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Abstract

RBI (risk-based inspection) is an inspection scheduling method that relies on risk to produce inspection intervals for equipment. RBI is done by producing a risk characterization for the equipment in question and based on the level of risk, inspection intervals are determined. However, most of RBI processes use outdated approaches to handle the risk and they rely on old risk descriptions that do not capture the whole risk picture. This what motivates the current study in which an attempt is made to evaluate IKM's RBI and look for opportunities for improving it.

The study relies on qualitative data collected through open ended interviews with IKM employees. The goal of the interviews is to understand the approach followed by IKM to do their RBI.

The study resulted in discovering issues with assumptions in the program, finding multiple sources of uncertainty, highlighting issues with the knowledge behind the assessment, highlighting issues related to the risk description and ranking system, and discovering risk handling strategies deficiencies.

The study ended with some suggested improvements to reduce uncertainties in IKM's RBI. Some of the main suggestions are: inclusion of probability of detection and human error in the assessment, adoption of a better risk ranking system, having a strength of knowledge judgement system, uncovering assumptions which are not obvious (tacit assumptions), adoption of risk averse handling strategies, and finally, having a management review and judgement step.

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List of Acronyms and Abbreviations

IKM	A group of multidiscipline companies that are sub suppliers to the oil and gas industry
RBI	Risk based inspection
SK	Specific knowledge
GK	General knowledge
ALARP	As low as reasonably practicable
CBA	Cost-benefit analysis
Pof	Probability of failure
Cof	Consequence of failure
Sok	Strength of knowledge

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This master thesis is the final step to get my master's degree in risk analysis and governance. Although I have a passion for technical subjects and calculations, I found the program very interesting and challenging at the same time.

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1 Introduction

The risk science has been a focus point of discussion over the last decades. This was mainly due the inadequacy of the way risk is conceptualized, understood, and described. Those developments led to a new perspective that highlights uncertainty and knowledge dimensions instead of probability numbers. However, although those changes are judged necessary to cope with risk, current approach to describe and handled risk are still being inspired from old thinking which is outdated.

Science can be understood as:

"Science (in the broad sense) is the practice that provides us with the most reliable (i.e. epistemically most warranted) statements that can be made, at the time being, on subject matter covered by the community of knowledge disciplines, i.e. on nature, ourselves as human beings, our societies, our physical constructions, and our thought constructions."

(Hansson, 2013 as cited in Aven, 2019)

So, it is linked to time. And the use of an outdated approach towards risk when the risk science and field has provided more solid ways to conceptualize and describe risk is unreasonable. Those developments give a chance to improve IKM's RBI (risk-based inspection) program which is main purpose of this thesis.

An RBI program is a decision-making tool that should help and support the decision-making process to come up with inspection intervals based on the level of risk. Risk in an RBI program is the main component and ignoring some aspects of risk can potentially lead to a deficient inspection program. This is the main motive of this research.

This research project investigates IKM's RBI to highlight the sources of uncertainty in the program. The goal is to treat those sources of uncertainty. In other words, the thesis is looking to answer the following question:

"How to reduce uncertainties in IKM's RBI?"

This thesis is structured as follow. First, a literature review is done to highlight some of the important developments in the risk analysis field and to describe current approaches for RBI and highlight some of its potential weaknesses from a risk analysis point of view. Second, the methodology used to conduct the research is presented. Third, the results of the data collection and analysis are presented. Fourth, a discussion of the results is presented. Finally, the researcher makes some conclusions and recommendations for IKM to improve their RBI program.

2 Literature review

This section contains a literature review of some recent developments within the risk analysis field and risk-based inspection. Many important aspects of risk analysis are discussed and a general approach for risk-based inspection is given.

As pointed out by Cooper (2015). Literature review has four purposes:

- Integrate what other have done in the researched field
- Link different topics
- Point to issues in the field
- Criticize the work done by others

Literature review provides an orienting lens in terms of what to look for and what type of issues should be highlighted and the questions to be asked. This gives some idea about what sort of data should be collected, how it should be analyzed and where to look for the data.

