related specifically to well barriers in PSA's Facility Regulations, §48, and guidelines providing further details, which link to specific parts of the NORSOK D-010 standard. The latter is the standard covering well integrity in drilling and well operations. Other standards related to well integrity in the petroleum industry include ISO/TS 16530-.2:2014 – Well integrity -- Part 2: Well integrity for the operational phase[7] and NOG 117 – Recommended guidelines for Well Integrity[8].

3.4 Risk assessment methods/tools/techniques

There exists a wide range of available methods/tools/techniques for assessing risks, varying in degree of depth and detail, complexity and requirements in terms of resources, the type of focus (e.g. quantitative or qualitative, probabilistic or deterministic), and its place in the risk assessment process. This section will briefly outline an overview of what exists, and will point to some of the main differences. The methods and classifications outlined, are based on the ISO 31010:2009 standard [12] as shown in Table 3-1, which was also used as a basis for the survey that was conducted.

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[1] http://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:31989L0392&qid=1458901186986
[2] http://www.iso.org/iso/catalogue_detail?csnumber=51528
[3] http://www.legislation.gov.uk/ukpga/1974/37/contents
[4] http://www.legislation.gov.uk/uksi/1992/2885/contents/made
[5] https://www.gpo.gov/fdsys/pkg/PLAW-107publ295/html/PLAW-107publ295.htm
[6] http://standards.globalspec.com/std/1272146/cenelec-en-50126-1
[7] http://www.iso.org/iso/catalogue_detail.htm?csnumber=57056
[8]https://www.norskoljeoggass.no/Global/Retningslinjer/Boring/117%20Norwegian%20Oil%20and%20Gas%20%20recommended%20guidelines%20Well%20Integrity.pdf

Table 3-1. Different available methods, tools and techniques for assessing risks [12].

Tools and techniques	Risk assessment process				
	Risk Identification	Risk analysis			Risk evaluation
		Consequence	Probability	Level of risk	
Brainstorming	SA[1]	NA[2]	NA	NA	NA
Structured or semi-structured interviews	SA	NA	NA	NA	NA
Delphi	SA	NA	NA	NA	NA
Check-lists	SA	NA	NA	NA	NA
Primary hazard analysis	SA	NA	NA	NA	NA
Hazard and operability studies (HAZOP)	SA	SA	A[3]	A	A
Hazard Analysis and Critical Control Points (HACCP)	SA	SA	NA	NA	SA
Environmental risk assessment	SA	SA	SA	SA	SA
Structure « What if? » (SWIFT)	SA	SA	SA	SA	SA
Scenario analysis	SA	SA	A	A	A
Business impact analysis	A	SA	A	A	A
Root cause analysis	NA	SA	SA	SA	SA
Failure mode effect analysis	SA	SA	SA	SA	SA
Fault tree analysis	A	NA	SA	A	A
Event tree analysis	A	SA	A	A	NA
Cause and consequence analysis	A	SA	SA	A	A
Cause-and-effect analysis	SA	SA	NA	NA	NA
Layer protection analysis (LOPA)	A	SA	A	A	NA
Decision tree	NA	SA	SA	A	A
Human reliability analysis	SA	SA	SA	SA	A
Bow tie analysis	NA	A	SA	SA	A
Reliability centred maintenance	SA	SA	SA	SA	SA
Sneak circuit analysis	A	NA	NA	NA	NA
Markov analysis	A	SA	NA	NA	NA
Monte Carlo simulation	NA	NA	NA	NA	SA
Bayesian statistics and Bayes Nets	NA	SA	NA	NA	SA
FN curves	A	SA	SA	A	SA
Risk indices	A	SA	SA	A	SA
Consequence/probability matrix	SA	SA	SA	SA	A
Cost/benefit analysis	A	SA	A	A	A
Multi-criteria decision analysis (MCDA)	A	SA	A	SA	A

1) Strongly applicable.
2) Not applicable.
3) Applicable.

A preliminary hazard analysis (PHA) is an example of a simple method requiring limited knowledge of the process or activity in question. It can be viewed as high-level, with the objective of prioritizing risks based on coarse probability or consequence assessments. The requirement for conducting such an analysis is not considerable, and also in terms of execution time, the process can be performed quickly. A PHA can typically be useful in the risk identification phase, but has limited value in the later analysis phase, as it is neither comprehensive nor detailed. The failure mode and effects analysis (FMEA) is another method that can be used to identify risks, but is somewhat more comprehensive as it requires listing of all relevant failure causes/modes/mechanisms by which a system component may fail. It requires more knowledge of the system in question than a PHA, and can become tedious if the number of assessed components is large. An example of an analysis that is more used in the risk analysis phase after the identification phase is the fault tree analysis (FTA). It uses logical gates, root causes or combinations of failures that could lead to a single, identified failure. This analysis is often used in engineered systems where the components have reliabilities. FTA thus has a quantitative focus, which often requires both time and a high level of expertise.

As previously mentioned, some analysis tools are more commonly applied in specific areas of application, and for assessing certain types of risks, and others have a wider range of application. For example, in the petroleum industry on the NCS, well integrity is strongly related to barrier analysis. Such analyses often revolve around technical or physical barriers and the failure modes such components may encounter. Thus, the use of e.g. FMEA/FMECA and FTA are commonly used methods in this context. In other areas, such as the nuclear industry or the carbon capture and storage (CCS) industry, scenarios analyses and checklists are commonly used together with the features, events and processes (FEP) approach as stated in [13, 19, 20].

It is also important to emphasize that the method classification presented in ISO 31010:2009 does not represent an objective “true” classification. It is simply one way of representing an overview of different methods for risk identification, analysis and evaluation. That does not mean that methods not listed in the standard are inferior in any way, or that the classification between identification, analysis and evaluation is the correct one. Monte Carlo simulation is by many viewed as more logically belonging to analysis than evaluation, and there are also arguments for not having many structured methods for evaluation at all, as this phase mostly focuses on comparing analysis results with regulations, acceptance criteria, etc. It was chosen to use ISO 31010:2009 as a basis for the survey, but allowing for adding methods not listed to any of the three parts of the risk assessment, precisely because of the aforementioned challenges.

4 Risk assessment survey

4.1 Objectives

The main objective of the survey performed in the GeoWell project was to get an overview of how risk assessments are performed in the geothermal and petroleum industries so that differences between the two sectors can be identified.

4.2 Methodology

4.2.1 A hypothesis

The petroleum industry may be considered more mature than the geothermal industry, with significantly more wells drilled, and stricter regulations. Based on this, a hypothesis that the geothermal industry has less mature standards on risk assessments than the petroleum industry seems reasonable. The primary purpose of the survey is to map the current application of risk assessment methods in both geothermal and petroleum industries and to identify differences that may be used to raise the standard of the geothermal industry to that of the petroleum industry.

Note that the differences in risk assessments might also be caused by:

- Difference in standards between onshore and offshore wells (offshore wells are more costly to drill and spills will spread in the water, causing harm over a larger area);
- Difference between legislations in different regions of the world (e.g. Norwegian regulations are considered strict compared to many other countries);
- Difference between sizes of companies (not all oil companies are staffed for costly and resource intensive assessments, or may lack personnel with the proper expertise).

Many companies involved in the geothermal industry are also involved in the petroleum industry. This is particularly true for the companies providing drilling services. It is likely that these companies will apply the same methods for both the petroleum and geothermal wells they are drilling. However, there may be differences in how the assessments are performed with respect to the collaboration between the contractors, service providers and operators.

4.2.2 Reasoning for survey questions

The web based survey, attached in Appendix I, consists of 7 pages. The initial page is a simple welcome page, explaining the background for the survey, such as the purpose of the survey, who is performing the survey and in what context, and how the results will be used. This provides necessary context for the receivers of the survey, which gives them confidence in the seriousness of the survey as well as an idea of how they should respond if any of the questions is considered to be ambiguous.

The second page asks for information about the responder. As respondents may not wish to supply personal information about themselves, the company they work for and the country they reside in are marked as optional. Most of the questions do not actually require a response; however, responses are expected by the inquirers. The reason for allowing many unanswered questions was to get as much as possible of the questionnaire completed, and the questionnaire does not create unnecessary barriers.

The other questions on page 2 relate to the type of company and the respondent's role in relation to risk assessments for wells. Common company types from the industry were used to identify their responsibilities related to wells.

Another question was posed to be able to separate the respondents working in the geothermal sector from those in the petroleum sector, as well as those working offshore from those working onshore. Offshore geothermal was not considered a relevant alternative. The final question on the second page; whether the respondent performs risk assessments related to wells is a qualifying question, intended to filter out those who would not be in a position to provide relevant answers to the more risk specific questions in the next sections of the questionnaire. This question also served to identify who is involved in risk assessments related to wells. Answering “no” to this question takes the respondent to the end of the survey, where they can provide their email addresses (for future dissemination activities) and any feedback they may have.

The third page is used to identify in which area the respondents apply risk assessments. As the main purpose of the GeoWell project is related to well integrity, it was desirable to distinguish assessment of downhole conditions from assessments related to the work processes. Different risk areas, accompanied with a short description, are:

- Health and safety risk: assessment regarding the health and safety of personnel.
- Project/financial risk: risk assessment related to project execution such as delays, timing, reputation, capital, regulatory etc.
- Geological risk: assessment related to reservoir characterization uncertainty.
- Geological event risk: risk assessment related to seismic events, fracking, reopening of faults etc.
- Pressure/well control risk: assessment regarding wellbore pressure control related incidents such as lost circulation, kick, stuck pipe etc.
- Equipment reliability: assessment of failure of non-barrier equipment such as drilling tools.
- Barrier reliability: assessment of the condition of integrity related equipment such as casing and cement.
- Environmental risk: assessment of environmental impact of operations.
- Flow assurance: assessment related to production.

The fourth page requests the respondent to identify which methods are used in risk identification, risk analysis and risk evaluation. These are common terms in risk management, and definitions can for example be found in ISO 31010:2009 [12]; see also Section 3.1. The methods were subject to discussion, as many different names are used for similar methods. As there was a large number of methods, trying to group the methods by types was considered. However, introducing new naming conventions would easily make it more difficult for the respondents to recognize which type of methods they are using. In the end, the names of the methods applicable to specific risk assessment activities as defined in ISO 31010:2009 were used. It was believed that most respondents would understand which methods would apply to them. Each method was also given a tool-tip text in the survey, giving a brief description of the method for clarification.

The fifth page breaks down the use of methods in the different life cycle phases of the well (including drilling, completion, production and maintenance).

The sixth page is similar to the fifth, breaking down which methods are applied to which risk areas (e.g. project/financial, geological and environmental risks). Similarly, only the previously selected methods and the previously selected areas were shown.

The final page of the survey informs the respondent on how the results will be communicated, and asks whether they are interested in attending a webinar for the purpose of dissemination and communication of the findings of the survey. Comments are also requested to get feedback on the survey and to get additional information.

4.2.3 Selection of the recipients

As the survey was targeted to map the status of risk assessments performed in a well integrity context in the geothermal and petroleum industries, the survey is sent to experts active in each or both of industries.

While the list of contacts for the petroleum industry was based on an internal IRIS database, the contact list for the geothermal industry was based on:

- Contacts provided in Hirosaki University, Aomori Campus, North Japan Research Institute for Sustainable Energy (NJRISE) (http://njrise.cc.hirosaki-u.ac.jp/hiro/indexE.html);
- Office of Scientific and Technical Information (OSTI) Database, United States Department of Energy (US DOE), (http://www.osti.gov/geothermal/)
- Geothermal Energy Association (GEA) membership list (http://geo-energy.org/gea_members.aspx);
- Geothermal Resource Council (GRC) publication database (https://www.geothermal.org/publications.html);
- Search through the paper database of IGA (International Geothermal Association) and finding active authors in the field (https://www.geothermal-energy.org/publications_and_services/conference_paper_database.html); and
- Contacts provided by GeoWell partners.

4.2.4 Data analysis methodology

The main purposes of data analysis are to look into who performs risk assessments and which methods they use, with a particular focus on differences between the geothermal and petroleum industries.

The number of respondents is probably not sufficient to compare the geothermal and petroleum industries directly, and to draw statistically significant conclusions. In addition, due to a lack of control on who responds to the survey, possible differences in respondent representativeness for their industry can reduce the significance of the results. Thus, the data will mainly be considered as an indication of differences, so that a narrative of differences can be constructed that can be evaluated rather than executing an extensive statistical analysis.

4.3 Preparatory requirements

Prior to the risk assessment survey, different preparatory and quality assurance considerations were made, as listed in Table 4-1.

Table 4-1. Different preparatory and quality assurance considerations for the survey.

Consideration	Remarks	Quality assurance checklist
Length of the survey	All questions were discussed to see if they could be excluded without losing needed information. Reasonable and short (about 10 min estimated by survey provider)	Can any question be excluded? Is it too time consuming to complete it?
Simplicity	As simple as possible	Are all the questions simple? Are the questions understandable for the target audience?
Layout	Clear and consistent form with the GeoWell's logo	
Target group	Relevance to the recipients and precise definition of target group	Is the survey clear on who the recipients are, and are the questions suitable for them?
Type of questions	Clear and relevant	Are all the questions relevant? Are all the questions balanced? Are all the questions unambiguous? Will the questions provide the answers that are desired? Is there a combination of open and closed questions? Are the questions asked in a logical order? Do the questions match the alternatives?
Type of answers	Mainly multiple choices are provided. Alternatives based on literature sources, e.g. ISO standard.	Are the alternatives exhaustive? Are the alternatives mutually exclusive? Is similar type of scale used consistently throughout the survey?
Time for sending the survey	The survey sent at a time that the respondents have time to answer it (during summer time). Risk of being overlooked due to being in summer vacation.	
Results	Recipients have been informed about the use of results.	Is the purpose of the survey clear? Is it clear how the results will be used?
Reminder sending	One reminder was sent to those who had not left their e-mail in the questionnaire.	
Incentives use	Communication of the results through a planned webinar has been promised.	Why would the target audience complete the survey?
Teaser format	An e-mail invite is used as a teaser. Target audience incentivized by the e-mail invite.	How has the target group been informed about the survey?
Communication	An email account was specifically created for communication with recipients of the survey.	Is there any contact information provided for future communication between recipients and the GeoWell team?

All of the considerations listed in Table 4-1 are obvious, but the most important ones are to create questions that serve the objectives, are simple to understand and unambiguous, and have alternatives that are exhaustive and mutually exclusive. In addition, the survey should be able to provide results that are of mutual interests to both recipient and the survey team.

4.4 Post survey evaluation

The survey status as of September 14, 2016, includes 46 finished responses, 18 partial responses (in total 64 response) as well as 31 in progress. Most of those who completed the survey spent less than 10 minutes (to the left in Figure 4-1). Of those that did not finish, most stopped at the company information page, (i.e. first page, see Appendix I and II for the questionnaire and its collected data, respectively) as seen to the right in Figure 4-1, and some did just not press the finish button. These results indicate that the last part of the questionnaire was not time consuming enough to make the respondents stop, which due to the matrix functionality of the question, was feared. Alternatively, one could argue that due to comprehensiveness, respondents rushed through just to get finished with the survey, giving random answers along the way. While this could of course be the case, we do not see any arbitrariness or contradictory survey results suggesting this.

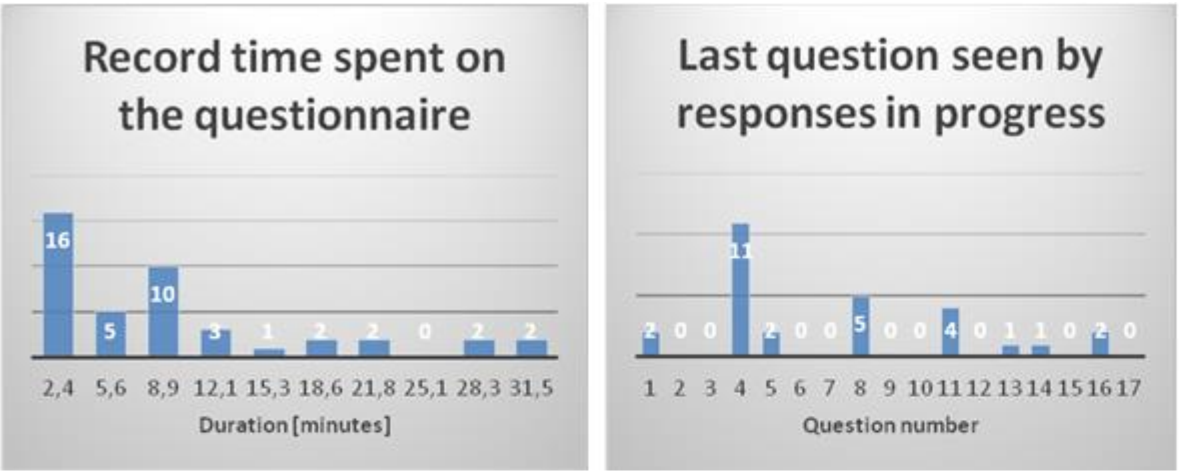

Figure 4-1. Registered time spent for respondents spending less than 2 hours (left) and registered last question answered for the unfinished responses (right).

Only two comments on the survey itself have been received through the comment functionality. One was particular to the mentioned matrix functionality between methods and application area, where many combinations had to be considered if the respondent used many methods and applied them to many areas. The respondent commented that many methods and applications overlap, which means many boxes had to be ticked off. Knowing that filling out parts of survey could take a lot of time in some cases makes the appreciation for their efforts even larger.

The other comment was that too many “risk-insider” terms were used in the questionnaire, and that this may lead to unclear results. Introducing custom categories for the methods was a concern, as this could possibly lead to different interpretations of the categories. To ensure consistency and traceability, the methods as mentioned in the ISO standard were used, with tool-tip text describing the methods. However, many might not have seen the tool-tip text, or been inclined to read it for every method. Thus, the actual methods chosen by the respondents should only be used as indications of the risk assessments performed, rather than the conclusive basis for use of the methods.

5 Results and discussion

5.1 Risk assessment status in the petroleum industry – Literature

Risk assessment as a pronounced and defined activity has its origins from the middle of the 20th century, where the aerospace industry used quantitative risk assessment methods, and the nuclear industry used a probabilistic risk assessment approach in the 1960s. The next decade saw the introduction of the Seveso Directive [14] and the chemical industry applying quantitative risk assessments, whilst the oil and gas industry followed in the 1980s. There has been an increasing number of tools, and techniques added, both from other industries and the petroleum industry itself, and risk assessment is today an important part of the oil and gas nomenclature. According to OnePetro[1], where publications of the society of petroleum engineers (SPE) are published, a search for the term “risk assessment” yields approximately 9,400 search results. Similarly, the term “well integrity” gives ca. 3,100 results.

Some of the most commonly used methods, qualitative or quantitative, in the oil and gas industry, are [15]

- Preliminary hazard analysis (PHA)
- Hazard and operability studies (HAZOP)
- Hazard identification studies (HAZID)
- Failure mode and effects analysis (FMEA)
- Fault tree analysis (FTA)
- Event tree analysis (ETA)
- Layer of protection analysis (LOPA)
- Safety integrity level (SIL)
- Bow tie analysis

The PHA, originating from the military, is a technique to assess system and sub-system hazards as well as to prevent accidents during routine and non-routine activities during the operation phase. Regardless of the application, the main objective is to support decisions to avoid accidents and to eliminate unsafe conditions [16]. A PHA can be performed with either special software or using basic office tools. After a PHA has been performed, sometimes it is common to re-evaluate the risks after mitigating measures are implemented. The analysis is also often used as input to quantitative analysis such as FTA, bow tie, ETA and consequence and effect analysis [15].

HAZOP is a very structured approach providing a guideline for assessing process deviation, causes, consequences, and when possible, proposing mitigating measures. HAZOPs are often used during the operational phase, in conjunction with process modifications. It can be a meticulous and demanding type of analysis, and one of the main drawbacks is that it does not explain in detail the equipment failures and therefore it does not define specific action for the equipment [15].

FTA, originating from the military during the 1960s, is a quantitative analysis method that uses logic gates to events that trigger top-level events. Top events are typically accidents or equipment failure. As some events are inter-dependent, it is often distinguished between static FTA and dynamic FTA. Also, depending on the time frame in question, probabilities of the events may change over time, and it also gives meaning to use the notions time-dependent and time-independent FTA. The FTA often follows a PHA, PRA or HAZOP, to better predict the probability of occurrence, to verify risk classification and to assess the

[1] https://www.onepetro.org/

effect of preventative measures [15]. The ETA, contrary to the FTA, focuses on mitigating measures and consequences, and begins from left to right, starting with the initiating event and continuing to a sequence of events. This time-dependent approach shows the risk over time, helping to define actions to keep risk at an acceptable level [15].

LOPA, an extension of ETA, considers layers of protection preventing an initiating event from turning into an accident, and may be time-dependent or not. The barrier approach, stemming from the NORSOK D-010 standard [17], is an example of a similar analysis approach. This is also a quantitative analysis, relying on the availability of failure rates for all components analyzed.

SIL analysis stems from the mechanical industry, and was used to verify the integrity of an emergency control system. It is a semi-quantitative analysis which in the petroleum industry is used to review whether it is necessary to implement a safety integrity function (SIF) as a layer of protection, and to assess whether the system has an acceptable risk level [15].

Bow tie analysis, first used by Shell in the early 1990s, is actually an inclusion of FTA, ETA and LOPA concepts, and mainly covers potential causes, control measures, loss of control, recovery measures and consequences.

Besides the methods aimed at performing common risk assessment activities, the petroleum industry today also has a strong focus on well integrity, and in particular on so-called well integrity management systems (WIMS). WIMS can be defined as “a meaningful solution to define the commitments, requirements and responsibilities of an organization to manage the risk of loss of well containment over the well lifecycle. Such systems are often facilitated by software solutions; examples being iQRA[1], Well-Master[2], Simeo[3], OREDA[4], DSWIM[5] and WellView[6]. Such systems contain risk registers, well barriers and envelopes, performance standards, barrier verification or assurance processes and documentation.

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[1] http://www.intetech.com/iqra
[2] http://www.exprosoft.com/products/wellmaster-ims/
[3] http://www.oxand.com/simeo
[4] https://www.oreda.com/
[5] https://www.landmark.solutions/DecisionSpace-Well-Integrity-Management
[6] https://www.peloton.com/software/wellview

5.2 Risk assessment status – Survey

In this sub-section, an analysis of the respondents to the risk assessment survey is presented. The analysis particularly looks at who performs risk assessments for wells. Note that the analysis is limited to fully completed responses who have selected “yes” when asked whether they perform risk analysis for wells or not. This reduces the number of relevant respondents to 25. Although this number is too low to generate statistically significant results, the results will still give an indication as to what is performed related to well risk assessments. These results look into what methods are applied, to which activities in the well lifecycle, and by whom.

5.2.1 Respondent overview

In Section 4, a description of the recipients of the risk assessment survey is provided. Due to the encouragement to forward the survey to relevant contacts, there was no real control over the respondents. This sub-section provides information about the respondents of the survey.

There is a possibility that there may be regional differences concerning how risk assessments are performed. Some countries have stricter regulations related to the risk assessment than others do, and different parts of the world may have different geological challenges. Similarly, there may be differences between geothermal, and petroleum offshore and onshore activities. The distribution of the respondents among the continents is displayed in Figure 5-1, with the distribution between onshore and offshore shown in Figure 5-2. In both pie charts, responses where no information was available have been excluded, and those marked “other” have been interpreted and assigned to the most relevant response where possible.

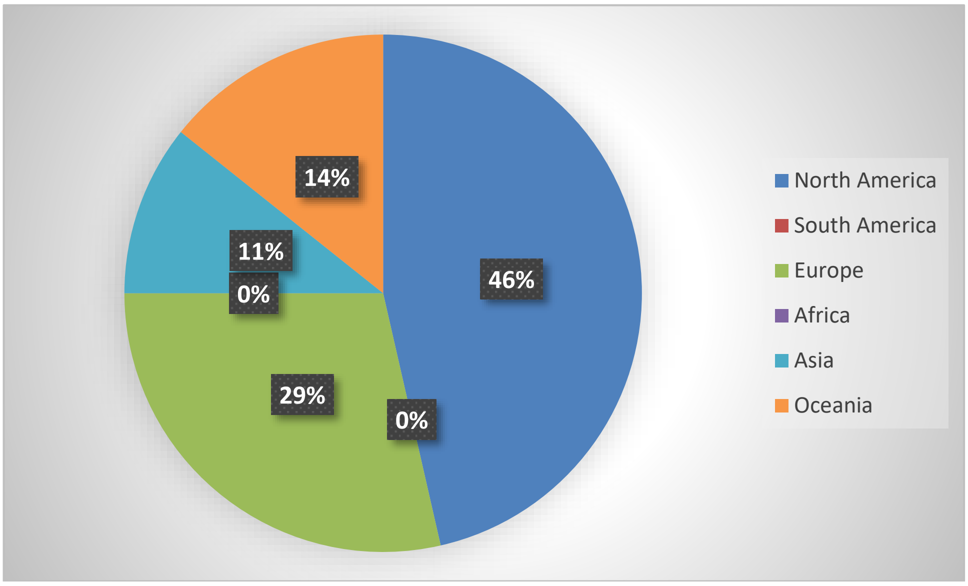


Figure 5-1. Registered continents of respondents.

Figure 5-1 shows participation from most continents. The bulk of respondents comes from North America and Europe, which is not surprising, as the survey was distributed mainly to these continents. Some responses were also received from Asia and Oceania, while none came from Africa or South America (although there were representatives from these regions in the survey mailing list).

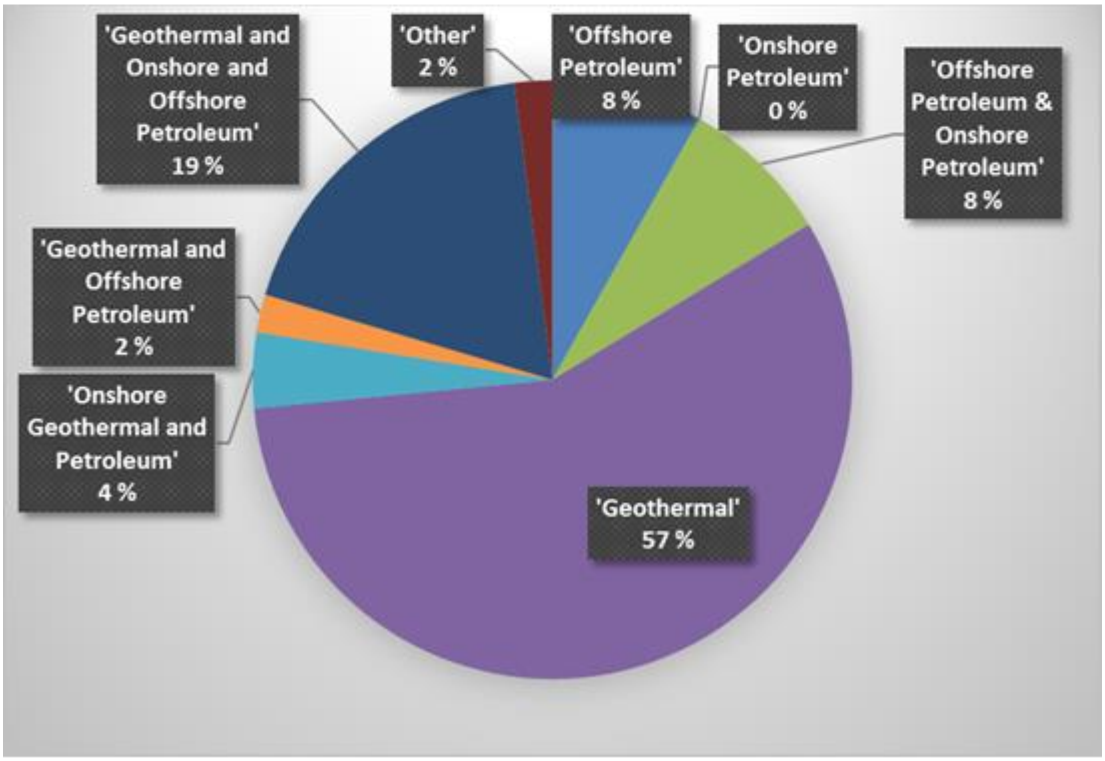


Figure 5-2. Industry as categorized by the respondents.

Most of the responses came from the geothermal industry, probably due to the survey being posted on geothermal websites and being sent to more geothermal industry contacts. Many of the traditional petroleum companies also defined themselves as involved in geothermal, while few categorized themselves as pure petroleum companies. 35% of the respondents were involved in offshore petroleum, which is expected to have stricter regulations due to the larger consequences of potential spills, limited area and the lack of escape opportunities for personnel. None of the companies was only working in onshore petroleum. 14% stated they worked only in petroleum, without any activity in geothermal.

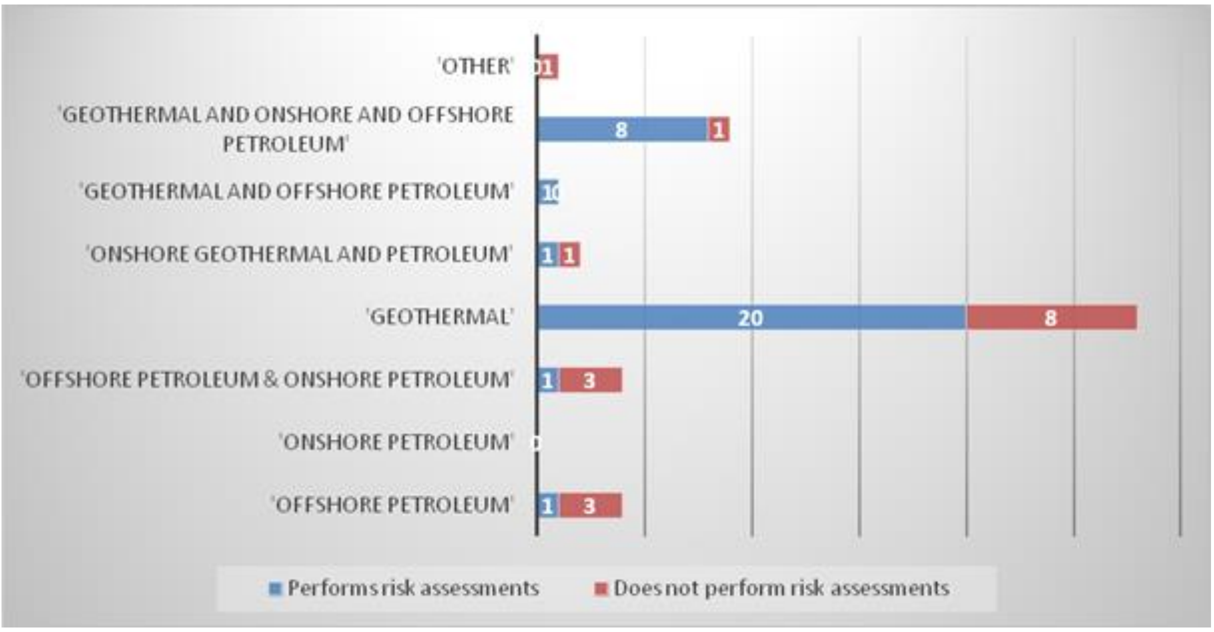
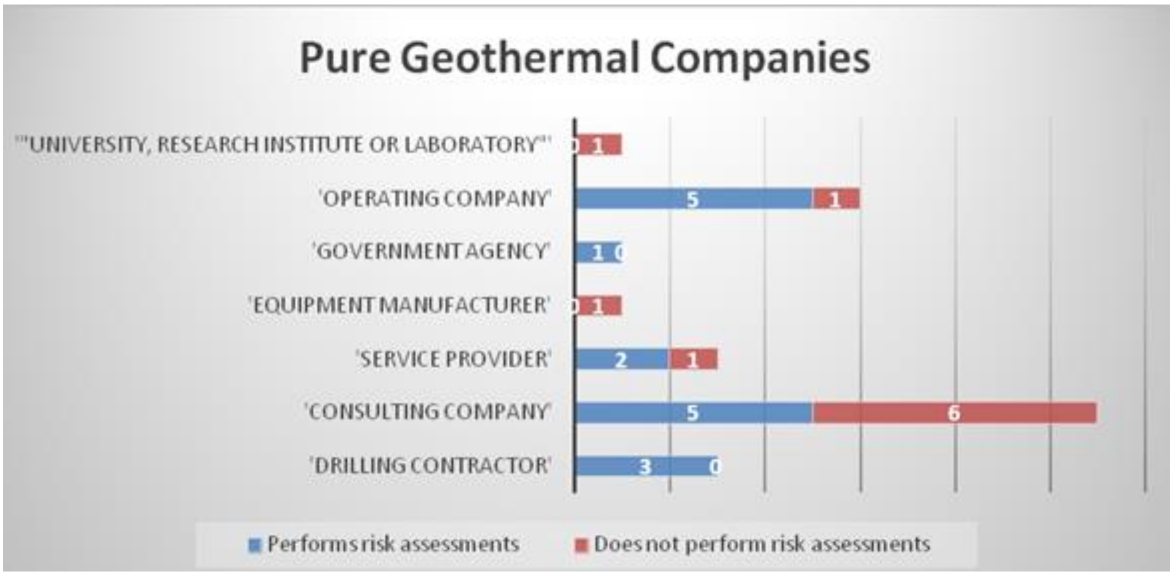


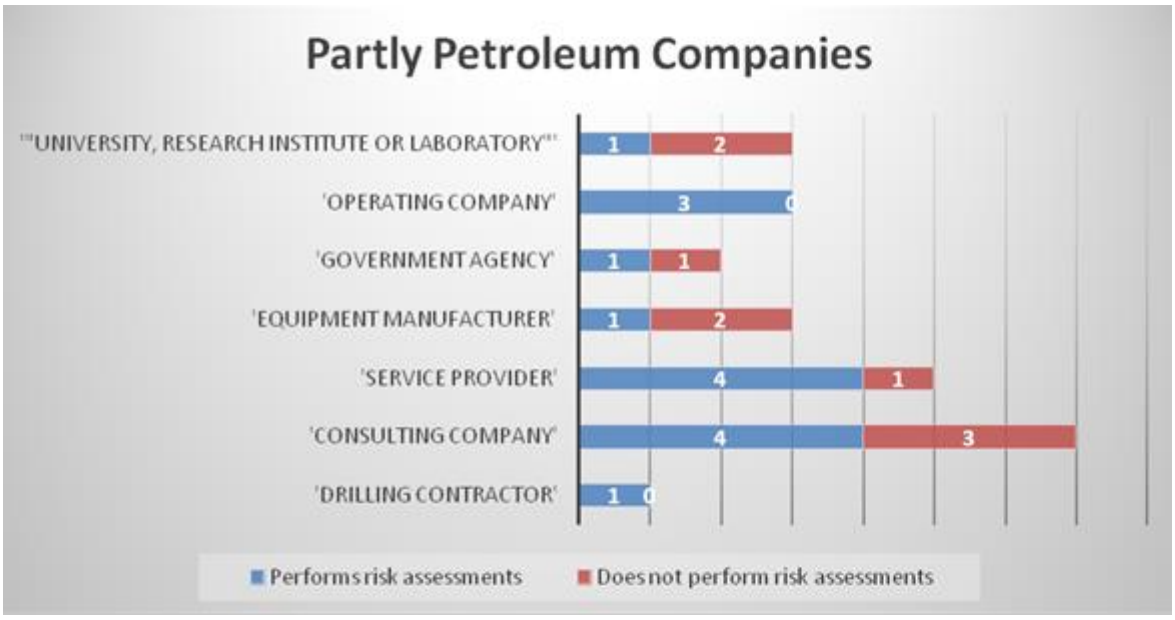
Figure 5-3. Breakdown of respondents performing risk assessments on wells per industry.

Figure 5-3 aims to show who actually finished the survey completely, and answered "yes" to the question of whether or not they perform risk assessments for wells. This figure shows that none of those classifying themselves as working only within the petroleum either finished the survey or performed risk assessments for wells. As these will not give any input on which methods they use, the survey will not be able to provide information about the use of risk assessment used only in the petroleum industry. Thus, in the subsequent sub-sections investigating the used risk assessment methods, the industry will be divided into pure geothermal companies and companies involved in both petroleum and geothermal. The assumption here is that companies involved in both will have its origin from the petroleum industry, and use the same risk assessment methods for both petroleum and geothermal wells.

As many of the respondents of the survey are not performing risk assessments related to wells, it could be interesting to see which types of companies performs the risk assessments in geothermal and petroleum industries. This is shown in Figure 5-4 (a and b) that also shows which types of companies have responded to the survey. No real difference between the industries can be seen.



(a)



(b)

Figure 5-4. Breakdown of the respondents based on company type, and whether or not they perform risk assessments of wells; (a) From geothermal company, and (b) From petroleum company (possibly in addition to geothermal).

Many of the respondents categorized themselves in several of the company categories. The first order combinations can be seen in Figure 5-5. This shows that there is no mixing between governmental agencies and the industry. In most cases, the operators also seem to be a focused business with a single core area. To simplify later analyses, in the subsequent sub-sections the companies will be divided into three separate entities: operators, regulators (academic and governmental agencies), and “other” companies (service providers, consulting companies, drilling contractors and equipment manufacturers).

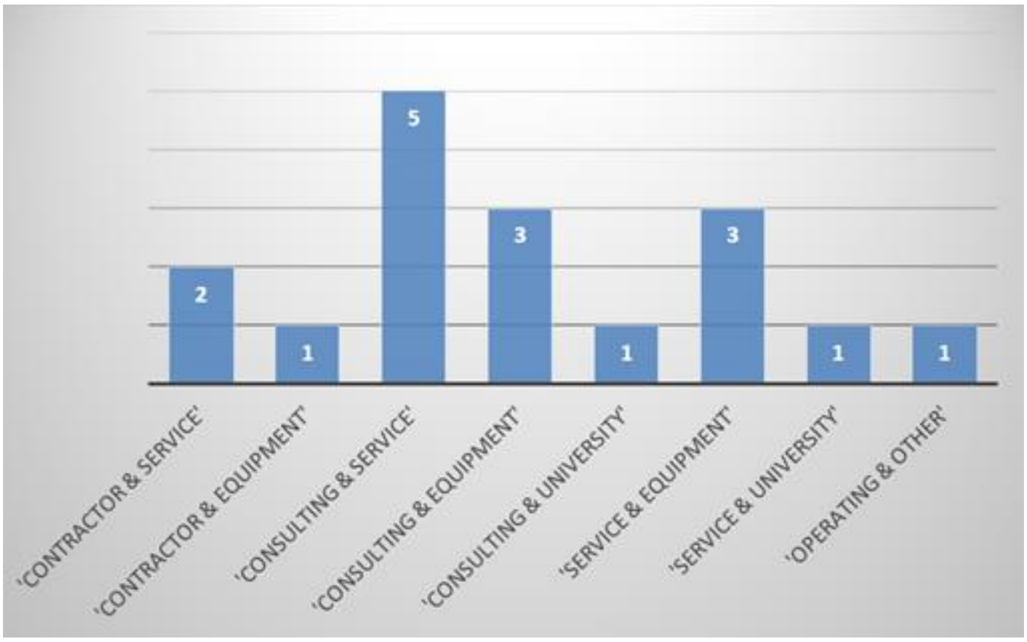


Figure 5-5. Company categories selected together.

5.2.2 Risk methods overview

Only the respondents who fully completed the questionnaire and selected that their company was performing risk assessments related to wells is considered with respect to which methods they apply. These respondents are divided into two groups: the “geothermal” group that consists of those working only in the geothermal industry (i.e. no activity in the petroleum industry), and the “petroleum” group, where at least “offshore petroleum” or “onshore petroleum” was selected, often in combination with “onshore geothermal”, as was explained in the previous sub-section. The groups consist of 15 and 10 respondents, respectively. Regarding the selection of risk methods, there were no limitations on how many methods could be selected.

Figure 5-6 shows the methods used during risk identification. Brainstorming is the most popular method, used by almost 80% of the respondents, with checklists a bit less common, with an overall use just above 50%.

The overall trends between geothermal and petroleum seems similar, where the methods frequently used in petroleum are also the more frequently used methods in geothermal. However, every individual method is used more frequently in petroleum than it is in geothermal. This means that the respondents from the petroleum related industry have selected more methods than the respondents from the geothermal industry. An interpretation of these responses is that the petroleum related industry uses a wider range of methods. The only method not used by anyone for risk identification is reliability centred maintenance (RCM).

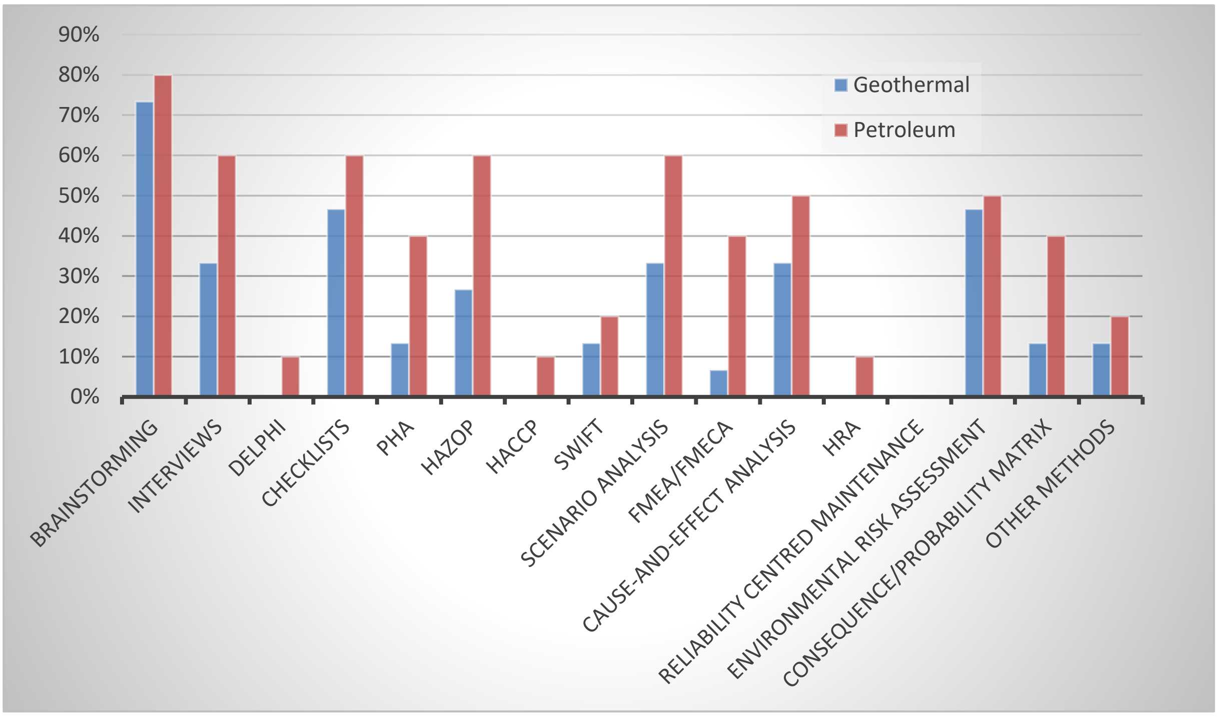


Figure 5-6. Overview of methods used for risk identification.

The same general trend can be seen in Figure 5-7 related to the risk analysis methods used. In particular, FMEA/FMECA, FTA, ETA and bow-tie analysis are frequently used by the petroleum respondents, but not by the geothermal respondents. Likely this is largely due to the areas they apply these risk analysis methods, as is seen in sub-section 5.2.3.

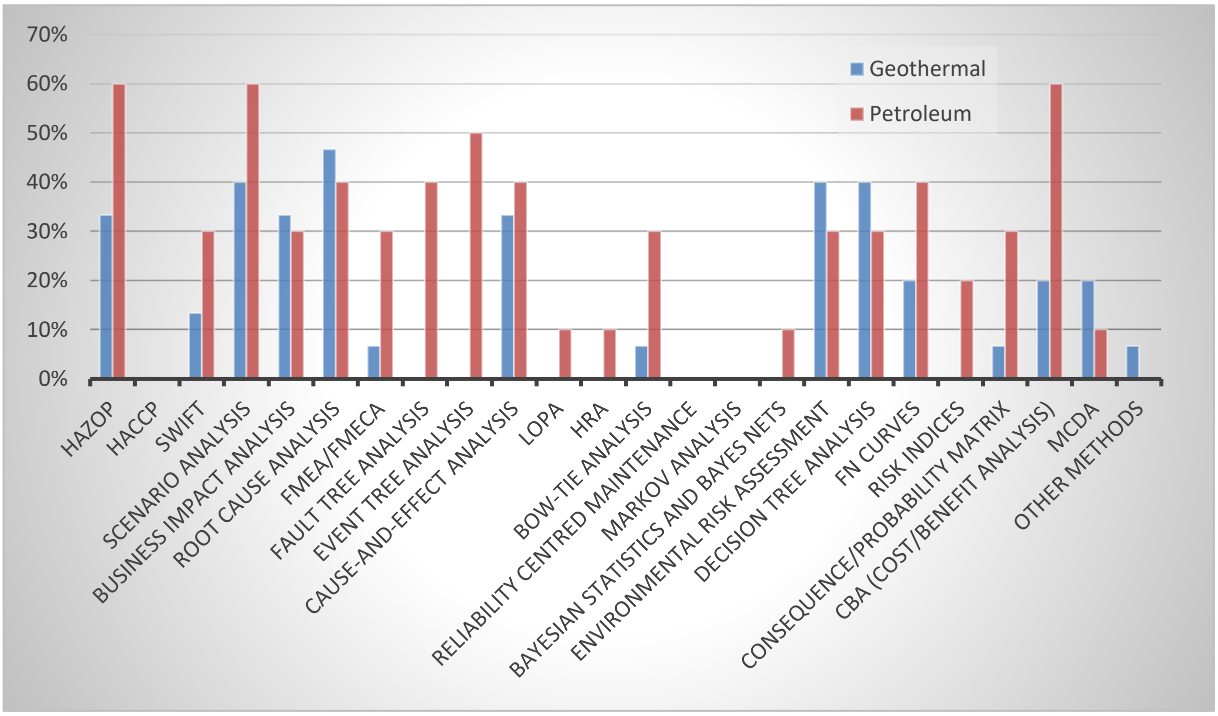


Figure 5-7. Overview of methods used for risk analysis.

For the risk evaluation, shown in Figure 5-8, the trend is less clear. The geothermal respondents use methods that the petroleum respondents do not use, and vice versa. It is significant to note that half of the petroleum respondents and one from geothermal did not find their used methods sufficiently listed in the suggested methods. These other methods are “top-set”, “risk matrices and risk tolerance criteria”, “risk register”, “hazard Identification risk assessment and controls (HIRAC)”, “extreme event statistics” and “formal quantitative risk analysis”. The ISO terminology is not always well understood or even commonly used. For example, “consequence/probability matrix” would commonly be understood as a risk matrix.