The literature review is conducted by the following steps suggested by Creswell and Creswell (2018):

- Identify keywords related to the topic: generic keywords were initially used to find as much scientific articles as possible. For example: risk analysis, uncertainty, risk descriptions, risk analysis development, maintenance, maintenance optimization, maintenance scheduling, risk-based inspection, etc.
- Locate articles using relevant keywords: around 200 articles were initially located. Some of them were related to the research methodology.
- Filter based on the research needs: the articles were quickly read through to see which ones are relevant to the study.
- Summarize the articles.
- Make the literature review.

Considering the purpose and nature of the thesis, the literature review is placed at the beginning of the thesis in order to stimulate an inductive research design (Creswell & Creswell, 2018).

2.1 The risk analysis field

2.1.1 The definitions and descriptions of risk across time

The word risk, which can be tracked to at least the 12th century (Aven, 2012), is widely used in everyday conversations. Depending on the context, it means different things and can be either negative or positive. For example, when we talk about cancer, risk is being understood as the probability of a negative event. However, when we talk about risk in an investment context, taking risk can be of something positive as there is a potential for making a profit. In the 12th century, depending on the language of use, the meaning of the word was different back then. For example, the word risk is originated from the Arabic

word “rizq” which has different meanings. Rizq means fortune, chance, or anything given by god (Althaus, 2005; Aven, 2012) . While in Italian, the word means a possibility of harm (Aven, 2012).

While the concept of risk is loosely defined in everyday language, it must be defined based on solid foundations in order to understand and acknowledge risk and therefore to better manage the risk. For example, in literature, the concept of risk is found to have different meanings (Boholm, Möller, & Hansson, 2016) such as:

- an unwanted event that may or may not occur
- the cause of an unwanted event that may or may not occur
- the probability of an unwanted event that may or may not occur
- the statistical expectation value of an unwanted event that may or may not occur
- the fact that a decision is made under conditions of known probabilities

The concept of risk continued in changing over time and the way risk is described has also changed as a result. Aven (2012) found that risk definitions have been on a change since 1711. At that time risk was defined by Moivre as an expected value (Hald, de Moivre, & McClintock, 1984). For more about the how concept of risk is defined and understood, the reader is referred to (Aven, 2012).

Many risk definitions exist. Some of those definitions highlight exposure (Burt, 2001), while others focus on objectives (ISO, 2018). However, in this thesis, the following risk definition is adopted:

“Risk is the consequences of the activity and associated uncertainties” (SRA, 2018)

2.1.2 Risk analysis

While risk analysis can be understood as the process of understanding and expressing risk (Aven, 2015b), it can also understood in a broader way. For example, in Society for Risk Analysis, risk analysis includes risk assessment, risk characterization risk communication, risk management, and risk policy (SRA, 2018). In this thesis, the first understanding is used.

Risk analysis, which is the process of expressing risk, is done using many approaches depending on the level of detailing needed. Some of them rely on quantitative descriptions based on an expected value or expected loss, while others rely on a qualitative description that expresses risk levels using a scale ranging from low to high. Table 1 summarizes the different risk analysis categories, types, and their descriptions.

As mentioned before, expressing risk can be done under many forms. Some use probability and consequence descriptions under a risk matrix while others use an expected consequence. For example, in (Eskandarzade, Ratnayake, & Ershadi, 2020; Bai & Jin, 2015), they used a risk matrix to describe risk and therefore all risk related decision are based on a two-dimensional risk matrix. Risk matrices are not always a bad form of risk description, but they are not always capable of capturing the whole risk picture. Also, in

(Krishnasamy, Khan, & Haddara, 2005; Ozguc, 2020; Rachman & Ratnayake, 2019; Rusin & Wojaczek, 2019; Putra, Aryawan, & Purnawanti), they used another form of risk description which is the expected loss or consequence that also fails to capture the whole risk picture and ignores important aspects of risk which are uncertainties.