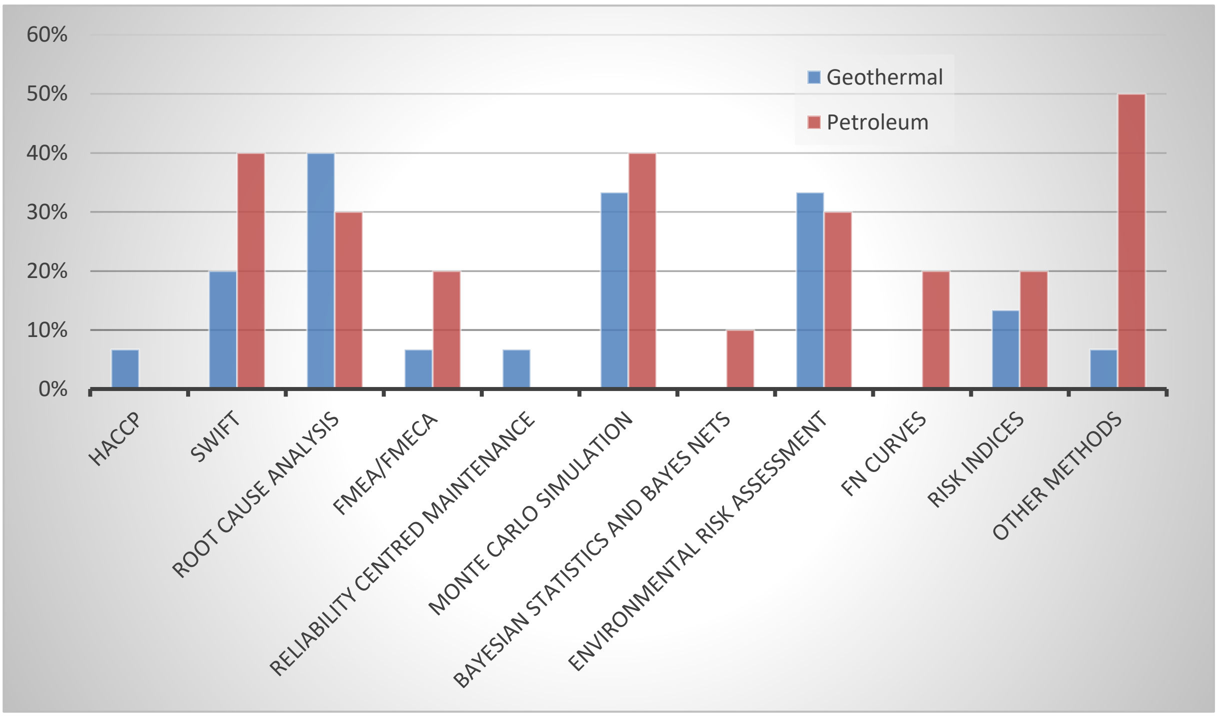
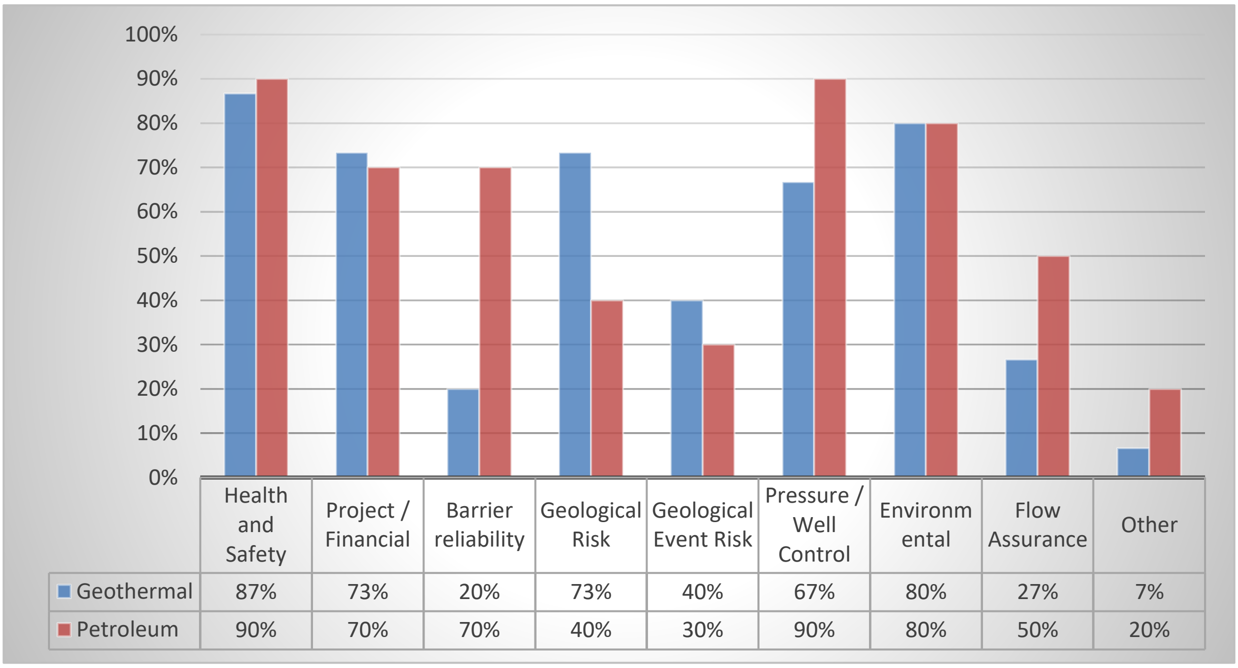


Figure 5-8. Overview of methods used for risk evaluation.

5.2.3 Areas of application

Risk assessments are performed for different purposes. Figure 5-9 shows how many of the respondents perform risk assessment in the previous defined areas. There is no difference between those in the “geothermal” group and those in the “petroleum” group in the areas of health and safety, environmental and project/financial risk. This is reasonable, as these are important for any activity. However, a significant difference can be seen for barrier reliability, and a smaller difference for well control. These seem to be more important in the petroleum industry than in the geothermal industry. This is further emphasized by the two “petroleum” respondents in the “other” category, which both responded to assess well integrity. The geothermal industry, on the other hand, has a larger focus on geological risk and geological event risk. Flow assurance is another category that is more prevalent in the petroleum industry.



	Health and Safety	Project / Financial	Barrier reliability	Geological Risk	Geological Event Risk	Pressure / Well Control	Environm ental	Flow Assurance	Other
Geothermal	87%	73%	20%	73%	40%	67%	80%	27%	7%
Petroleum	90%	70%	70%	40%	30%	90%	80%	50%	20%

Figure 5-9. Percentage of respondents performing risk assessments in different areas of application, comparing the geothermal and the petroleum industries.

Differences in which risk identification methods are applied within each of these areas is shown in Figure 5-10. The bars are shown as the percentage of respondents using the method out of all the respondents performing risk assessments in that area. Thus, 44% using cause-and effect analysis for flow assurance means four of nine respondents (refer to Appendix II for number of respondents) performing risk assessment related to flow assurance use cause-and-effect analysis for this purpose.

The most commonly used method is brainstorming, which is applied by almost 70% of all the respondents. The lower use in geological event risk might be due to fewer responses within this area, but should also be seen in context of the increased use of checklists. Interviews are also fairly often used for risk identification, while only a few respondents use the more advanced Delphi method. Structured what-if technique (SWIFT) analysis sees some use in all areas, but not much.

Comparing between the two industries, shows that the greatest difference in terms of area of application for risk identification methods, is for geological risk and geological event risk, quite a bit higher for petroleum than geothermal, as seen in Figure 5-11 a) and b). Generally, the proportion of methods used is higher for all areas of application for petroleum than for geothermal.

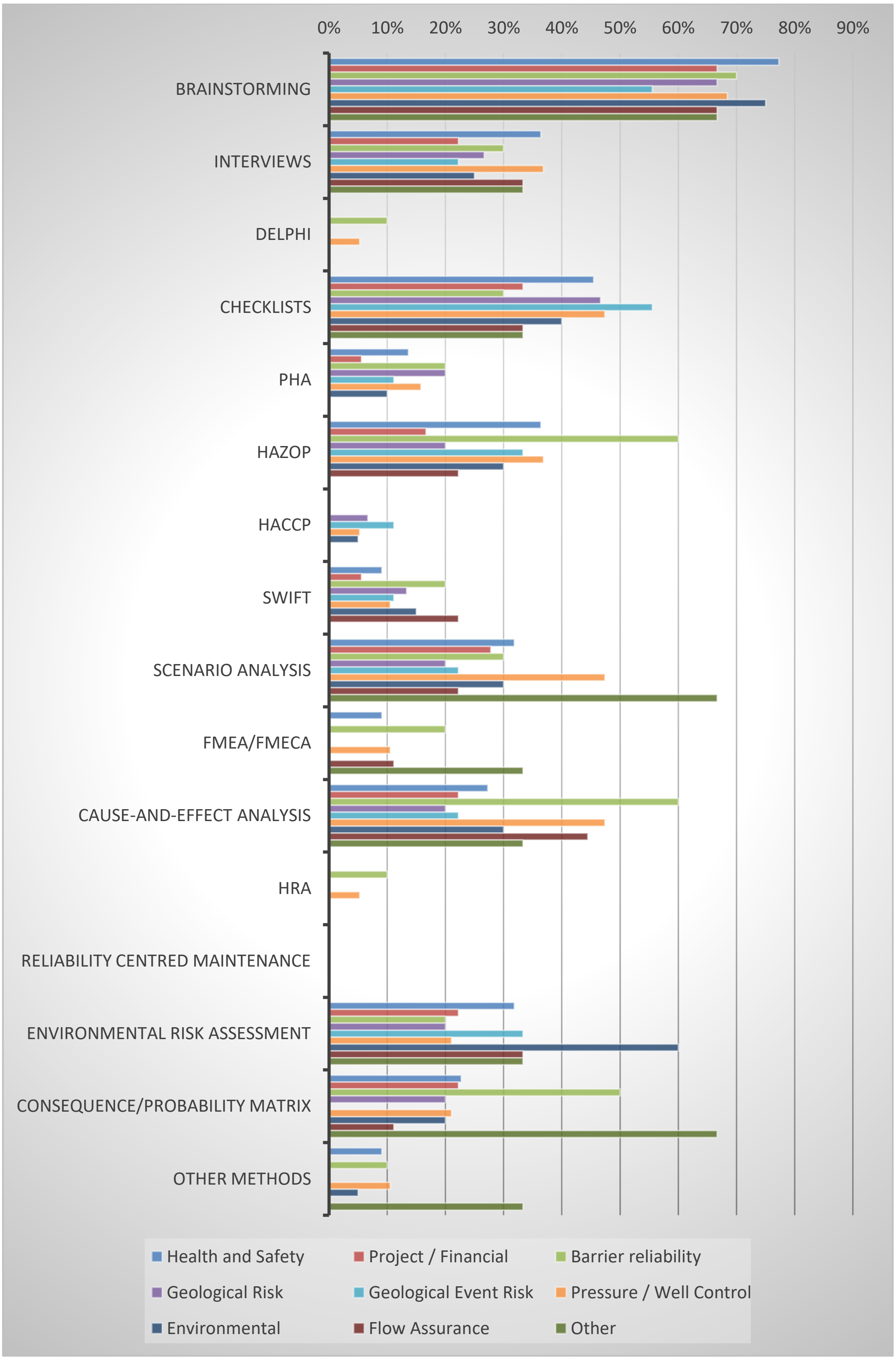


Figure 5-10. Risk identification methods used by the respondents, broken down on application areas.

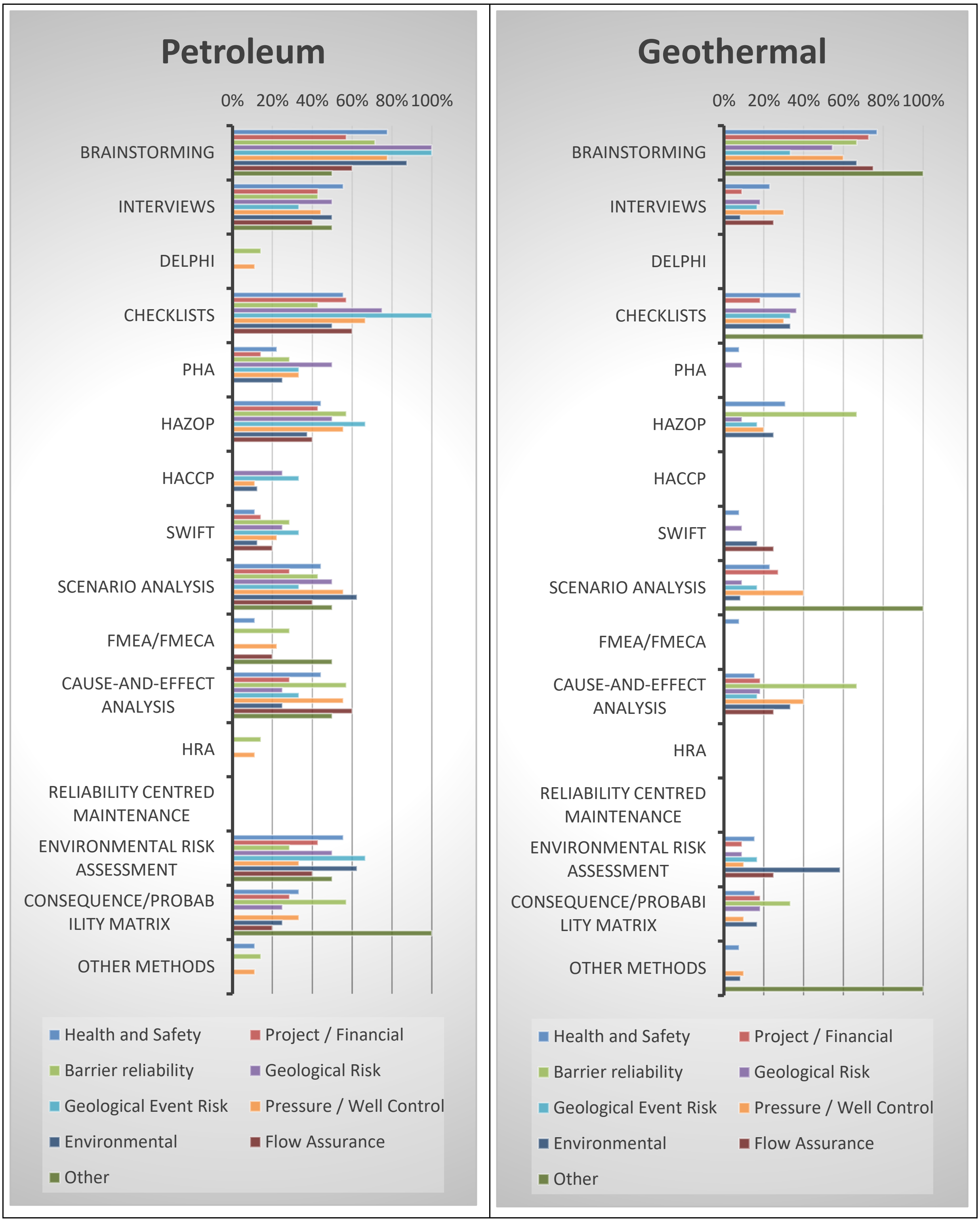


Figure 5-11 a) Risk identification methods used by the petroleum respondents, broken down on application areas, and b) Risk identification methods used by the geothermal respondents, broken down on application areas

The human reliability analysis (HRA) method is also hardly used, and only applied within barrier reliability and well control. The consequence/probability matrix method, such as risk matrices, is also used for risk identification, but only sees a significant use in barrier reliability and well integrity (“other”).

The use of checklists is a popular method within all areas, although it is less used in project/financial risk, barrier reliability and flow assurance. Preliminary hazard analysis is another method with some use in all areas except for flow assurance. However, the use is limited. HAZOP seems to be an established method frequently used, in particular related to barrier reliability and well control, geological event risk, health and safety, and environmental risk. HACCP sees only limited use.

FMEA/FMECA is a well-known method within the reliability domain, which is reflected by its use in barrier reliability and well integrity ("other"). There is also some use related to health and safety, well control and flow assurance. However, the method is not frequently used even in these areas. The respondents do not use RCM for the purpose of risk identification.

Scenario analysis and cause-and-effect analysis are both used by more than 20% of the respondents. The highest usage is within well control and related to well barriers. Environmental risk assessment (ERA) is mostly used within environmental risk, as expected. However, it is used by more than 20% of the respondents in the other categories as well.

Figure 5-12 shows the methods used for risk analysis for each of the applications. Many methods used for risk analysis are also used for risk identification, such as HAZOP, HACCP, SWIFT, scenario analysis, FMEA/FMECA, cause-and effect analysis, HRA, RCM, ERA and consequences/probability matrix. There are some differences with respect to how much they are used compared to risk identification, though we will not go into details here. Of methods not discussed in the risk identification section are methods such as business impact assessment, which is used to some degree in all areas. The methods FTA and ETA are used for barrier reliability and well integrity, but are used very little elsewhere. Bow-tie analysis is used in a similar way, but is also used for geological event risk. LOPA and RCM are barely used, as is Markov analysis. Bayesian statistics and Bayesian nets are also used to a very low degree, and mostly related to barriers. Decision tree analysis and FN-curves are used for a wider range of areas of applications. Risk indices and MCDA are also not much used, and risk indices are mostly applied to barrier reliability and well control. Cost/benefit analysis (CBA) is a very popular method, used by more than 25% of respondents in all the areas.

Comparing between the two industries, shows that the greatest difference in terms of area of application for risk analysis methods, is for barrier reliability and other areas, somewhat higher for petroleum than geothermal, as seen in Figure 5-13 a) and b). Generally, the proportion of methods used is higher for all areas of application for petroleum than for geothermal.

Fewer methods have been listed for risk evaluation, and the use of the methods can be seen in Figure 5-14. The only method not previously included in risk identification and risk analysis is Monte Carlo simulation, which seems to be the most popular method according to Figure 5-14. It is much used both for project/financial risk and activities related to well integrity.

Comparing between the two industries, shows that the greatest difference in terms of area of application for risk evaluation methods, is for barrier reliability and other areas, somewhat higher for petroleum than geothermal, as seen in Figure 5-15 a) and b). Generally, the proportion of methods used is higher for all areas of application for petroleum than for geothermal.

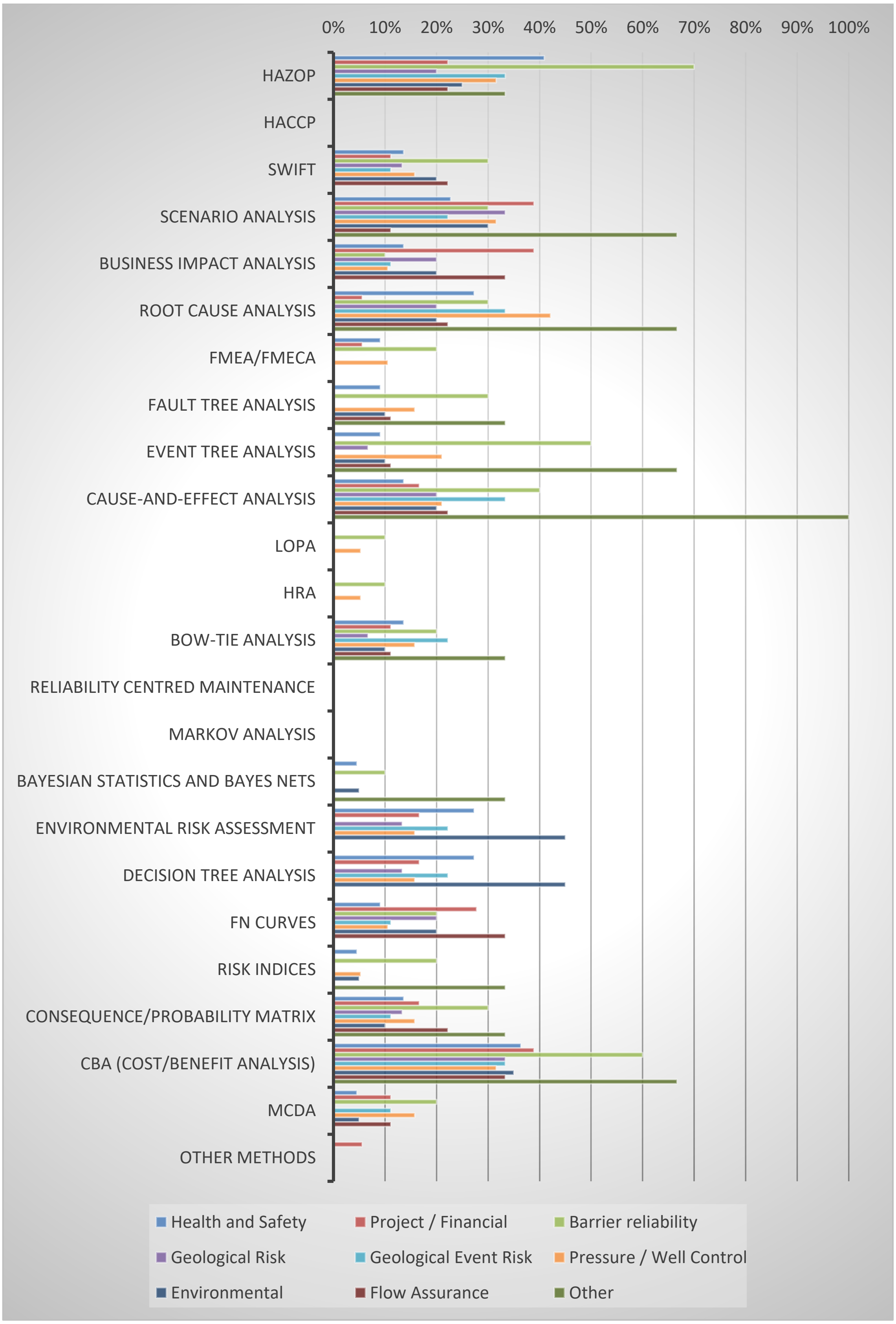
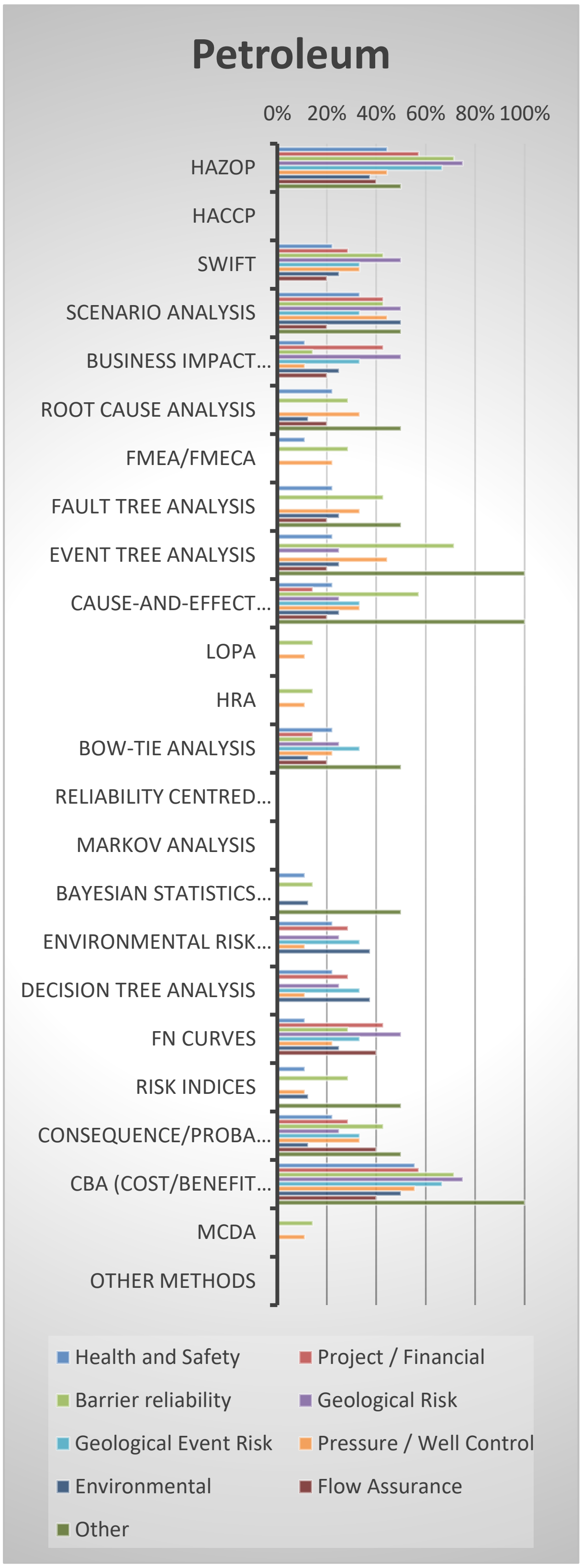


Figure 5-12. Risk analysis methods used by the respondents, broken down on application areas.



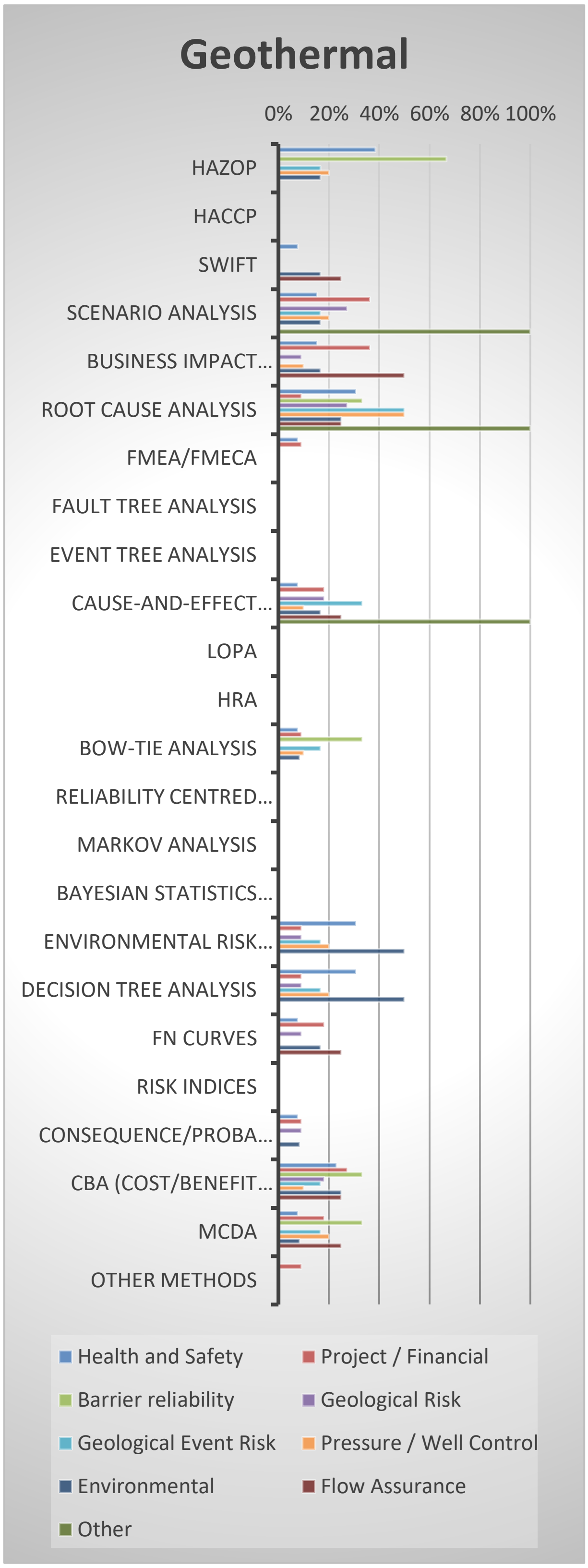


Figure 5-13 a) Risk analysis methods used by the petroleum respondents, broken down on application areas and b) Risk analysis methods used by the geothermal respondents, broken down on application areas

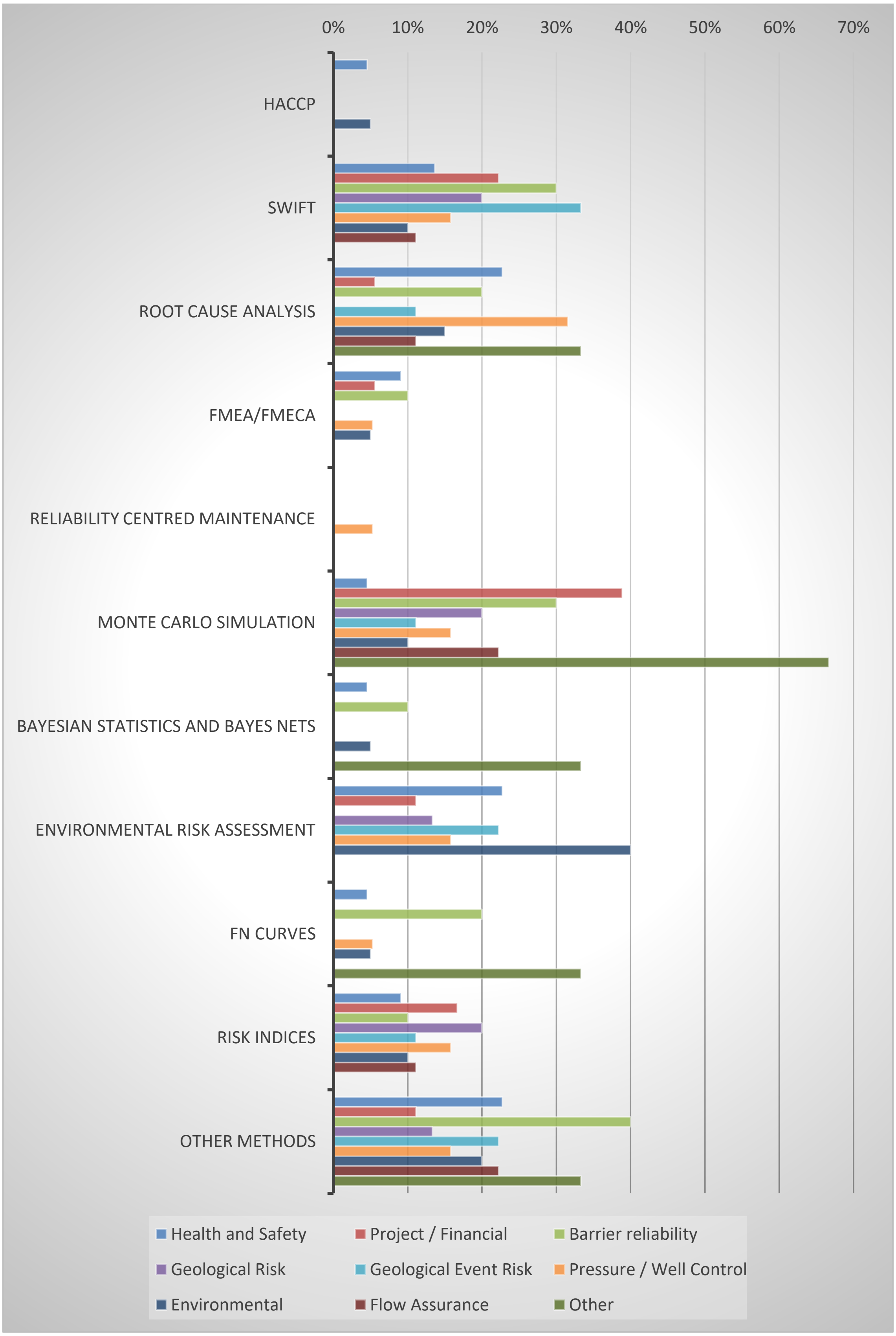


Figure 5-14. Risk evaluation methods used by the respondents, broken down on application areas.

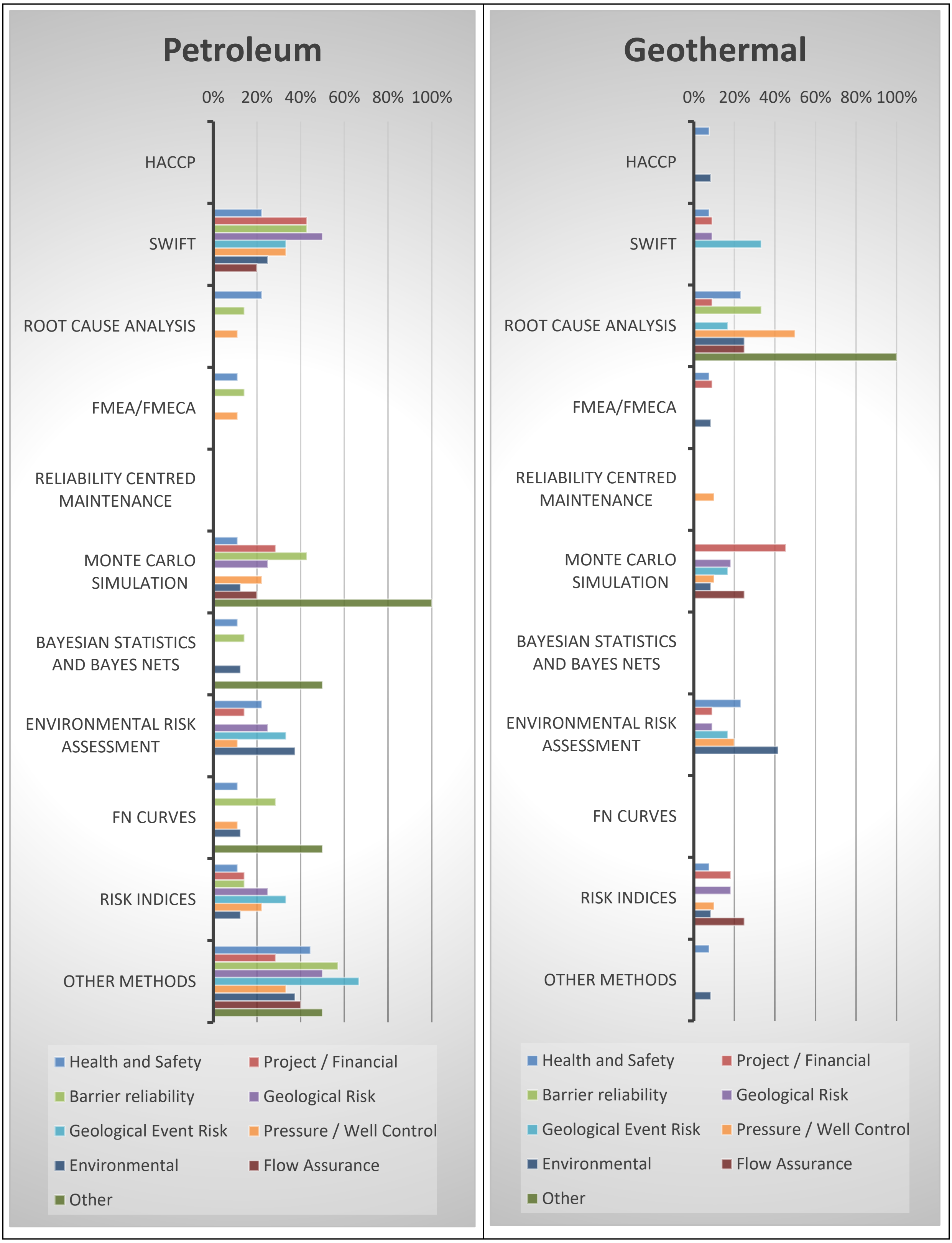


Figure 5-15 a) Risk evaluation methods used by the petroleum respondents, broken down on application areas and b) Risk evaluation methods used by the geothermal respondents, broken down on application areas

5.2.4 Well life cycle phases

The GeoWell risk assessment survey also requested the recipients to define which methods they applied in different phases of a well's lifecycle (see Figure 1-1, excluding plug and abandonment). The findings of these questionnaire results have to some extend already been covered in the discussion of areas of application in the previous section, and is not repeated here. The results are shown in Figure 5-16 through Figure 5-22, and are given as the percentage of respondents who used methods for the particular phase.

As shown in Figure 5-16, almost all of the respondents applied methods to drilling, while about 60-80 % applied methods to the other phases. Thus, there is a focus on the drilling phase among the respondents. No clear difference between the petroleum and geothermal respondents can be found in this case.

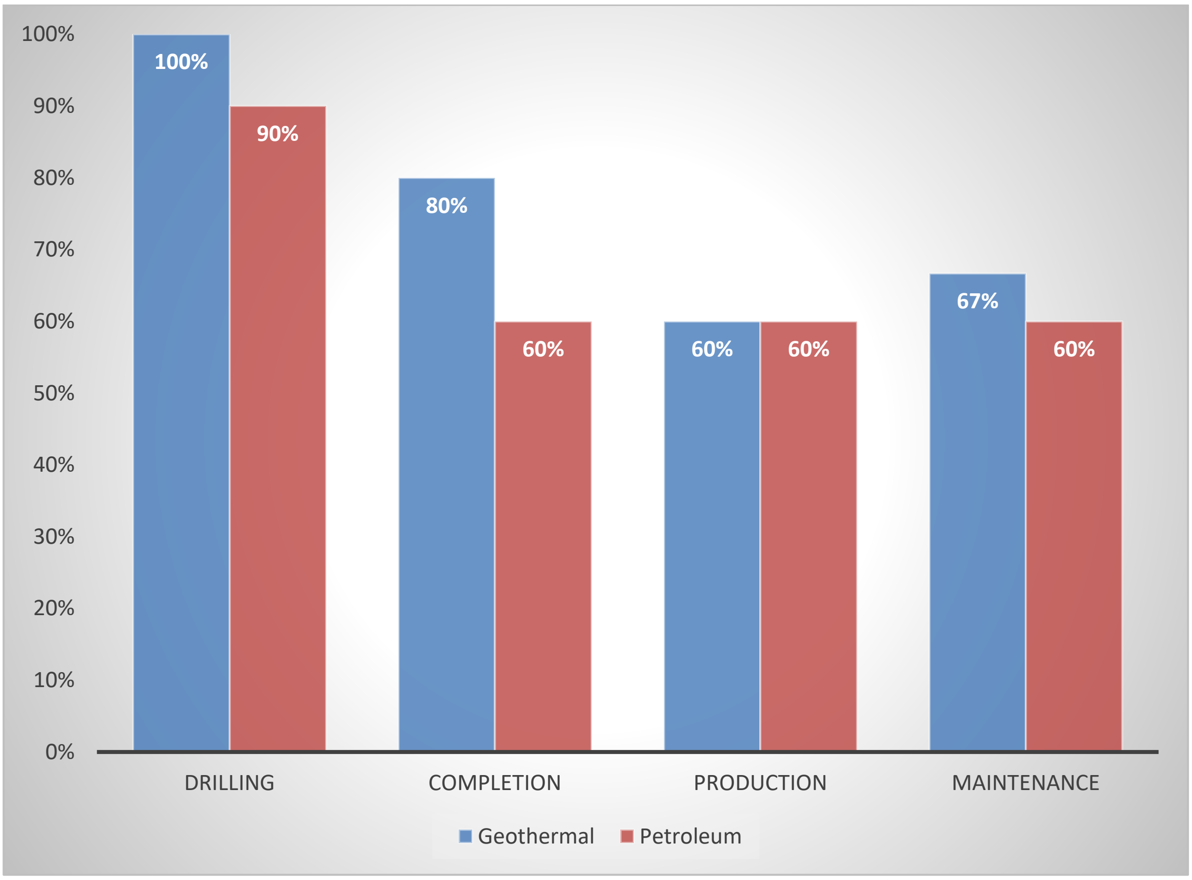


Figure 5-16 Portion of respondents applying one or more risk assessment methods for each of the life cycle phases, split into petroleum and geothermal respondents.

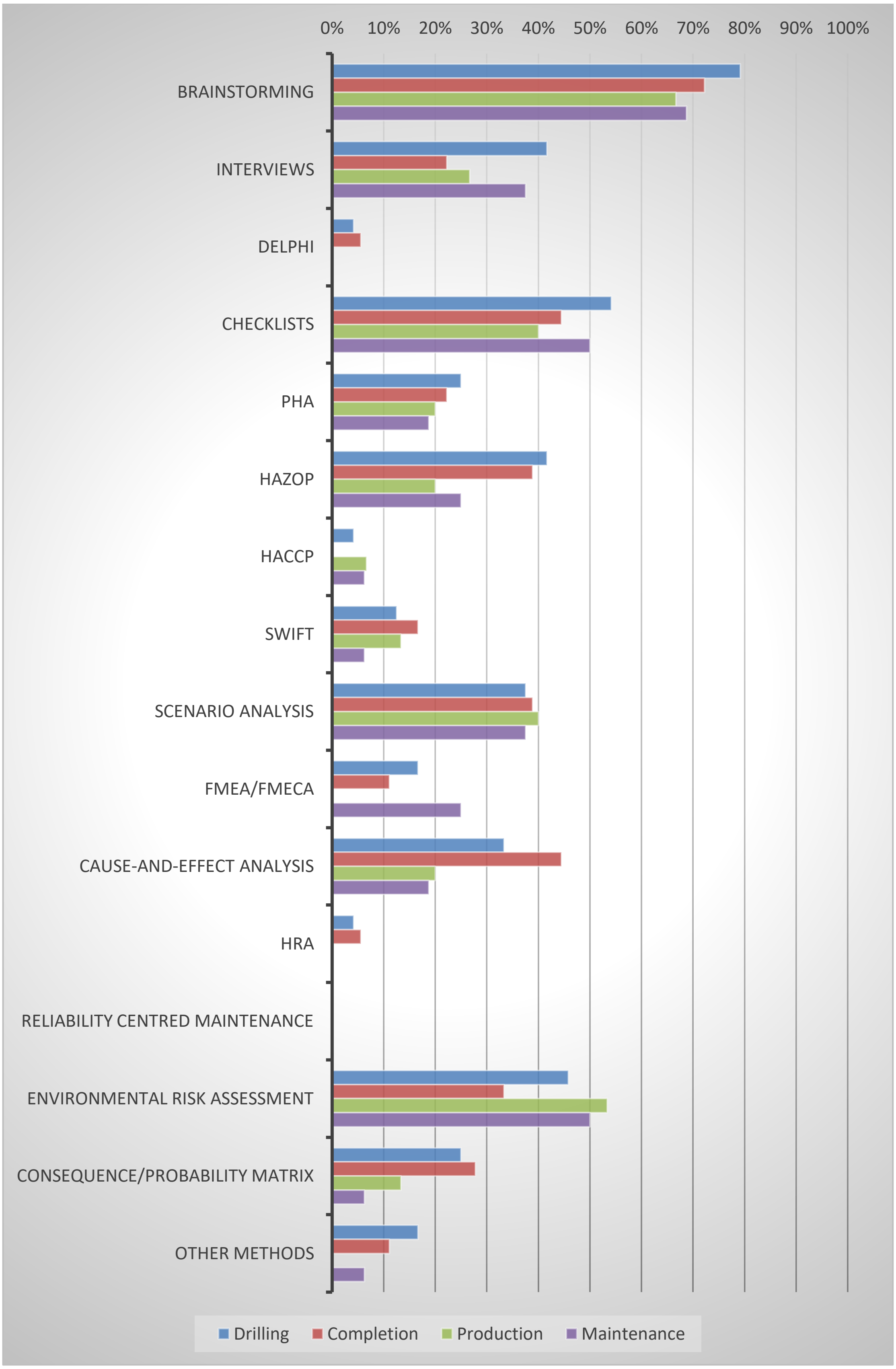


Figure 5-17. Overview of methods respondents used for risk identification, broken down on well phases.

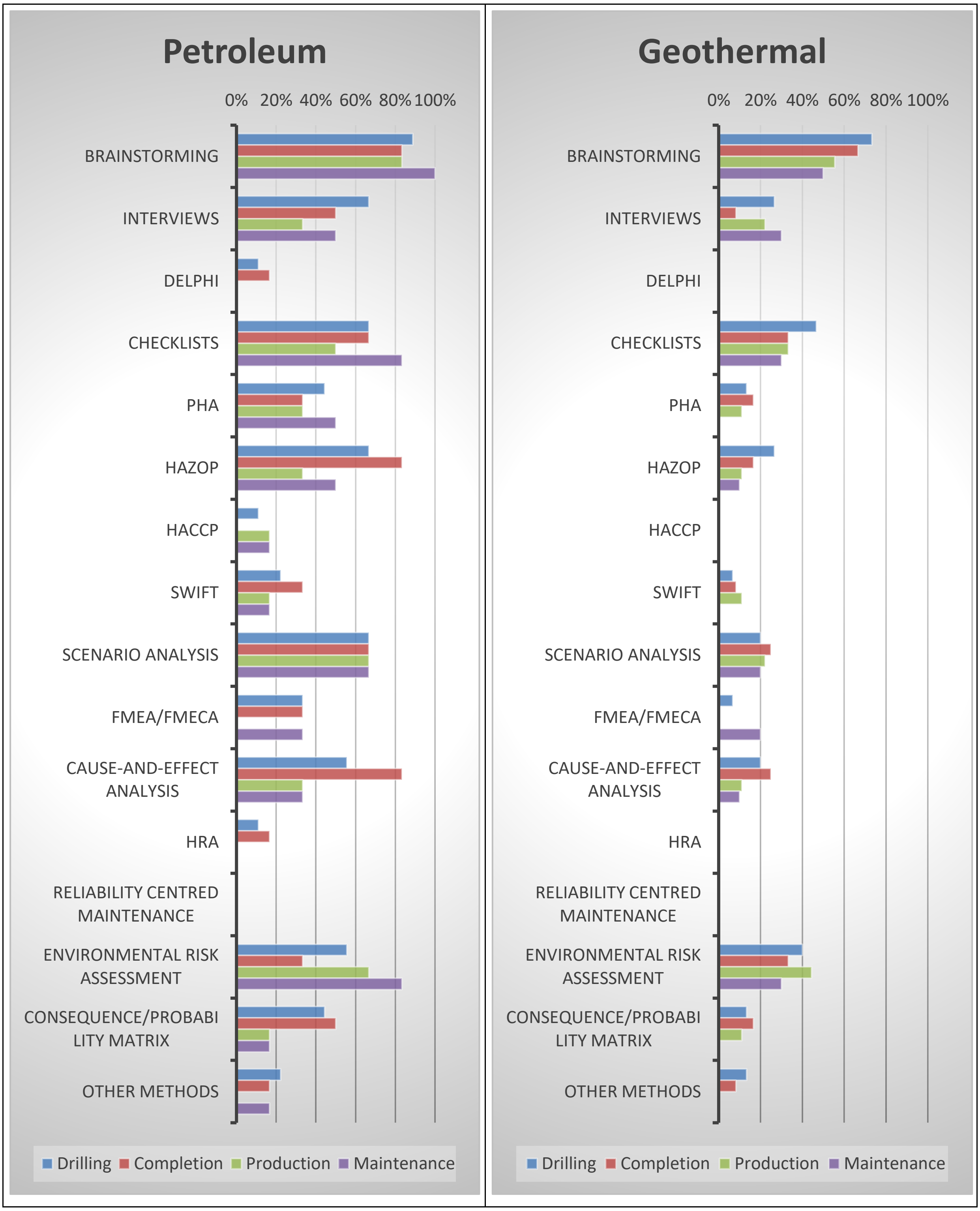


Figure 5-18 a) Overview of methods petroleum respondents used for risk identification, broken down on well phases, and b) Overview of methods geothermal respondents used for risk identification, broken down on well phases

Comparing the proportions of Figure 5-18 a) and b), suggests a higher share of application in the petroleum industry than in the geothermal area for nearly all risk identification methods. The differences are largest for HAZOP, scenario analysis and cause-and-effect analysis.

As earlier stated, the three most used methods for risk identification, all life cycle phases considered, are brainstorming, checklists and environmental risk assessment. This is also the case for Drilling, Production and Maintenance. Completion differs only in that cause-and effect analysis is more frequently used than environmental risk assessment.

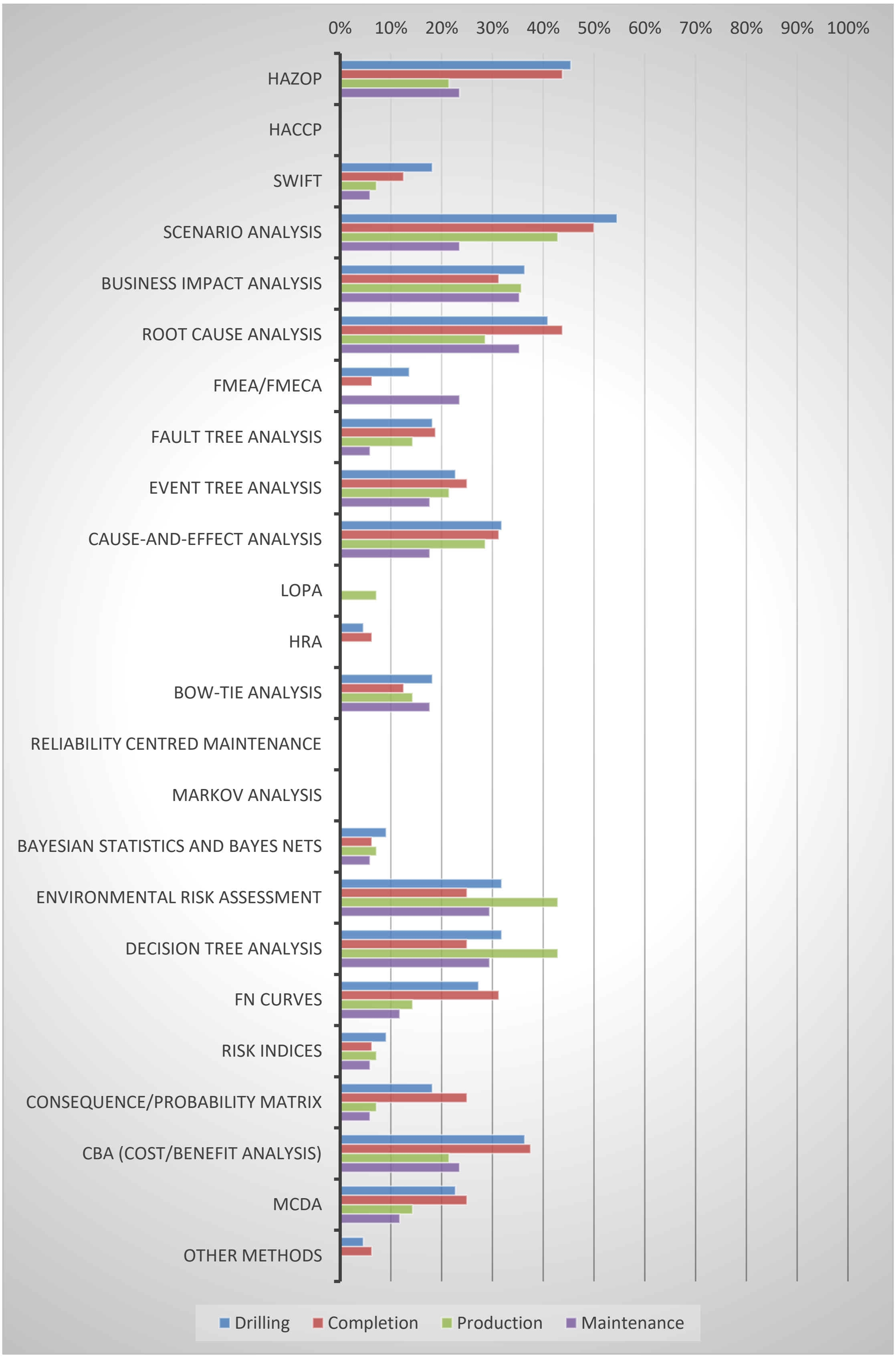


Figure 5-19. Overview of methods respondents used for risk analysis, broken down on well phases.