Table 1 Main categories of risk analysis methods

Category	Type of analysis	Description
Simplified	Qualitative	Simplified risk analysis is an informal procedure that establishes the risk picture using brainstorming sessions and group discussions. The risk might be presented on a coarse scale, for example, low, moderate or high, making no use of formalised risk analysis methods.
Standard	Qualitative or quantitative	Standard risk analysis is a more formalised procedure in which recognised risk analysis methods are used, such as Hazard and Operability study (HAZOP) and coarse risk analysis, to name a few. Risk matrices are often used to present the results.
Model-based	Quantitative	Model-based risk analysis makes use of techniques such as event tree analysis and fault tree analysis to calculate risk.

Source: (Aven, 2015b).

The importance of having a proper risk definition is that they way risk is defined and described affects the way risk is handled. For example, some expressions of risk that are based in expected values (see examples in the previous paragraph) ignore the possibility of adopting better strategies to handle the risk. This is going to be illustrated in the following section.

For example, if we take two events A and B with probabilities of occurrence P(A)=0.1 and P(B)=0.9 and expected consequences of $E(C_A)=9$ and $E(C_B)=1$. The risk description based on expected values should, in this case, produce the same risk value. Hence, putting those two events on the same level in terms of risk. However, the two events should be managed differently. This is one of the weaknesses of using the expected value as risk description.

The use of expected values in a risk context is justified by the portfolio theory (Abrahamsen, Aven, Vinnem, & Wiencke, 2004). The portfolio theory says that the total risk is equal to a systematic plus an unsystematic risk (Jones, 2001). The systematic risk is related to general market movement while the unsystematic risk is related to a single project. According to the portfolio theory, if there is diversification in projects, unsystematic risk related to the portfolio is ignored.

While the theory seems reasonable, it ignores the fact that risk from a single project can influence the other projects as well. To illustrate the problem, imagine that there is a

company called “X” managing different projects at the same time. At some point in time, an accident related to one of the projects occurs. Based on the portfolio theory, risk from that one single project should not be of great importance since the overall risk should be stable and equals the systematic risk. However, if that accident causes a loss of reputation for the company, the other projects should be affected as well. Therefore, in some situations, the portfolio theory is not a good basis for risk related decision making.

Basing the risk descripting on probabilities alone is also problematic. Since probabilities are usually based on some background information, describing the risk only based on probability is not a complete risk description. Take as an example someone named Robert. Robert usually leaves his house for work early in the morning. The weather is so cold and there is ice formation on his doorsteps. Robert assumed that his wife, who usually leaves for work before him, sprinkled some salt on the doorsteps to melt the ice and walk outside safely. Once he stepped outside his door, he slipped and broke his ankle because of the ice formation. Robert assumed something that influenced his judgement about the risk and his decision was based on the assumption that his wife sprinkled some salt on the doorsteps. While in fact, his wife did not sprinkle any salt that day as she was in a hurry to her work. This illustrates the importance of addressing more than just probabilities when measuring or describing risk.

The above example shows that risk description or measurement is usually based on some background information that includes all the assumptions and data used to assess the risk. This provides a motive to have a better risk description that includes the background knowledge as a part of the risk description. The background knowledge is linked to the potential of having a surprise in the form of an accident. The acknowledgment of that is crucial in order to manage the risk better.

The above types of risk descriptions also have some validity related issues (Aven, 2019, pp. 88-93). While validity can be divided to 7 types (Fitzner, 2007), in a risk context, validity can be understood as the degree to which a tool used to describe or measure risk is able to actually describe the risk. This is one of the reasons a new way to describe risk was found.

The understanding of risk and acknowledgment of risk are both important in order to manage the risk. While the understanding of risk involves understanding the possible scenarios and events that may occur. In other words, understanding risk means understanding the risk picture, how to use it, and what are its limitations. The acknowledgement of risk is linked to the fact that uncertainty is always there and the potential of surprise is always present (Amundrud & Aven, 2015).