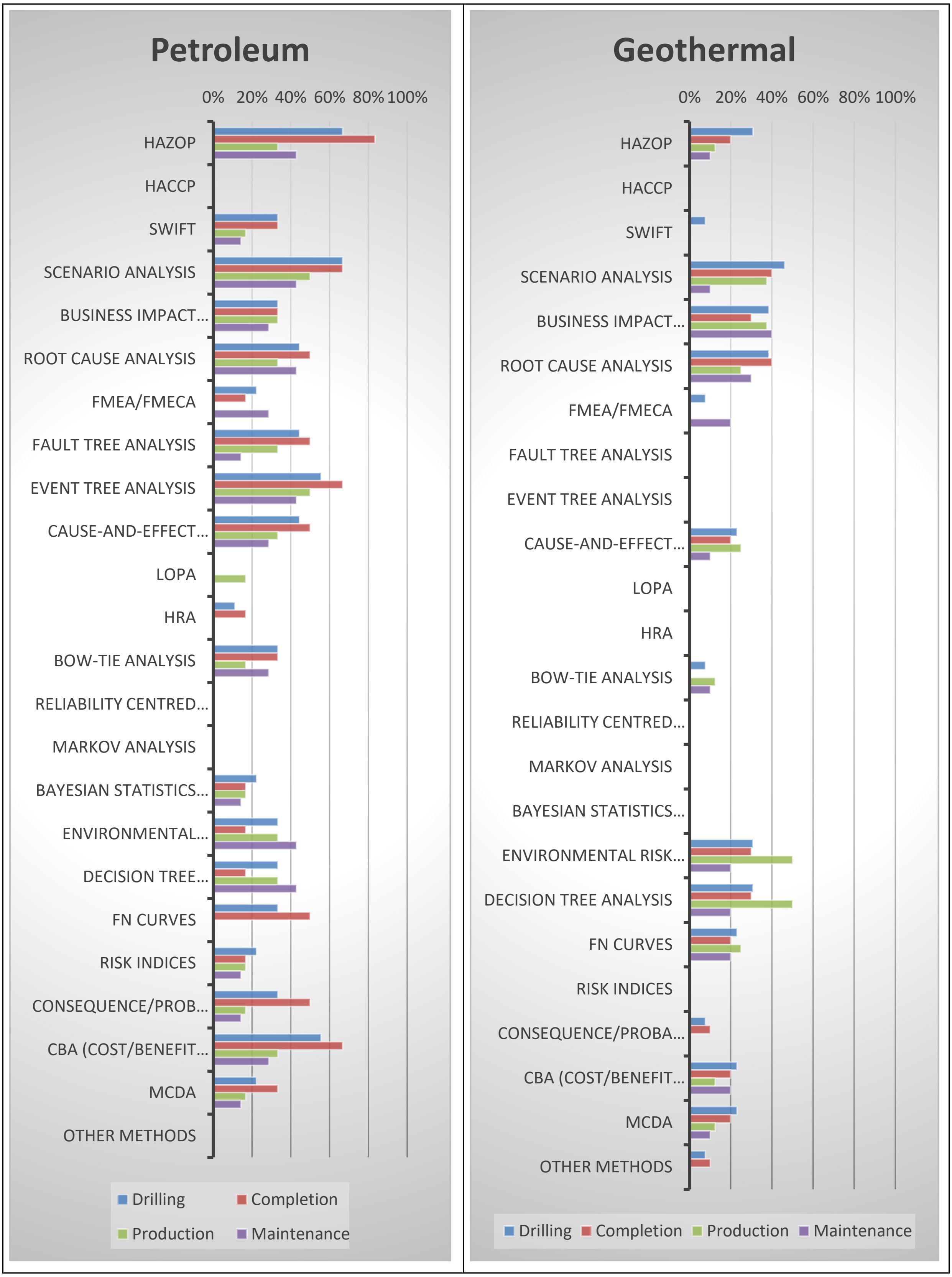


Figure 5-20 a) Overview of methods petroleum respondents used for risk analysis, broken down on well phases and b) Overview of methods geothermal respondents used for risk analysis, broken down on well phases

Comparing the proportions of Figure 5-20 a) and b), suggests a higher share of application in the petroleum industry than in the geothermal area for roughly 2/3 of all risk analysis methods. The differences are largest for event tree analysis, HAZOP, and fault tree analysis. Business impact analysis and other methods are slightly more frequently used in the geothermal risk analyses, judging from the survey.

The three most used methods for risk analysis, all life cycle phases considered, are scenario analysis, root cause analysis and business impact analysis. For Drilling and Completion, HAZOP is more frequently used than scenario analysis. For Production, environmental risk analysis and decision tree analysis are more used than either root cause analysis and business impact analysis, while for Maintenance, these same two methods are more used than scenario analysis.

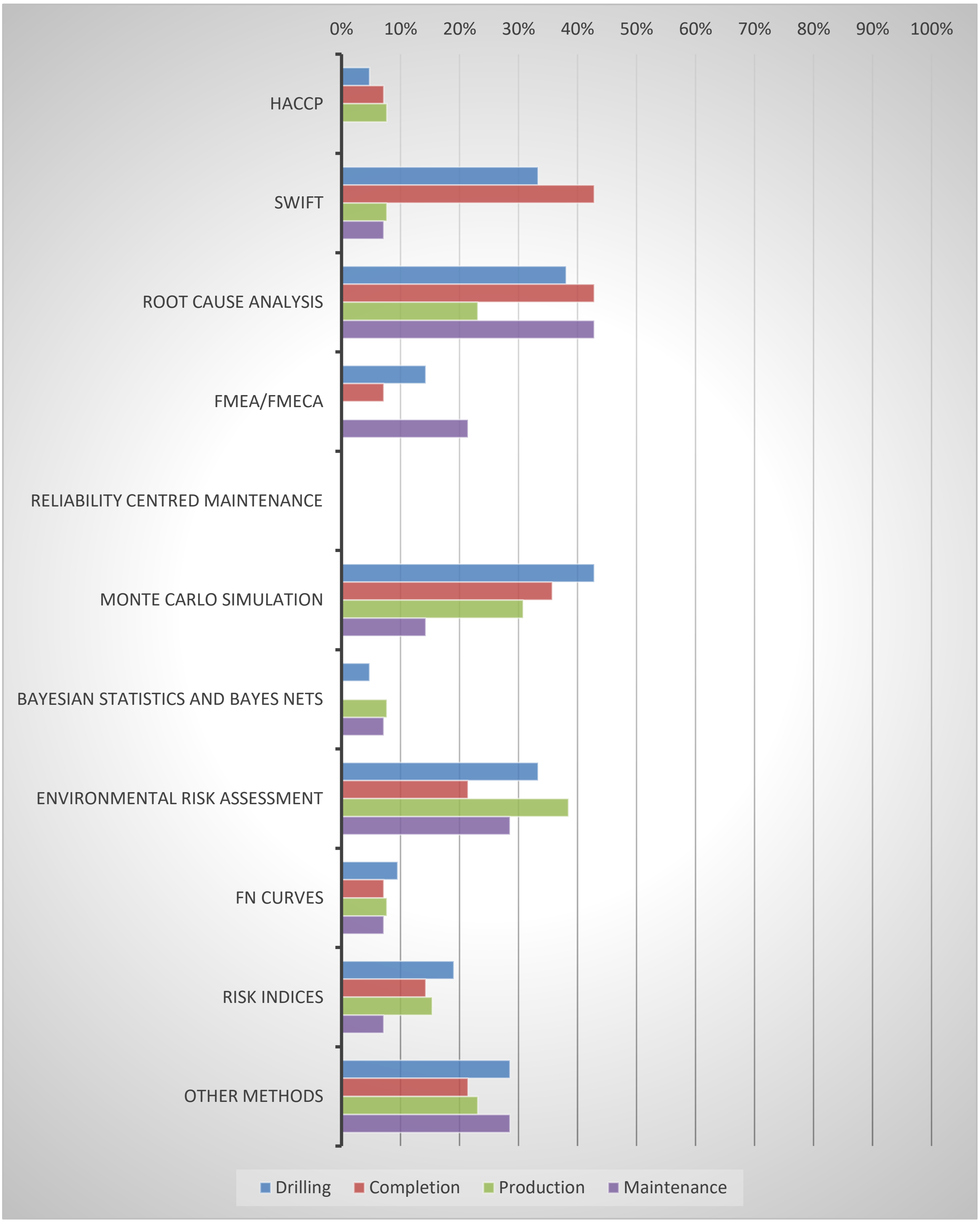


Figure 5-21. Overview of methods respondents used for risk evaluation, broken down on well phases.

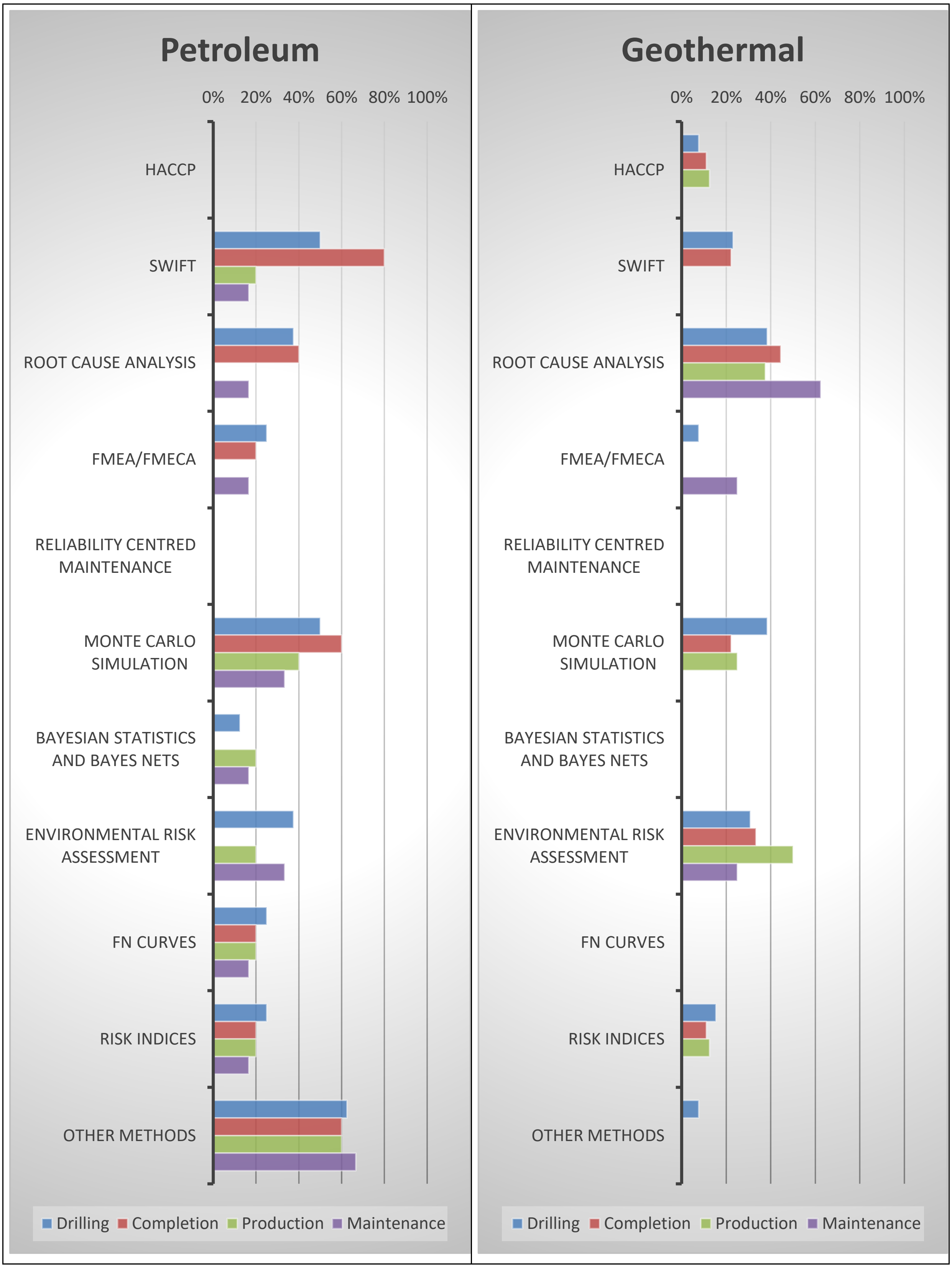


Figure 5-22 a) Overview of methods petroleum respondents used for risk evaluation, broken down on well phases, and b) Overview of methods geothermal respondents used for risk evaluation, broken down on well phases

Comparing the proportions of Figure 5-22 a) and b), suggests a higher share of application in the petroleum industry than in the geothermal area for roughly 2/3 of all risk evaluation methods. The differences are largest for other methods, SWIFT analysis and Monte Carlo simulation. Root cause analysis and environmental risk analysis are more used for geothermal applications, judging from the survey.

The three most used methods for risk evaluation, all life cycle phases considered, are root cause analysis, Monte Carlo simulation and environmental risk assessment. This is also true for Drilling, where additionally also SWIFT analysis is used. Completion is similar to Drilling, although SWIFT analysis is somewhat less used. Other methods are also among the most frequently used for the Production and Maintenance phase.

5.3 Summary of the analysis

A literature review and a questionnaire analysis have been performed to investigate differences in how the various industries approach risk assessments. While the literature gives a more detailed description of examples than a questionnaire can provide, the questionnaire will give a better representation of what is actually done in the industries. This summary also includes findings from the geothermal literature review reported in D6.1.

From the results, no clear distinction in terms of who performs risk assessments could be found when comparing the geothermal and petroleum industries. Almost all operating companies are performing them without distinction between the geothermal and petroleum sectors; service providers, consulting companies and drilling contractors perform assessments with similar trends between the two industries, as was seen in Figure 5-4.

The dominant area of application in the literature is project and financial risk assessments. This is also highly focused on in the questionnaire, like in the areas of health and safety, pressure/well control and environment which are equally or even more focused on project and financial risks. The high focus on project and financial risk in the literature is likely due to an academic and industrial interest in the commercial potential of geothermal. It fits well with geological risk being a frequent topic in both the literature survey and the questionnaire, as the characterization of the reservoir is closely tied to project/financial risk. The focus on the economy of activities in the geothermal industry is not surprising given the historical difference in profit margin between the two industries.

It is not surprising that the questionnaire sees health, safety and environment (HSE) and pressure/well control as two of the most frequently applied areas, as this is relevant for all work related to a well, no matter what other responsibilities one has. In particular, pressure control is generally considered more important for the petroleum industry (from the perspective of the public) due to the potential for explosions, fires and oil -spills. Although geothermal resources are generally associated with lower pressures and water, pressure control remains very important in order to control shallow gas, toxic gases and the potential for a water steam blowout for high temperature wells.

Both in the literature and in the questionnaire well integrity is less focused on by the geothermal industry, while it is highly focused on by the petroleum industry. From the questionnaire, a main difference is found in the barrier reliability. Given the high temperatures and potentially corrosive environment, it seems to get more attention in the risk assessments.

Concerning the methods used, the questionnaire indicates that a wider range of methods is applied in the petroleum industry; however, the most frequently used methods tend to be applied both in the geothermal and the petroleum sectors. The most frequently used methods are brainstorming, checklists, HAZOP, scenario analysis, root cause analysis, cause-and effect analysis, ERA, Decision tree analysis, SWIFT analysis and Monte Carlo simulations. Of these, HAZOP is the only method primarily basing itself on looking at the functions of the system parts, while the others are mostly supporting methods or scenario based methods. There are some differences between the methods used in geothermal and petroleum industries however, these are partly due to difference in application areas. The most noticeable difference is the more frequent use of methods suitable for barrier analysis, such as FMEA/FMECA, fault trees, event trees and bow-tie analysis in the petroleum industry.

In Figure 5-23, the methods selected by the respondents of the questionnaire have been classified according to their complexity (the complexity classification is based on ISO 31010:2009 [12]). The figure also includes methods classification as per ISO 31010:2009, as a baseline for comparison. The figure illustrates that even though few methods are classified as having low complexity, these are relatively more used. The main reason is that the easier to use methods, such as brainstorming and checklists, are frequently applied during risk identification. It should also be noted that there is little difference between the industries, and that neither industry shies away from high complexity methods.

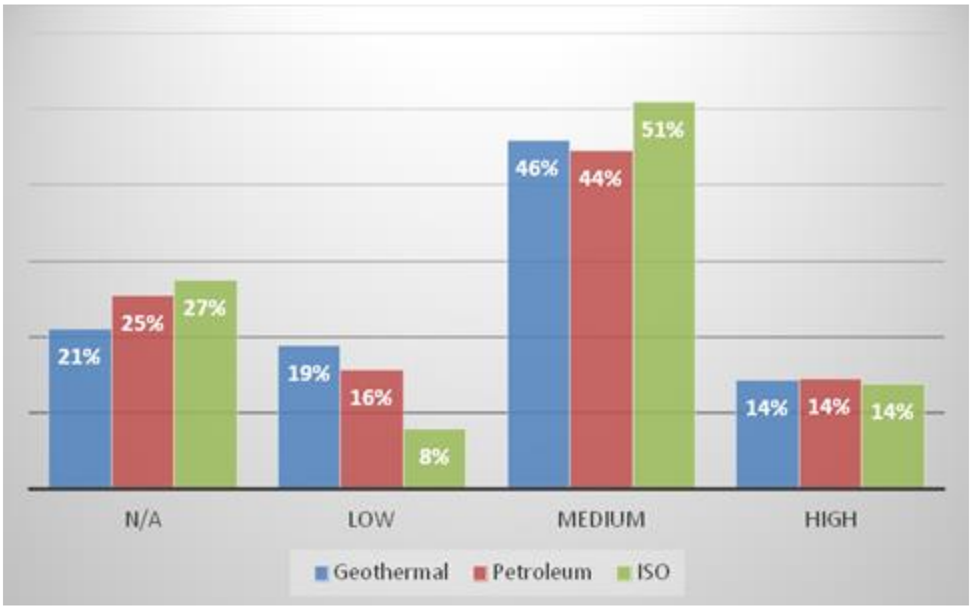


Figure 5-23. Complexity of risk assessment methods used, shown as a percentage of all methods used.

(Note: The series named ISO represents how the different methods are classified as per ISO 31010:2009. N/A represents methods which have not been given a complexity classification in the standard)

Comparing complexity of the methods, a few clear differences between the geothermal and petroleum industries have been identified. However, Figure 5-24 seems to indicate that the geothermal industry tends towards qualitative methods to a larger degree than the petroleum industry. Both industries use more qualitative methods than quantitative methods, and to a larger degree than the baseline in ISO 31010:2009. The main reason for this is likely to be the application of methods related to barrier analysis. Another reason might be that the petroleum industry has a larger amount of historical data to utilize in their risk assessments.

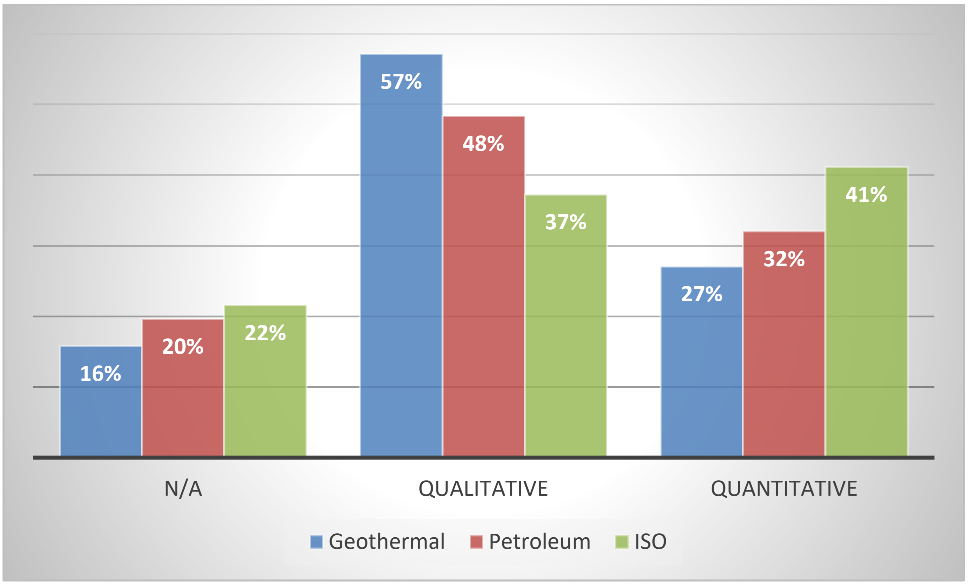


Figure 5-24. Percentage of all methods used covering qualitative and quantitative assessment methods.

(Note: The series named ISO is for comparison with the classification of all the methods that are presented in ISO 31010:2009.)

5.4 Transferability of methods

Based on the analysis, it seems most methods are used in both industries. Further investigations are required to confirm or reject this hypothesis, due to the relatively small sample size of the survey. However, going into the actual execution of how the industry deals with risks, there are likely to be lessons to learn. The focus here will be on topics related to well integrity.

5.4.1 Discussion on transferability

The use of risk assessment methods in the geothermal industry could be based on lessons learned from the more mature petroleum industry by focusing on the underlying reasons for why these methods have found success in the petroleum industry (or lack thereof), and identify whether this is more or less relevant for the geothermal industry. This would also have to account for any obstacles preventing changes within the geothermal industry.

Often a method becomes the customary method to use because there is not enough to gain from developing and applying methods that are more advanced. When the status changes, due to new technologies or because of the purpose of the well, the customary method sometimes needs to be re-evaluated. An example of this is casing design, which is typically based on a stress design of the worst-case scenario and applying a safety margin. In a time of increased focus on well cost, a reliability based design approach might be better, in particular for geothermal wells which already require high quality casings.

A main difference between the geothermal and petroleum industry, is the maturity and profitability of the petroleum industry resulting in access to high amounts of data. Although some of the data from the petroleum sector may be representative for some geothermal wells, in general this cannot be assumed. Thus, methods from the petroleum industry that are highly reliant on historic data, cannot easily be applied in the geothermal industry. However, learning from the petroleum industry concerning what types of data are useful, and how these can be compiled and utilized can enable the use of such methods in the future. An example is the OREDA database for reliability data used by the petroleum industry .

Regarding regulations, the petroleum industry is highly regulated, but there are few regulations directly enforcing risk assessment in the geothermal industry. Therefore, geothermal risk assessments are likely governed indirectly through legislation for e.g. mining or through protection of potable water resources. The petroleum industry has specific standards governing the executing of risk assessments, such as NORSOK D-010.

5.4.2 Transferable risk assessment methods

Given the wide range of methods used and the similarities between the petroleum and geothermal industries, it may be more relevant to discuss which methods "could" be applied in geothermal, rather than which methods can be transferred from petroleum. A conceptual schematic of how a risk assessment method/tool in the petroleum industry can be applied to the geothermal industry is depicted in Figure 5-25. Examples of relevant tools might be WIMS systems and industry wide databases. Some of the widely-applied methods and relevant software tools, e.g. RiskSpectrum FMEA, ELMAS (Ramentor) and MAROS (DNV), are listed in the website of ROSS Gemini Centre[1].

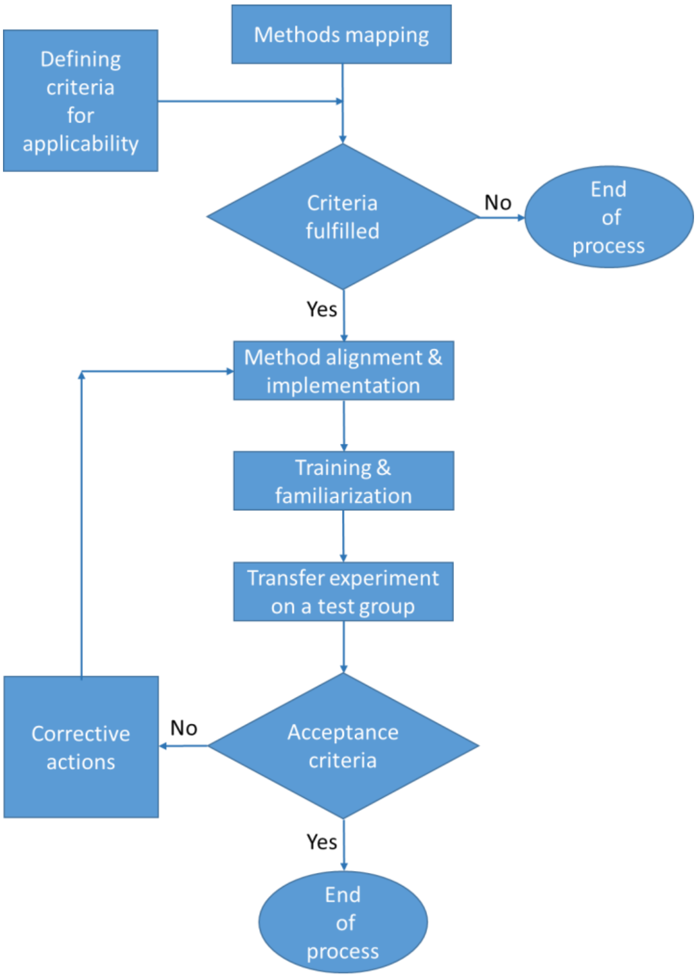


Figure 5-25: The workflow of transfer of risk assessment methods from the petroleum to the geothermal sector.

In addition, adjustments to the risk terminology can be more important in the transition. In Norway, the PSA is adjusting the concept of risk within the regulations, by defining risk as the consequences of the activities, with associated uncertainty. This is to step further away from

[1] http://www.ntnu.edu/ross/info/software

the classical interpretation of risk as probability multiplied with consequences, and rather take uncertainty properly into account by requiring companies to systematize and visualize what they know and what they do not know. Given the lower amount of experience data from geothermal wells and the claimed uniqueness of every geothermal well, this adjustment to the definition of risk could be even more important for geothermal wells [18].

6 Conclusions

The main findings of deliverable 6.2, based on findings from the literature review and analysis of responses to the GeoWell risk assessment survey, can be summarized as:

- There has been an increasing number of tools and techniques used, both from the petroleum industry itself and other industries. Risk assessment is today an important part of the oil and gas industry. Besides the methods aimed at performing common risk assessment activities, the petroleum industry today also has a strong focus on well integrity, and in particular on so-called well integrity management systems (WIMS).
- Based on the survey, the overall impression is that geothermal and petroleum industries are similar when it comes to supporting tools for performing risk assessment. The methods frequently used in the petroleum industry are also the more frequently used methods in the geothermal industry. However, every method is used more frequently in the petroleum industry than they are in the geothermal industry. In general, the petroleum industry uses a wider range of methods.
- In terms of types of risks assessed, both industries have a strong focus on health and safety, environmental risk and project/financial risk. However, a significant difference can be seen for barrier reliability, where there is a considerable focus in the petroleum industry, but not in the geothermal industry. A similar, but smaller difference can also be observed concerning pressure/well control. The geothermal industry, on the other hand, has a greater focus on geological risk and geological event risk.
- Main differences between the geothermal and petroleum industry, relate to the maturity and profitability of the petroleum industry resulting in access to large amounts of data. Learning from the petroleum industry what types of data are useful, and how these can be compiled and utilized, can enable the use of such methods in the geothermal industry in the future.
- Regarding regulations, the petroleum industry is highly regulated, and has specific standards, such as NORSOK D-010, which concern the well integrity of oil and gas wells. For geothermal wells, on the other hand, there are few regulations related to/supporting risk assessment.
- The use of risk assessment methods in the geothermal industry could be based on lessons learned from the more mature petroleum industry by focusing on the underlying reasons for why these methods have found success in the petroleum industry (or lack thereof), and by identifying their relevance for the geothermal industry.

7 Future activities

Thus far, the work in GeoWell WP6 has focused on establishing a foundation for the present state of risk assessment in the geothermal and petroleum industries. With this information, the work package will focus more on particular challenges associated with integrity of geothermal wells by including input from the other work packages of the project. The following tasks will build on the work performed in tasks 6.1 and 6.2 of GeoWell:

- Task 6.3 is entitled “Develop risk assessment methods for phenomena that are currently not covered for geothermal wells, particularly at elevated temperatures up to 450 °C”. The aim is to establish barrier definitions for geothermal wells and corresponding risk assessment tools for the relevant barriers. The results from this task will supply a framework for a quantitative approach to risk assessment for geothermal wells.
- Task 6.4 is entitled “Develop a European protocol for risk assessment in geothermal drilling in compliance with European and domestic regulations”. Here, the foundations for geothermal well integrity and risk assessment methodology will be established as a basis for a future European protocol. This can contribute to developing a basis for a common European standard for planning and execution of geothermal well construction.
- Task 6.5 is entitled “Reliability analysis of new developed materials and technology”. In this task, results from GeoWell work packages dealing with new materials (casing, cement and tubulars) and corresponding technology will be input. An evaluation will be done to answer to what degree the newly developed technologies can replace existing ones in terms of risk properties.

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Appendices

Appendix I: The GeoWell risk assessment survey

EU-GeoWell Risk Assessment Survey

Welcome to the GeoWell Risk Assessment Survey

The International Research Institute of Stavanger (IRIS), Norway, conducts a short survey within the framework of the GeoWell project. The project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement no. 654497. The purpose of this survey is to collect and analyze information that can help to map the currently used methods for risk assessment in the geothermal and petroleum industries and more specifically during the drilling and completion, production and maintenance phases. The findings will be communicated to the participants via a planned webinar in Fall 2016. Please take your time to answer this survey that should take no more than 10 minutes to complete. Answers to most of the questions are given by selecting the alternative which best describes your company and its practice. Please direct any questions or comments to the GeoWell team at IRIS. Email: GeoWell@iris.no

1 Company Information

- Company Name (Optional) (1)
- Country (Optional) (2)

2 How would you define your company/organization type?

- ❑ Operating Company (1)
- ❑ Drilling Contractor (2)
- ❑ Service Provider (3)
- ❑ Consulting Company (4)
- ❑ Equipment Manufacturer (5)
- ❑ Government Agency (6)
- ❑ University, Research Institute or Laboratory (7)
- ❑ Other (Please Specify) (8) ____________________

3 In which of the following areas is your company/organization active?

- ❑ Onshore Geothermal (1)
- ❑ Offshore Petroleum (2)
- ❑ Onshore Petroleum (3)
- ❑ Other (Please Specify) (4) ____________________

4 Is your company responsible for performing risk assessments in the context of well operations?

- ❍ Yes (1)
- ❍ No (2)

5 Which types of risk assessments do you perform?

- ❑ Health and Safety Risk (1)
- ❑ Project/Financial Risk (2)
- ❑ Geological Risk (3)
- ❑ Geological Event Risk (4)
- ❑ Pressure/Well Control Risk (5)
- ❑ Equipment Reliability (6)
- ❑ Barrier Reliability (7)
- ❑ Environmental Risk (8)
- ❑ Flow Assurance (9)
- ❑ Other (Please Specify) (10) ____________________

Note: According to IEC/ISO 31010, a risk assessment process is accomplished in three different steps including: i) Risk identification - Risk identification is activities related to the identification of sources of risks, areas of impacts, events and their causes and their potential consequences. ii) Risk analysis - Risk analysis is the consideration of the causes and sources of risk, their positive and negative consequences, and the likelihood that those consequences can occur. iii) Risk evaluation - Risk evaluation involves the comparison of the level of risk found in the risk analysis with risk criteria established, taking into account tolerance to risk.

6 Which of the following methods are used for risk identification at your company?

- ❑ Brainstorming (1)
- ❑ Interviews (Structured or Semi-structured) (2)
- ❑ Delphi (3)
- ❑ Checklists (4)
- ❑ PHA (Preliminary Hazard Analysis) (5)
- ❑ HAZOP (HAZard and Operability studies) (6)
- ❑ HACCP (Hazard Analysis and Critical Control Points) (7)
- ❑ SWIFT (Structured What-If Technique) (8)
- ❑ Scenario Analysis (9)
- ❑ FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis) (10)
- ❑ Cause-and-Effect Analysis (11)
- ❑ HRA (Human Reliability Analysis) (12)
- ❑ Reliability Centred Maintenance (13)
- ❑ Environmental Risk Assessment (14)
- ❑ Consequence/Probability Matrix (15)
- ❑ Other Methods (Please Specify) (16) ____________________

7 Which of the following methods are used for risk analysis at your company?

- ❑ HAZOP (HAZard and Operability studies) (1)
- ❑ HACCP (Hazard Analysis and Critical Control Points) (2)
- ❑ SWIFT (Structured What-If Technique) (3)
- ❑ Scenario Analysis (4)
- ❑ Business Impact Analysis (5)
- ❑ Root Cause Analysis (6)
- ❑ FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis) (7)
- ❑ Fault Tree Analysis (8)
- ❑ Event Tree Analysis (9)
- ❑ Cause-and-Effect Analysis (10)
- ❑ LOPA (Layer of Protection Analysis) (11)
- ❑ HRA (Human Reliability Analysis) (12)
- ❑ Bow-Tie Analysis (13)
- ❑ Reliability Centred Maintenance (14)
- ❑ Markov Analysis (15)
- ❑ Bayesian Statistics and Bayes Nets (16)
- ❑ Environmental Risk Assessment (17)
- ❑ Decision Tree Analysis (18)
- ❑ FN Curves (19)

- ❑ Risk Indices (20)
- ❑ Consequence/Probability Matrix (21)
- ❑ CBA (Cost/Benefit Analysis) (22)
- ❑ MCDA (Multi-Criteria Decision Analysis) (23)
- ❑ Other Methods (Please Specify) (24) ____________________

8 Which of the following methods are used for risk evaluation at your company?

- ❑ HACCP (Hazard Analysis and Critical Control Points) (1)
- ❑ SWIFT (Structured What-If Technique) (2)
- ❑ Root Cause Analysis (3)
- ❑ FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis) (4)
- ❑ Reliability Centred Maintenance (5)
- ❑ Monte Carlo Simulation (6)
- ❑ Bayesian Statistics and Bayes Nets (7)
- ❑ Environmental Risk Assessment (8)
- ❑ FN Curves (9)
- ❑ Risk Indices (10)
- ❑ Other Methods (Please Specify) (11) ____________________

Please specify the phases you perform risk management methods. Note that every phases also include pre-planning prior to execution.

9 Please check the corresponding phases you perform risk identification methods:

	Drilling	Completion	Production	Maintenace
Risks that are selected in Q.6	O	O	O	O

10 Please check the corresponding phases you perform risk analysis methods:

	Drilling	Completion	Production	Maintenace
Risks that are selected in Q.7	O	O	O	O

11 Please check the corresponding phases you perform risk evaluation methods:

	Drilling	Completion	Production	Maintenace
Risks that are selected in Q.8	O	O	O	O

12 Please check the corresponding risks you apply the risk identification methods:

	Risks that are selected in Q.5	risks that are selected in Q.5
Methods that are selected in Q.6	O	O

13 Please check the corresponding risks you apply the risk analysis methods:

	Risks that are selected in Q.5	risks that are selected in Q.5
Methods that are selected in Q.7	O	O

14 Please check the corresponding risks you apply the risk evaluation methods

	Risks that are selected in Q.5	risks that are selected in Q.5
Methods that are selected in Q.8	O	O

15 Please provide your email address here if you are interested in participating in a webinar presenting the findings of this survey.

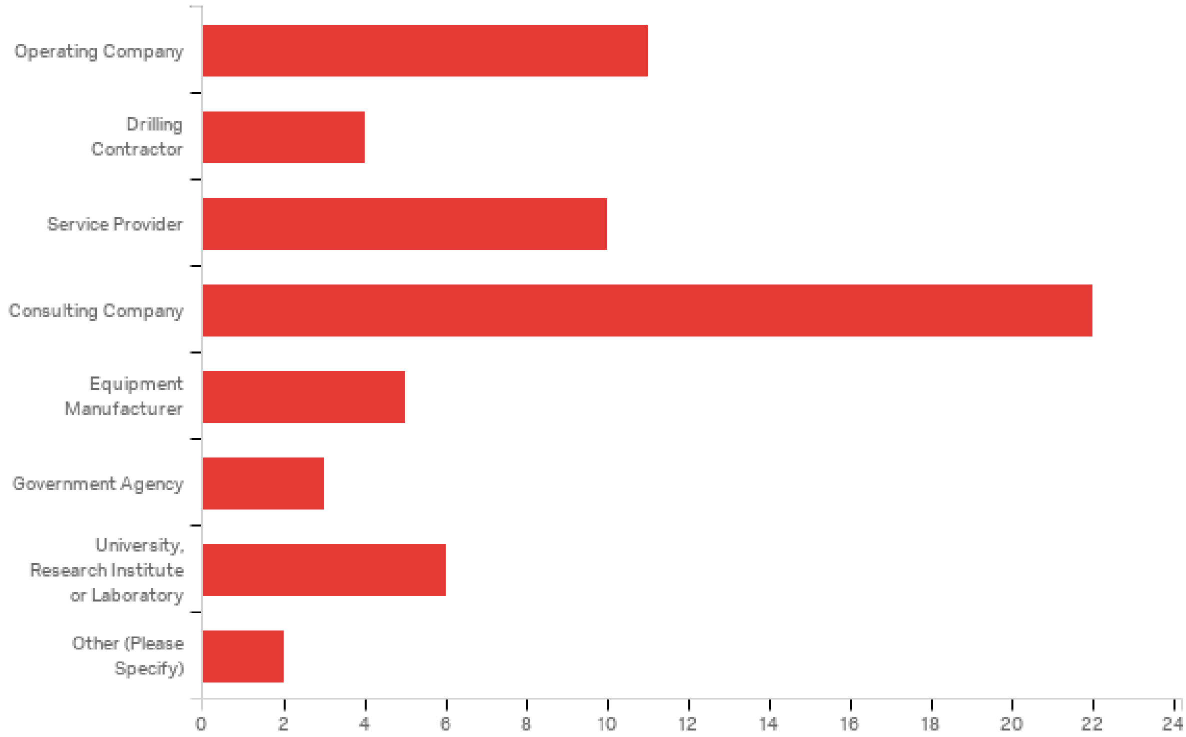
16 Do you have any other comments, questions or concerns?

Appendix II: Responses to the survey

1 - Company Information

Please note that because of confidentiality issues, these information are excluded from the report.

2 - How would you define your company/organization type?

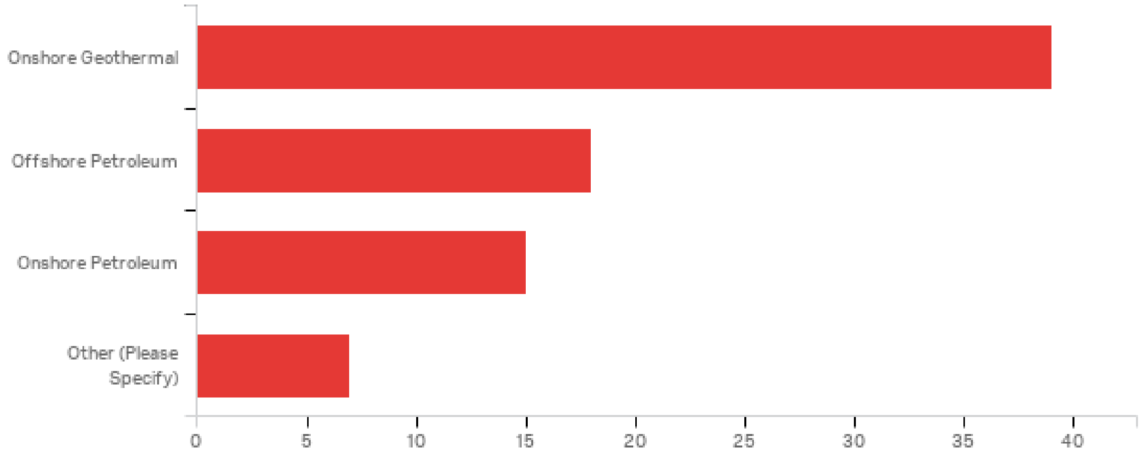


Answer	%	Count
Operating Company	22.45%	11
Drilling Contractor	8.16%	4
Service Provider	20.41%	10
Consulting Company	44.90%	22
Equipment Manufacturer	10.20%	5
Government Agency	6.12%	3
University, Research Institute or Laboratory	12.24%	6
Other (Please Specify)	4.08%	2
Total	100%	49

Other (Please Specify)

Other (Please Specify)
Pilot plant of CLEAG Geothermal energy
Contract drilling supervision

3 - In which of the following areas is your company/organization active?

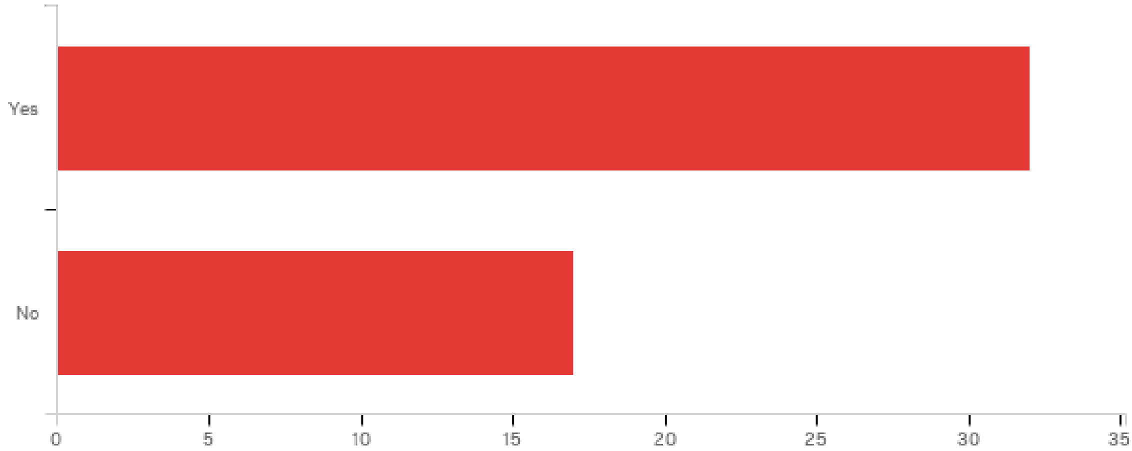


Answer	%	Count
Onshore Geothermal	79.59%	39
Offshore Petroleum	36.73%	18
Onshore Petroleum	30.61%	15
Other (Please Specify)	14.29%	7
Total	100%	49

Other (Please Specify)

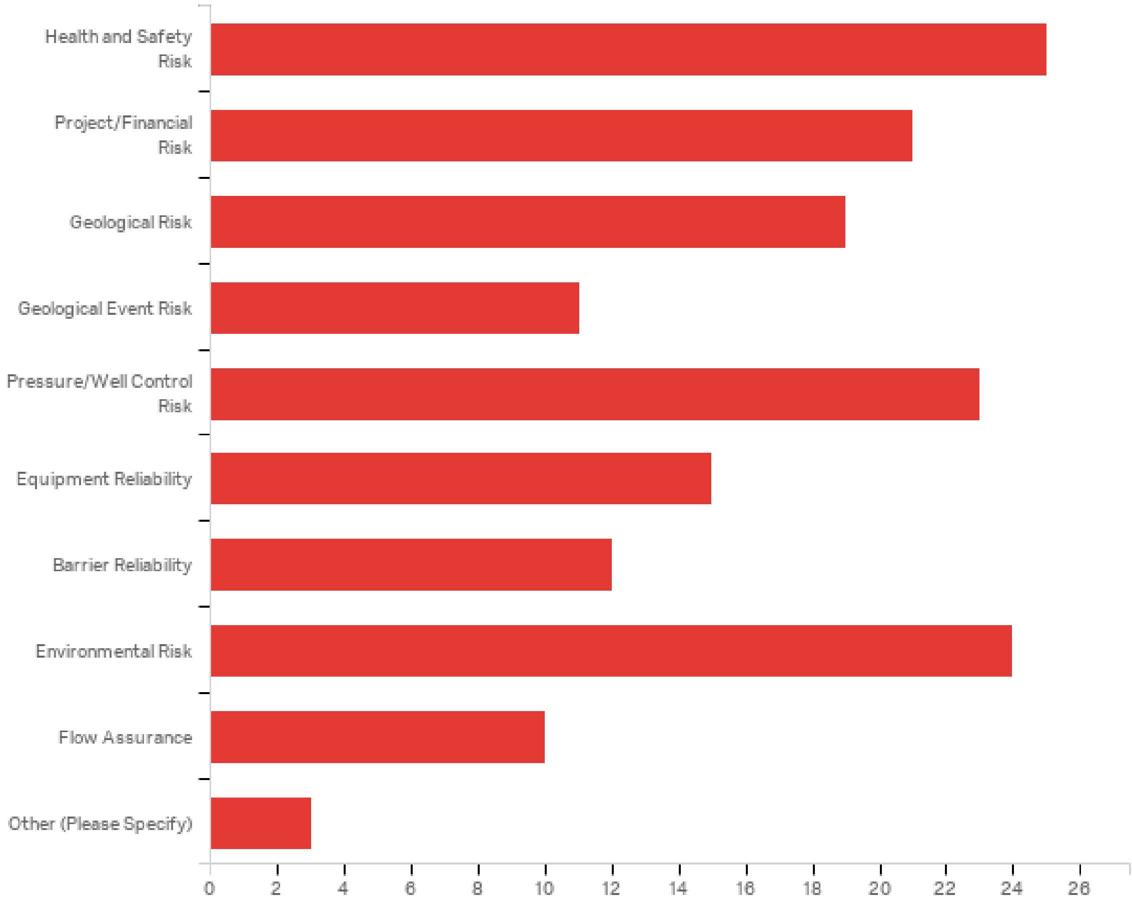
Other (Please Specify)
Mineral prospecting
CLEAG CloZEd Loop Energy
Offshore wind
mapping
Geothermal
Pipeline Failure Analysis
Mining, Geotechnical

4 - Is your company responsible for performing risk assessments in the context of well operations?



Answer	%	Count
Yes	65.31%	32
No	34.69%	17
Total	100%	49

5 - Which types of risk assessments do you perform?