Both of those concepts are related to the way risk is managed. A strong understanding of risk means having a good risk picture which can be used as a basis for decision making. The acknowledgement of risk is important to consider the uncertainty aspect of risk and adopt better risk handling strategies.

2.1.3 A better risk description

As stated before, excluding the background knowledge from the risk description leads to a short risk description in terms of capturing the whole risk picture. This motivates a new approach towards risk description. This section will introduce some of the improved risk descriptions and choose one to be used with the RBI.

In literature, risk is being described in many ways. Some risk descriptions highlight the probability of occurrence while others focus on expressing risk using an expected loss value. However, most of those risk descriptions fail to capture an important source of uncertainty.

For example, the (A,C,P) perspective is widely used and highlights three components of risk. A represents the event, C is the related consequence given the event A occurred, and P is the associated probabilities. This type of description ignores the fact that probabilities are usually based on some background knowledge and hence ignoring an important aspect of uncertainty when describing risk.

The second type of risk description, (A,C,U), highlights uncertainties instead of probabilities. This type of description acknowledges the fact that there is uncertainty related to the occurrence of the event A and what would the consequences be if A occurred. Risk in this description can be seen as objective and subjective if those uncertainties are linked to the assessor's knowledge or not. However, this can be improved by acknowledging and highlighting an important aspect of uncertainty which is knowledge. Leading to another risk description that adds the knowledge dimension K. Risk then would be described by (A,C,U,P,K) (Aven, 2010). Adding P and K to the description means that uncertainties are usually described by a probability P while highlighting K as there is always knowledge behind the probability numbers.

The inclusion of the background knowledge alone is, however, not enough. As the knowledge can be strong or weak which can lead to a poor risk description. Those issues are still being ignored up to this date in many risk assessments. Leading to surprises, or so-called black swans, in form accidents that are new to the knowledge behind the risk assessment.

So, the background knowledge should be included in the risk descriptions along with its strength (Sok: strength of knowledge). The following scoring system suggested by Flage and Aven (2009) can be used to say something about the strength of knowledge. The system is based on looking at the set of assumptions, data, experts' opinion, and the understanding of the involved phenomena.

- The knowledge is considered weak if at least one of the following conditions is met:
  - The assumptions made represent strong simplifications.
  - Data/information are non-existent or highly unreliable/irrelevant.
  - There is strong disagreement among experts.

        - The phenomena involved are poorly understood, models are non-existent or known/believed to give poor predictions.
    - On the opposite side. If the all the following conditions are met, the knowledge is considered strong:
        - The assumptions made are seen as very reasonable.
        - Large amount of reliable and relevant data/information are available.
        - There is a broad agreement among experts.
        - The phenomena involved are well understood; the models used are known to give predictions with the required accuracy.
    - Cases in between weak and strong are considered medium.

The inclusion of strength of knowledge leads to another perspective on risk description known as the (C,Q,K). C represents the set of consequences including the initiating events and risk sources. Q is the measure of uncertainty related to C and it contains both the probability numbers and the strength of knowledge (Sok) behind the assessment. K is the knowledge behind the assessment. For the purpose of this thesis, (C,Q,K) perspective is adopted as a describe risk.

The importance of having a similar risk description to (C,Q,K) is that it allows for differentiating between cases judged with high consequences and high uncertainties and other cases judged with low uncertainties. This gives the possibility of adopting different risk handling strategies instead of just using a risk acceptance criterion or basing the decision on a cost benefit type of analysis. This is elaborated in detail in the coming section.

Having a description of the three risk dimensions, a risk ranking can be made in order to understand which risks are higher than the others. The following risk ranking system is suggested by Aven and Flage (2018) to do such ranking:

- Very high risk: potential for extreme consequences, relatively large associated probability of such consequences and/or significant uncertainty (relatively weak background knowledge).
- High risk: potential for extreme consequences, relatively small associated probability of such consequences and moderate or weak background knowledge.
- Moderate risk: between low and high risk. For example, the potential for moderate consequences and weak background knowledge.
- Low risk: no potential for serious consequences

The understanding and acknowledgment of uncertainties when it comes to risk, changes the way risk is treated. Different strategies are used to deal with risk depending on the level of uncertainties. Going from a cautionary/precautionary principle to a strategy that is based on cost-benefit analysis. For example, in situations of events judged to have high consequences and the associated uncertainties are also high, the cautionary principle is to be adopted. This means to neglect inputs coming from analyses involving costs and benefits of the risk reducing measure. On the other hand, in situations where the

consequences are judged to be low and the related uncertainties are low, the strategy can be based on cost benefit type of analysis (Abrahamsen & Abrahamsen, 2015).

Since the knowledge changes from one assessor to another, the result of risk assessment also changes and therefore the risk characterization. To make this visible, the description of possible set of consequences is denoted by C' instead of C. The distinction between C' allows to distinguish the real consequences C from the specified consequences C'. C' is based on a selection and may change based on the background knowledge. This distinction is also important to denote the possibility of surprise.

2.1.4 The distinction between general and specific knowledge

The knowledge behind the assessment can be further divided into two types of knowledge (Aven & Kristensen, 2019). The first type is general knowledge and it is referred to as GK. The second type is specific knowledge and is referred to a SK.

The importance of gaining more knowledge is important from an economic perspective. If the knowledge is weak and the potential for severe consequences is high, then a cautionary approach for risk management is justified. However, being cautious means adapting robust and resilient design for the system. This does not come cheap. As making a system more robust means spending more money on extra safety layers. However, the risk handling strategy could be changed from a cautionary approach to a risk-based requirement approach if the knowledge is stronger and the uncertainties are low. If gaining more knowledge means reducing the uncertainties, then being conservative could be avoided.

To illustrate the importance of differentiating between GK and SK, an example is given in the next paragraph and illustrated by the Figure 1.

Figure 1 shows that an airplane is supposed to fly from Casablanca to Paris and then from Paris to Stavanger. In between those two flights, there is a one hour waiting time in order to onboard the Paris-Stavanger flight passengers. That one hour is not sufficient to conduct detailed assessment on the airplane to see if it is in a good shape for another flight. Instead, routine checks are performed to fulfil the risk based requirement or what can be called "good engineering practice" in ISO 17776 (ISO, 2016). The reason for adopting routine checks is that there is a lot of data of what can go wrong, and it would be unreasonably expensive to conduct a risk assessment for each flight. However, imagine another case where the airplane is going to fly through an area called Z where no airplane has been before. The atmosphere in area Z is similar to the atmosphere of Mars. In that case, it would be unreasonable to send the airplane to a new area without performing a risk assessment to see what the potential risks are, and whether it is a good decision to fly in area Z or not. The case of flying in area Z is a good example of weak SK. Flying in normal conditions is generally well understood and GK is strong. However, flying in area Z represents a new situation with weak SK. Performing detailed risk assessment or being cautious is then justified.

Figure 1 Airplane flying from Casablanca to Paris. Then from Paris to Stavanger.

The above example shows that the distinction between GK and SK is crucial to adopt better approach towards risk. The availability of flying data made it easier to fly by using all the data and expertise to produce routine checks. However, when flying in a totally new atmosphere, SK is weak as the atmosphere has changed. And unless more SK is generated, more conservative strategies should be adopted. Figure 2 gives a framework to adapt the risk handling strategy based on GK and SK.

2.1.5 Risk acceptance criteria and the tolerability of risk

The concept of risk acceptance criteria, or risk tolerability (Bouder, Slavin, & Löfstedt, 2007), denotes the existence of a threshold with which risk is compared, and a judgement is made about whether risk should be accepted or not. Figure 3 demonstrates three areas where risk is acceptable, tolerable, and intolerable. The risk acceptance criteria are usually needed in the risk assessment phase.