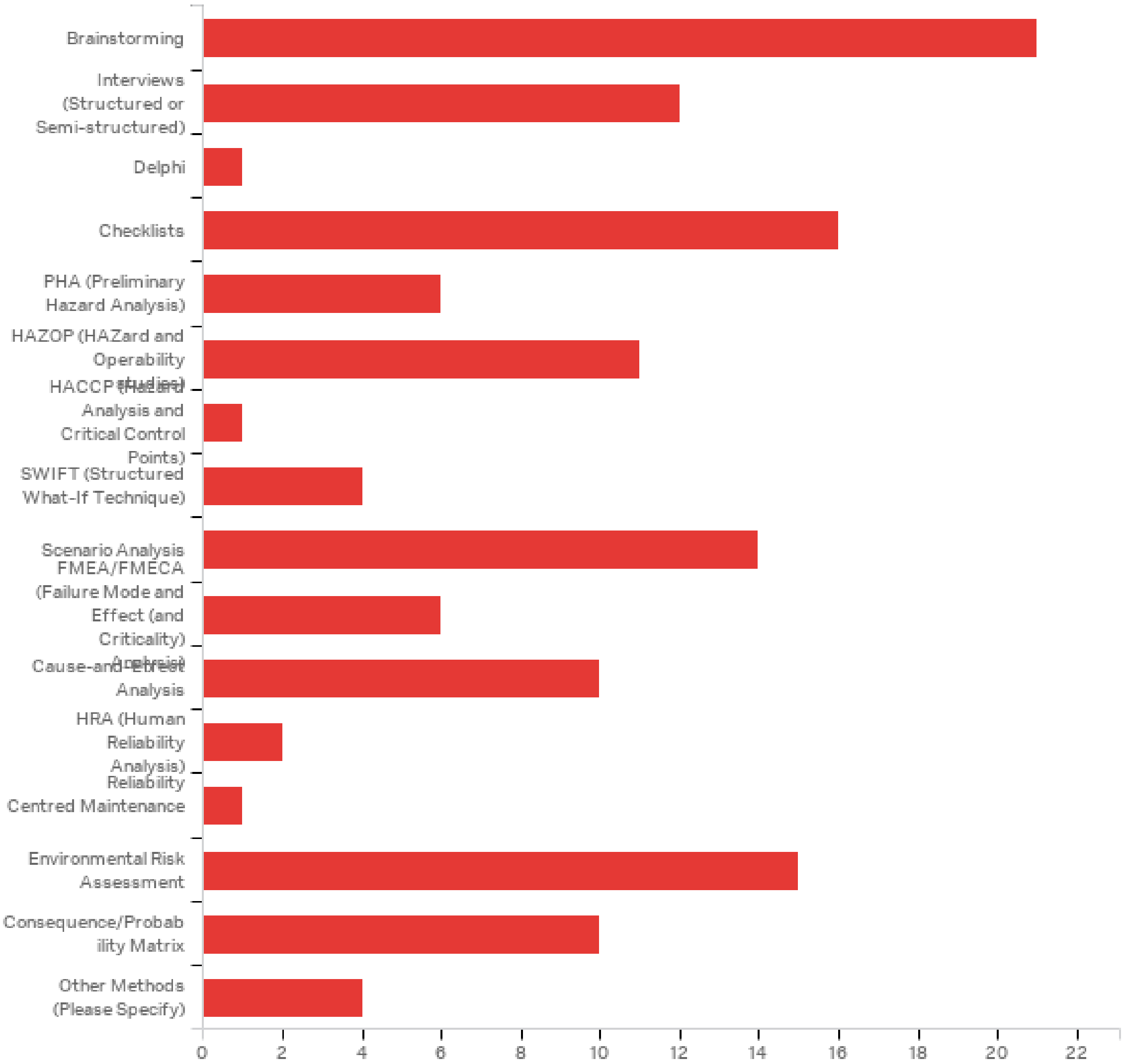


Answer	%	Count
Health and Safety Risk	80.65%	25
Project/Financial Risk	67.74%	21
Geological Risk	61.29%	19
Geological Event Risk	35.48%	11
Pressure/Well Control Risk	74.19%	23
Equipment Reliability	48.39%	15
Barrier Reliability	38.71%	12
Environmental Risk	77.42%	24
Flow Assurance	32.26%	10
Other (Please Specify)	9.68%	3
Total	100%	31

Other (Please Specify)

Other (Please Specify)
Integrity
Drilling Problem Risk
Well integrity risk (may be pressure, but not well control)

6 - Which of the following methods are used for risk identification at your company?

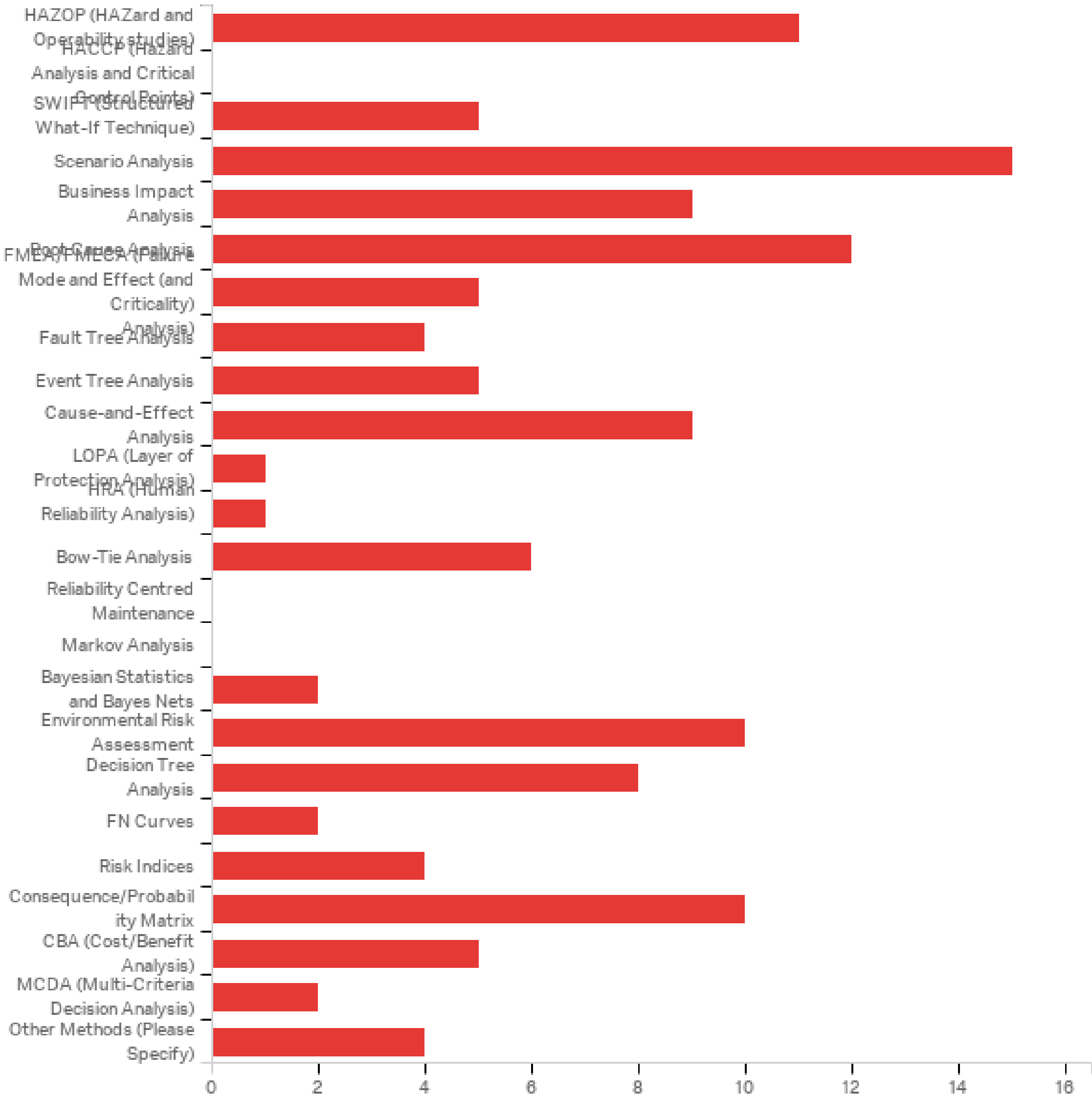


Answer	%	Count
Brainstorming	80.77%	21
Interviews (Structured or Semi-structured)	46.15%	12
Delphi	3.85%	1
Checklists	61.54%	16
PHA (Preliminary Hazard Analysis)	23.08%	6
HAZOP (HAZard and Operability studies)	42.31%	11
HACCP (Hazard Analysis and Critical Control Points)	3.85%	1
SWIFT (Structured What-If Technique)	15.38%	4
Scenario Analysis	53.85%	14
FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis)	23.08%	6
Cause-and-Effect Analysis	38.46%	10
HRA (Human Reliability Analysis)	7.69%	2
Reliability Centred Maintenance	3.85%	1
Environmental Risk Assessment	57.69%	15
Consequence/Probability Matrix	38.46%	10
Other Methods (Please Specify)	15.38%	4
Total	100%	26

Other Methods (Please Specify)

Other Methods (Please Specify)
Top-Set
Hazard Identification Risk Assessment and Controls (HIRAC)
Contractor & Service Prespud Operations Review
DWOP (Drill Well on Paper), CWOP (Complete Well on Paper)

7 - Which of the following methods are used for risk analysis at your company?

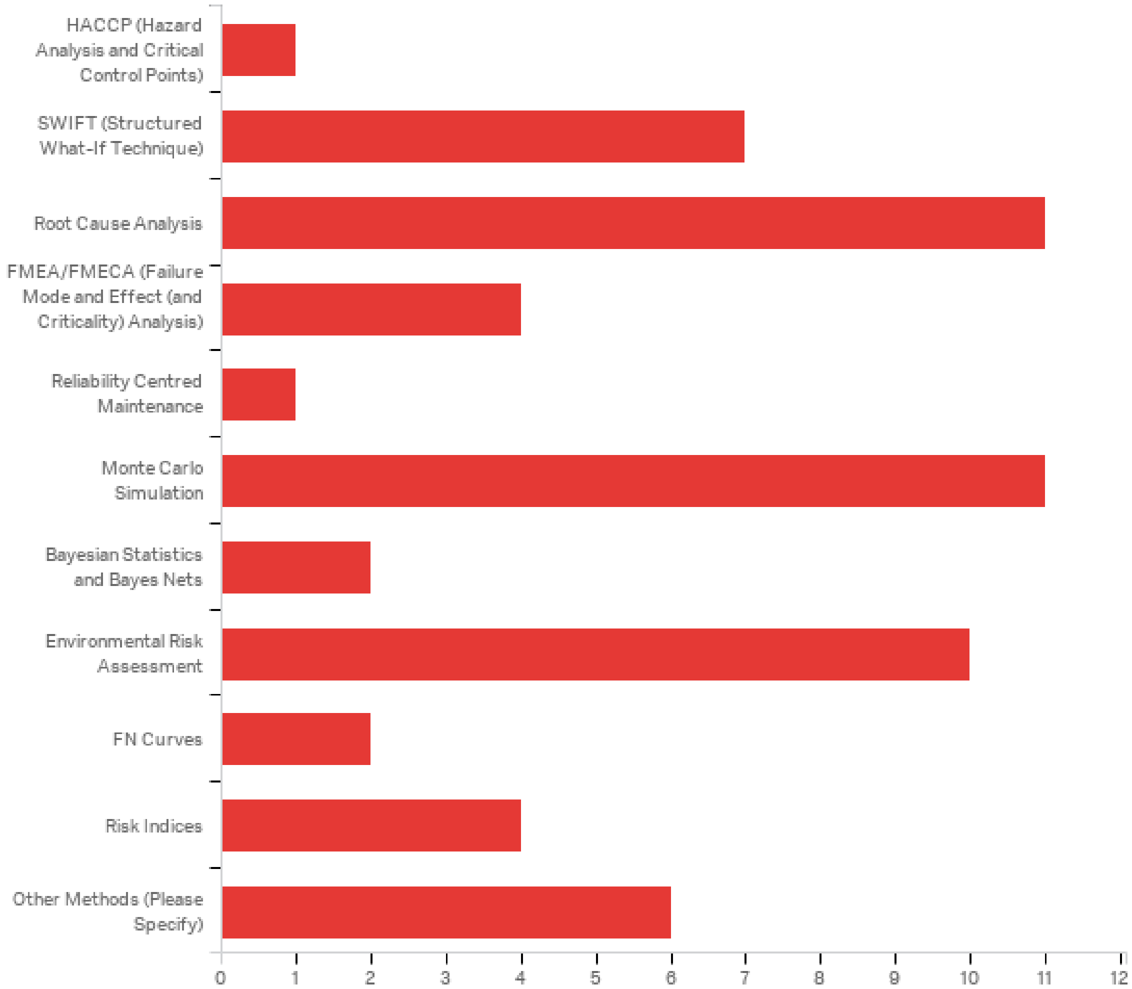


Answer	%	Count
HAZOP (HAZard and Operability studies)	42.31%	11
HACCP (Hazard Analysis and Critical Control Points)	0.00%	0
SWIFT (Structured What-If Technique)	19.23%	5
Scenario Analysis	57.69%	15
Business Impact Analysis	34.62%	9
Root Cause Analysis	46.15%	12
FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis)	19.23%	5
Fault Tree Analysis	15.38%	4
Event Tree Analysis	19.23%	5
Cause-and-Effect Analysis	34.62%	9
LOPA (Layer of Protection Analysis)	3.85%	1
HRA (Human Reliability Analysis)	3.85%	1
Bow-Tie Analysis	23.08%	6
Reliability Centred Maintenance	0.00%	0
Markov Analysis	0.00%	0
Bayesian Statistics and Bayes Nets	7.69%	2
Environmental Risk Assessment	38.46%	10
Decision Tree Analysis	30.77%	8
FN Curves	7.69%	2
Risk Indices	15.38%	4
Consequence/Probability Matrix	38.46%	10
CBA (Cost/Benefit Analysis)	19.23%	5
MCDA (Multi-Criteria Decision Analysis)	7.69%	2
Other Methods (Please Specify)	15.38%	4
Total	100%	26

Other Methods (Please Specify)

Other Methods (Please Specify)
Top-Set
qras, Monte carlo simulations
Hazard Identification Risk Assessment and Controls (HIRAC)
Formal quantitative risk analysis

8 - Which of the following methods are used for risk evaluation at your company?

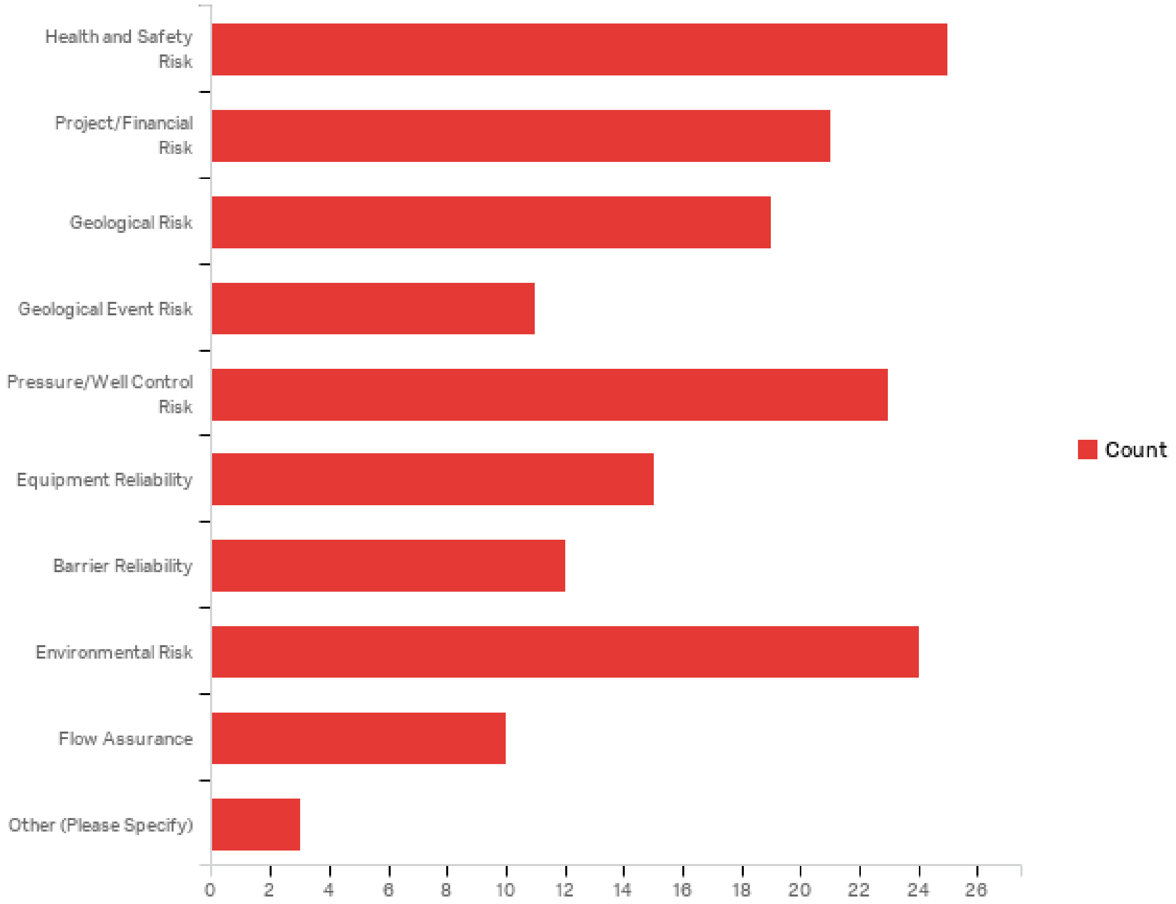


Answer	%	Count
HACCP (Hazard Analysis and Critical Control Points)	4.17%	1
SWIFT (Structured What-If Technique)	29.17%	7
Root Cause Analysis	45.83%	11
FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis)	16.67%	4
Reliability Centred Maintenance	4.17%	1
Monte Carlo Simulation	45.83%	11
Bayesian Statistics and Bayes Nets	8.33%	2
Environmental Risk Assessment	41.67%	10
FN Curves	8.33%	2
Risk Indices	16.67%	4
Other Methods (Please Specify)	25.00%	6
Total	100%	24

Other Methods (Please Specify)

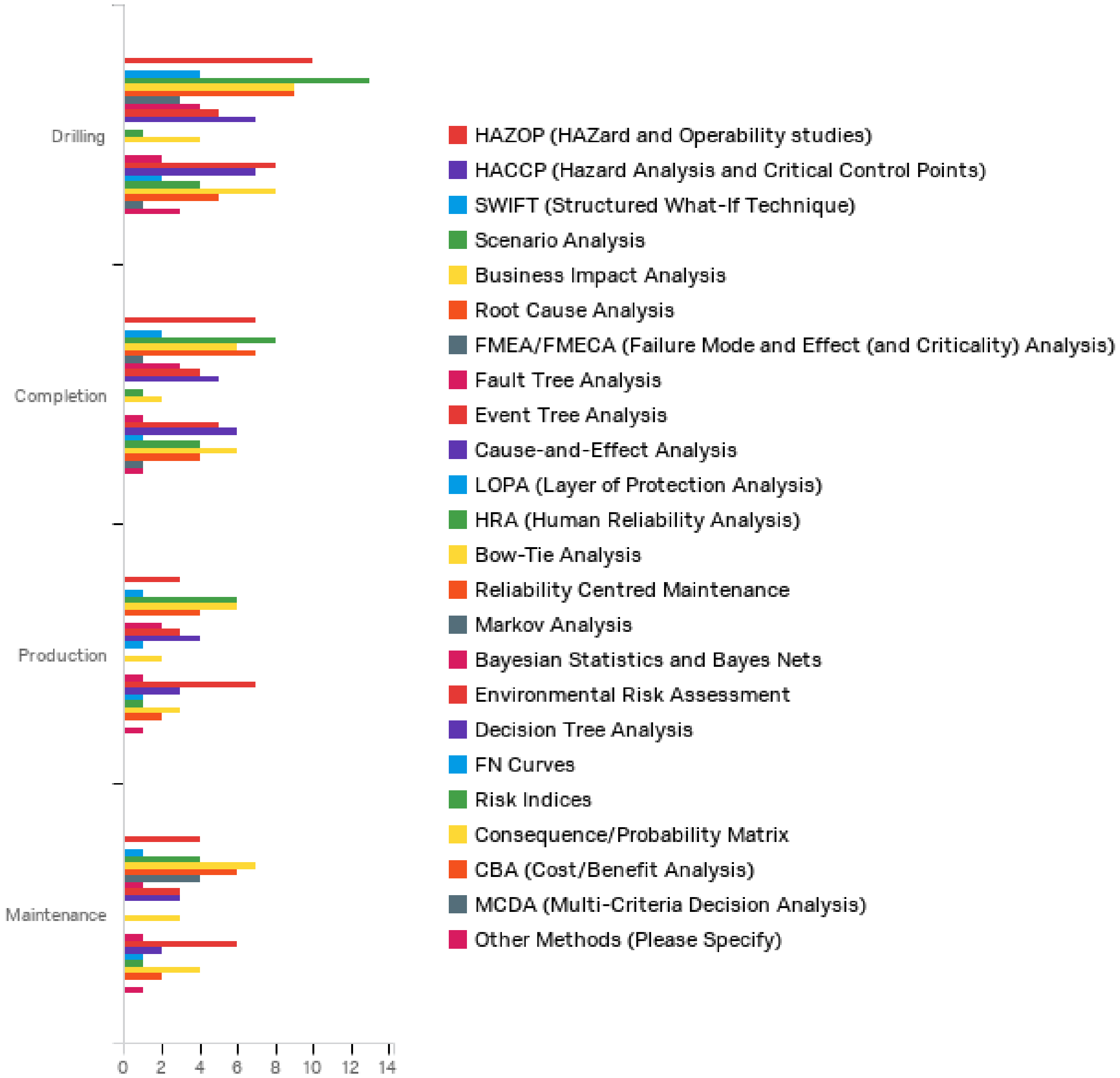
Other Methods (Please Specify)
Top-Set
Risk matrices, risk tolerance criteria
Risk Register
Hazard Identification Risk Assessment and Controls (HIRAC)
Extreme Event Statistics
Formal quantitative risk analysis

9 - Please check the corresponding phases you perform risk identification methods:



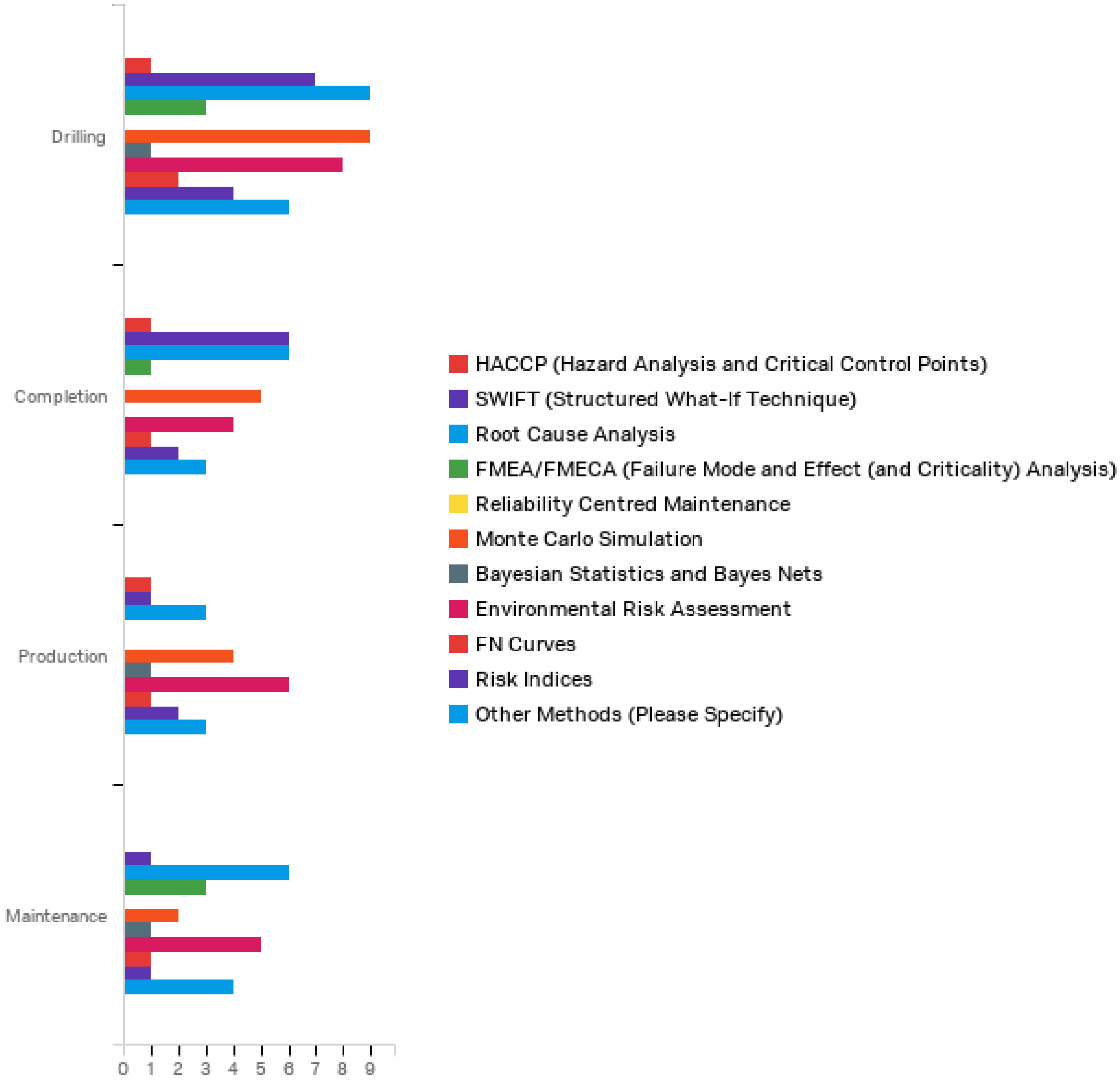
Question	Drilling	Completion	Production	Maintenance	Total
Brainstorming	100.00%	65.00%	50.00%	55.00%	20
Interviews (Structured or Semi-structured)	100.00%	45.45%	45.45%	63.64%	11
Delphi	100.00%	100.00%	0.00%	0.00%	1
Checklists	100.00%	64.29%	50.00%	64.29%	14
PHA (Preliminary Hazard Analysis)	100.00%	66.67%	50.00%	50.00%	6
HAZOP (HAZard and Operability studies)	90.91%	63.64%	27.27%	36.36%	11
HACCP (Hazard Analysis and Critical Control Points)	100.00%	0.00%	100.00%	100.00%	1
SWIFT (Structured What-If Technique)	100.00%	100.00%	66.67%	33.33%	3
Scenario Analysis	90.91%	63.64%	54.55%	54.55%	11
FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis)	80.00%	40.00%	0.00%	80.00%	5
Cause-and-Effect Analysis	100.00%	100.00%	37.50%	37.50%	8
HRA (Human Reliability Analysis)	100.00%	100.00%	0.00%	0.00%	1
Reliability Centred Maintenance	0.00%	0.00%	0.00%	0.00%	0
Environmental Risk Assessment	100.00%	58.33%	75.00%	75.00%	12
Consequence/Probability Matrix	100.00%	71.43%	28.57%	14.29%	7
Other Methods (Please Specify)	100.00%	50.00%	0.00%	25.00%	4

10 - Please check the corresponding phases you perform risk analysis methods:



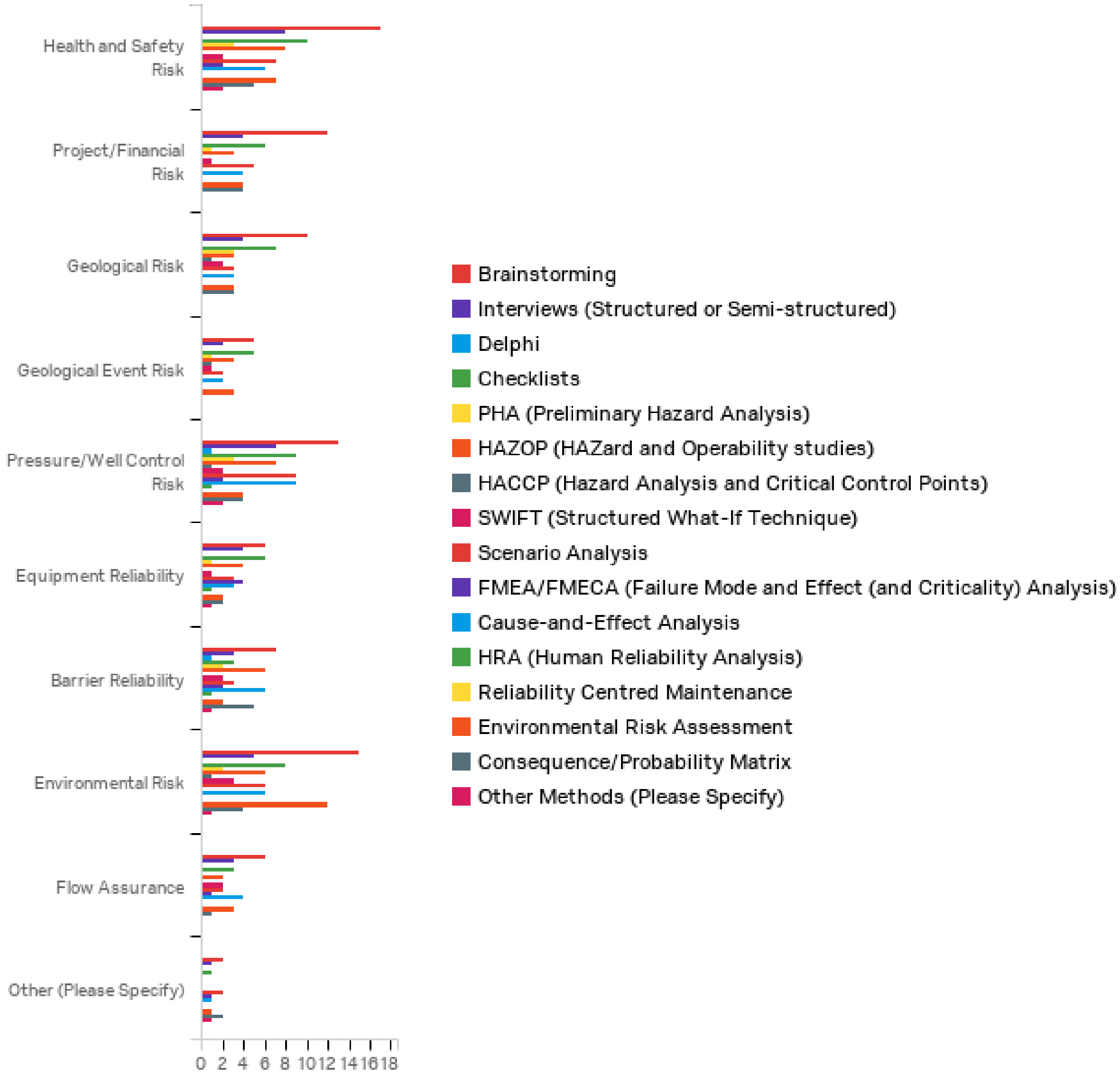
Question	Drilling	Completion	Production	Maintenance	Total
HAZOP (HAZard and Operability studies)	100.00%	70.00%	30.00%	40.00%	10
HACCP (Hazard Analysis and Critical Control Points)	0.00%	0.00%	0.00%	0.00%	0
SWIFT (Structured What-If Technique)	100.00%	50.00%	25.00%	25.00%	4
Scenario Analysis	100.00%	61.54%	46.15%	30.77%	13
Business Impact Analysis	100.00%	66.67%	66.67%	77.78%	9
Root Cause Analysis	90.00%	70.00%	40.00%	60.00%	10
FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis)	75.00%	25.00%	0.00%	100.00%	4
Fault Tree Analysis	100.00%	75.00%	50.00%	25.00%	4
Event Tree Analysis	100.00%	80.00%	60.00%	60.00%	5
Cause-and-Effect Analysis	87.50%	62.50%	50.00%	37.50%	8
LOPA (Layer of Protection Analysis)	0.00%	0.00%	100.00%	0.00%	1
HRA (Human Reliability Analysis)	100.00%	100.00%	0.00%	0.00%	1
Bow-Tie Analysis	80.00%	40.00%	40.00%	60.00%	5
Reliability Centred Maintenance	0.00%	0.00%	0.00%	0.00%	0
Markov Analysis	0.00%	0.00%	0.00%	0.00%	0
Bayesian Statistics and Bayes Nets	100.00%	50.00%	50.00%	50.00%	2
Environmental Risk Assessment	88.89%	55.56%	77.78%	66.67%	9
Decision Tree Analysis	100.00%	85.71%	42.86%	28.57%	7
FN Curves	100.00%	50.00%	50.00%	50.00%	2
Risk Indices	100.00%	100.00%	25.00%	25.00%	4
Consequence/Probability Matrix	100.00%	75.00%	37.50%	50.00%	8
CBA (Cost/Benefit Analysis)	100.00%	80.00%	40.00%	40.00%	5
MCDA (Multi-Criteria Decision Analysis)	100.00%	100.00%	0.00%	0.00%	1
Other Methods (Please Specify)	100.00%	33.33%	33.33%	33.33%	3

11 - Please check the corresponding phases you perform risk evaluation methods:



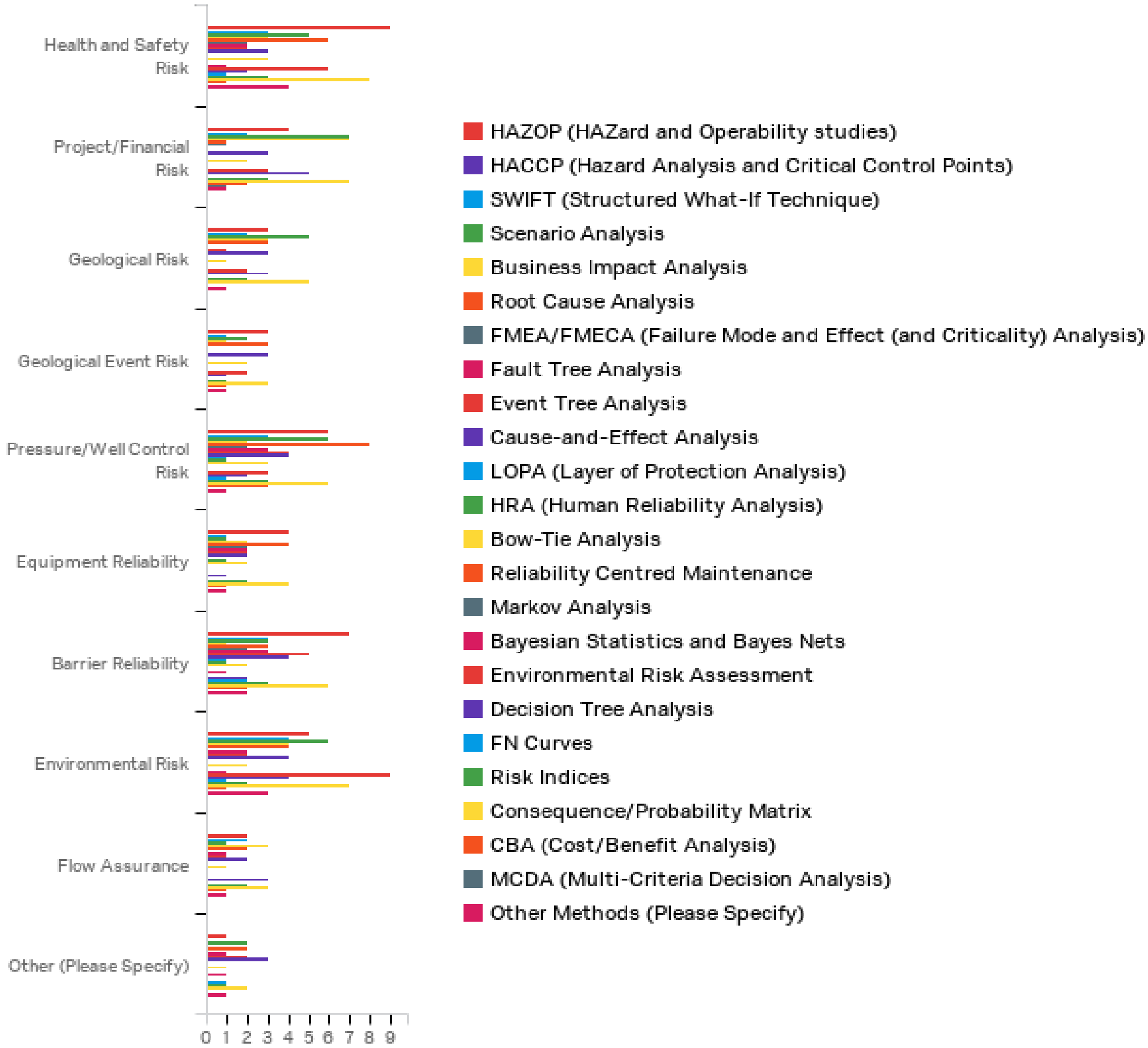
Question	Drilling	Completion	Production	Maintenance	Total
HACCP (Hazard Analysis and Critical Control Points)	100.00%	100.00%	100.00%	0.00%	1
SWIFT (Structured What-If Technique)	100.00%	85.71%	14.29%	14.29%	7
Root Cause Analysis	81.82%	54.55%	27.27%	54.55%	11
FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis)	75.00%	25.00%	0.00%	75.00%	4
Reliability Centred Maintenance	0.00%	0.00%	0.00%	0.00%	0
Monte Carlo Simulation	90.00%	50.00%	40.00%	20.00%	10
Bayesian Statistics and Bayes Nets	100.00%	0.00%	100.00%	100.00%	1
Environmental Risk Assessment	88.89%	44.44%	66.67%	55.56%	9
FN Curves	100.00%	50.00%	50.00%	50.00%	2
Risk Indices	100.00%	50.00%	50.00%	25.00%	4
Other Methods (Please Specify)	100.00%	50.00%	50.00%	66.67%	6

12 - Please check the corresponding risks you apply the risk identification methods:



Question	Health and Safety Risk	Project/Financial Risk	Geological Risk	Geological Event Risk	Pressure/Well Control Risk	Equipment Reliability	Barrier Reliability	Environmental Risk	Flow Assurance	Other (Please Specify)	Total
Brainstorming	89.47%	63.16%	52.63%	26.32%	68.42%	31.58%	36.84%	78.95%	31.58%	10.53%	19
Interviews (Structured or Semi-structured)	72.73%	36.36%	36.36%	18.18%	63.64%	36.36%	27.27%	45.45%	27.27%	9.09%	11
Delphi	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	1
Checklists	76.92%	46.15%	53.85%	38.46%	69.23%	46.15%	23.08%	61.54%	23.08%	7.69%	13
PHA (Preliminary Hazard Analysis)	50.00%	16.67%	50.00%	16.67%	50.00%	16.67%	33.33%	33.33%	0.00%	0.00%	6
HAZOP (HAZard and Operability studies)	72.73%	27.27%	27.27%	27.27%	63.64%	36.36%	54.55%	54.55%	18.18%	0.00%	11
HACCP (Hazard Analysis and Critical Control Points)	0.00%	0.00%	100.00%	100.00%	100.00%	0.00%	0.00%	100.00%	0.00%	0.00%	1
SWIFT (Structured What-If Technique)	50.00%	25.00%	50.00%	25.00%	50.00%	25.00%	50.00%	75.00%	50.00%	0.00%	4
Scenario Analysis	63.64%	45.45%	27.27%	18.18%	81.82%	27.27%	27.27%	54.55%	18.18%	18.18%	11
FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis)	33.33%	0.00%	0.00%	0.00%	33.33%	66.67%	33.33%	0.00%	16.67%	16.67%	6
Cause-and-Effect Analysis	60.00%	40.00%	30.00%	20.00%	90.00%	30.00%	60.00%	60.00%	40.00%	10.00%	10
HRA (Human Reliability Analysis)	0.00%	0.00%	0.00%	0.00%	100.00%	100.00%	100.00%	0.00%	0.00%	0.00%	1
Reliability Centred Maintenance	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0
Environmental Risk Assessment	58.33%	33.33%	25.00%	25.00%	33.33%	16.67%	16.67%	100.00%	25.00%	8.33%	12
Consequence/Probability Matrix	83.33%	66.67%	50.00%	0.00%	66.67%	33.33%	83.33%	66.67%	16.67%	33.33%	6
Other Methods (Please Specify)	50.00%	0.00%	0.00%	0.00%	50.00%	25.00%	25.00%	25.00%	0.00%	25.00%	4

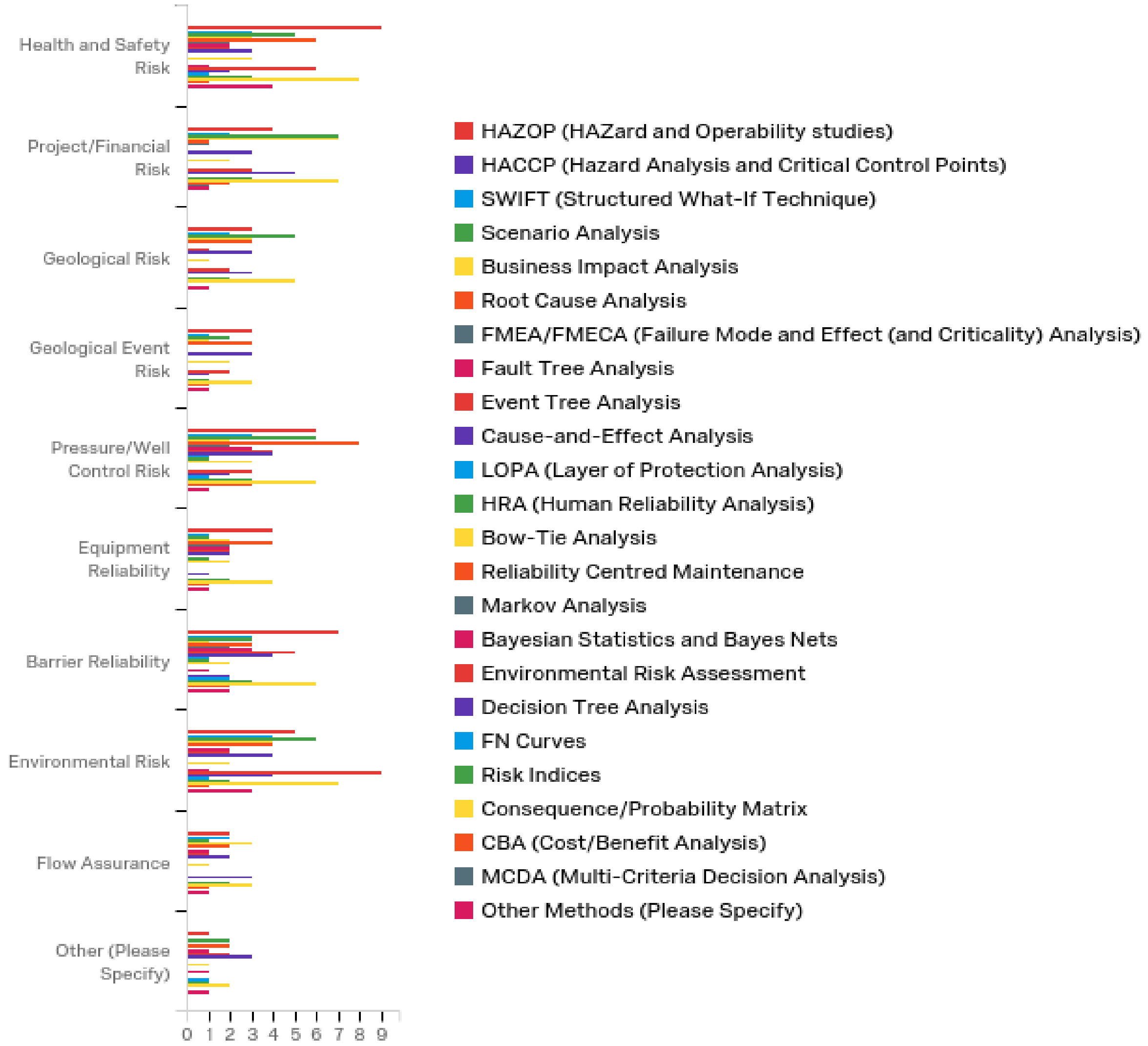
13 - Please check the corresponding risks you apply the risk analysis methods:



Question	Health and Safety Risk	Project/Financial Risk	Geological Risk	Geological Event Risk	Pressure/Well Control Risk	Equipment Reliability	Barrier Reliability	Environmental Risk	Flow Assurance	Other (Please Specify)	Total
HAZOP (HAZard and Operability studies)	81.82%	36.36%	27.27%	27.27%	54.55%	36.36%	63.64%	45.45%	18.18%	9.09%	11
HACCP (Hazard Analysis and Critical Control Points)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0
SWIFT (Structured What-If Technique)	60.00%	40.00%	40.00%	20.00%	60.00%	20.00%	60.00%	80.00%	40.00%	0.00%	5
Scenario Analysis	41.67%	58.33%	41.67%	16.67%	50.00%	8.33%	25.00%	50.00%	8.33%	16.67%	12
Business Impact Analysis	37.50%	87.50%	37.50%	12.50%	25.00%	25.00%	12.50%	50.00%	37.50%	0.00%	8
Root Cause Analysis	54.55%	9.09%	27.27%	27.27%	72.73%	36.36%	27.27%	36.36%	18.18%	18.18%	11
FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis)	40.00%	20.00%	0.00%	0.00%	40.00%	40.00%	40.00%	0.00%	0.00%	0.00%	5
Fault Tree Analysis	50.00%	0.00%	0.00%	0.00%	75.00%	50.00%	75.00%	50.00%	25.00%	25.00%	4
Event Tree Analysis	40.00%	0.00%	20.00%	0.00%	80.00%	40.00%	100.00%	40.00%	20.00%	40.00%	5
Cause-and-Effect Analysis	33.33%	33.33%	33.33%	33.33%	44.44%	22.22%	44.44%	44.44%	22.22%	33.33%	9
LOPA (Layer of Protection Analysis)	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	1
HRA (Human Reliability Analysis)	0.00%	0.00%	0.00%	0.00%	100.00%	100.00%	100.00%	0.00%	0.00%	0.00%	1
Bow-Tie Analysis	60.00%	40.00%	20.00%	40.00%	60.00%	40.00%	40.00%	40.00%	20.00%	20.00%	5
Reliability Centred Maintenance	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0
Markov Analysis	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0
Bayesian Statistics and Bayes Nets	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	100.00%	0.00%	100.00%	1
Environmental Risk Assessment	66.67%	33.33%	22.22%	22.22%	33.33%	0.00%	0.00%	100.00%	0.00%	0.00%	9
Decision Tree Analysis	28.57%	71.43%	42.86%	14.29%	28.57%	14.29%	28.57%	57.14%	42.86%	0.00%	7
FN Curves	50.00%	0.00%	0.00%	0.00%	50.00%	0.00%	100.00%	50.00%	0.00%	50.00%	2

Risk Indices	75.00%	75.00%	50.00%	25.00%	75.00%	50.00%	75.00%	50.00%	50.00%	25.00%	4
Consequence/Probability Matrix	88.89%	77.78%	55.56%	33.33%	66.67%	44.44%	66.67%	77.78%	33.33%	22.22%	9
CBA (Cost/Benefit Analysis)	25.00%	50.00%	0.00%	25.00%	75.00%	25.00%	50.00%	25.00%	25.00%	0.00%	4
MCDA (Multi-Criteria Decision Analysis)	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1
Other Methods (Please Specify)	100.00 %	25.00%	25.00%	25.00%	25.00%	25.00%	50.00%	75.00%	25.00%	25.00%	4

14 - Please check the corresponding risks you apply the risk evaluation methods



Question	Health and Safety Risk	Project/Financial Risk	Geological Risk	Geological Event Risk	Pressure/Well Control Risk	Equipment Reliability	Barrier Reliability	Environmental Risk	Flow Assurance	Other (Please Specify)	Total
HACCP (Hazard Analysis and Critical Control Points)	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	1
SWIFT (Structured What-If Technique)	42.86%	57.14%	42.86%	42.86%	42.86%	14.29%	42.86%	28.57%	14.29%	0.00%	7
Root Cause Analysis	50.00%	10.00%	0.00%	10.00%	60.00%	20.00%	20.00%	30.00%	10.00%	10.00%	10
FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis)	50.00%	25.00%	0.00%	0.00%	25.00%	50.00%	25.00%	25.00%	0.00%	0.00%	4
Reliability Centred Maintenance	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1
Monte Carlo Simulation	11.11%	77.78%	33.33%	11.11%	33.33%	11.11%	33.33%	22.22%	22.22%	22.22%	9
Bayesian Statistics and Bayes Nets	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	100.00%	0.00%	100.00%	1
Environmental Risk Assessment	62.50%	25.00%	25.00%	25.00%	37.50%	0.00%	0.00%	100.00%	0.00%	0.00%	8
FN Curves	50.00%	0.00%	0.00%	0.00%	50.00%	0.00%	100.00%	50.00%	0.00%	50.00%	2
Risk Indices	50.00%	75.00%	75.00%	25.00%	75.00%	0.00%	25.00%	50.00%	25.00%	0.00%	4
Other Methods (Please Specify)	83.33%	33.33%	33.33%	33.33%	50.00%	33.33%	66.67%	66.67%	33.33%	16.67%	6

15 - Please provide your email address here if you are interested in participating in a webinar presenting the findings of this survey:

Please note that because of confidentiality issues, this information has been excluded from the report.

16 - Do you have any other comments, questions or concerns?

Please note that because of confidentiality issues, this information has been excluded from the report.