Risk assessment is part of many risk management frameworks which contains two steps (ISO, 2018; IRGC, 2017). The first step is risk characterization and the second step is risk evaluation. During the first step, risk is given a description which could be a value (expected loss of lives) or a qualitative description (low, medium, or high). That description is then used in the risk evaluation phase and compared with a risk acceptance criterion to make a judgement about the acceptability of the risk.

So, the risk assessment phase has two inputs. The first one is the evidence that represents the physical reality of risk (consequences for example). While the second input is value judgement that represents the acceptability of risk.

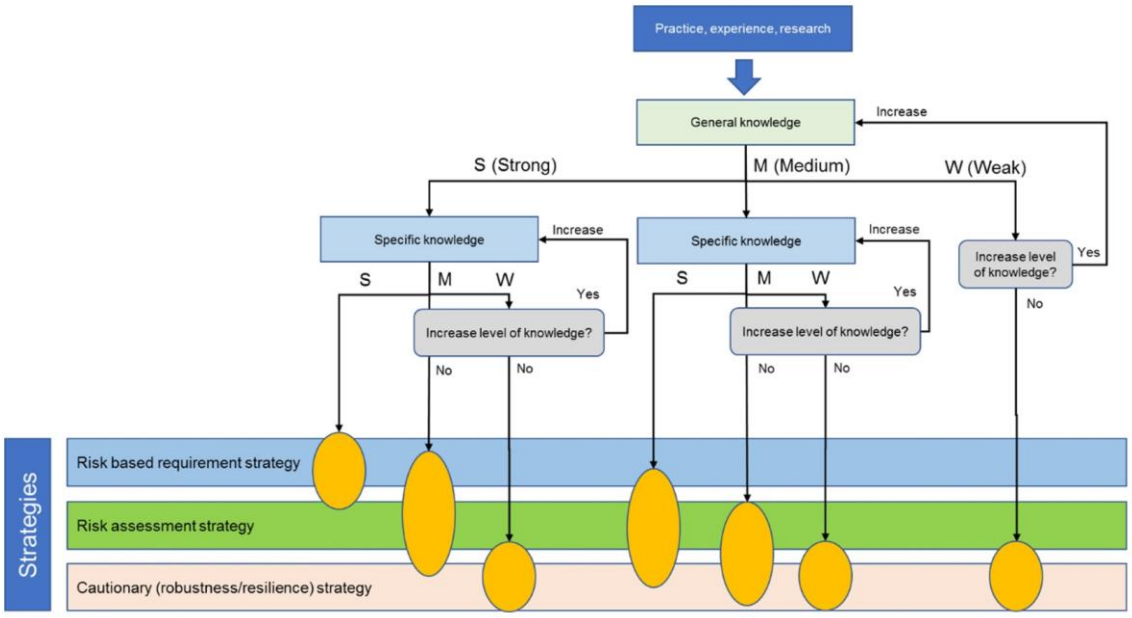

Figure 2 A model for risk management strategy, based on GK and SK.

Source: (Aven & Kristensen, 2019).

Making a judgement about the tolerability of risk is much more complicated that it looks like as it involves a value judgement. The value judgement is what sets the acceptance criterion to a high or low level because what might be considered too risky by group A, might be considered as not risky by group B.

The complexity of the value judgement changes with situations and types of risk and sometimes a discourse about evidence and/or values is needed (Renn, 2008). For example, in linear risks such as smoking, the situation is clear and the link between smoking and cancer is clear. An instrumental discourse which is about cooperation is needed. However, in other cases, other types of discourses are needed to either resolve a conflict (epistemic discourse for complex risks), reach a balance between excessive protection and being poorly protected (reflective discourse for uncertain risks), or to find a common ground for characterizing and evaluating ambiguous risks (Bouder et al., 2007).

2.1.6 Risk handling strategies

As stated in the previous chapter, different approaches are suitable to handle different risks based on the consequences and the uncertainties descriptions. In situations judged with high consequences and high uncertainties, a cautionary principle should be used instead of analysing the costs and benefits of the risk handling measures.

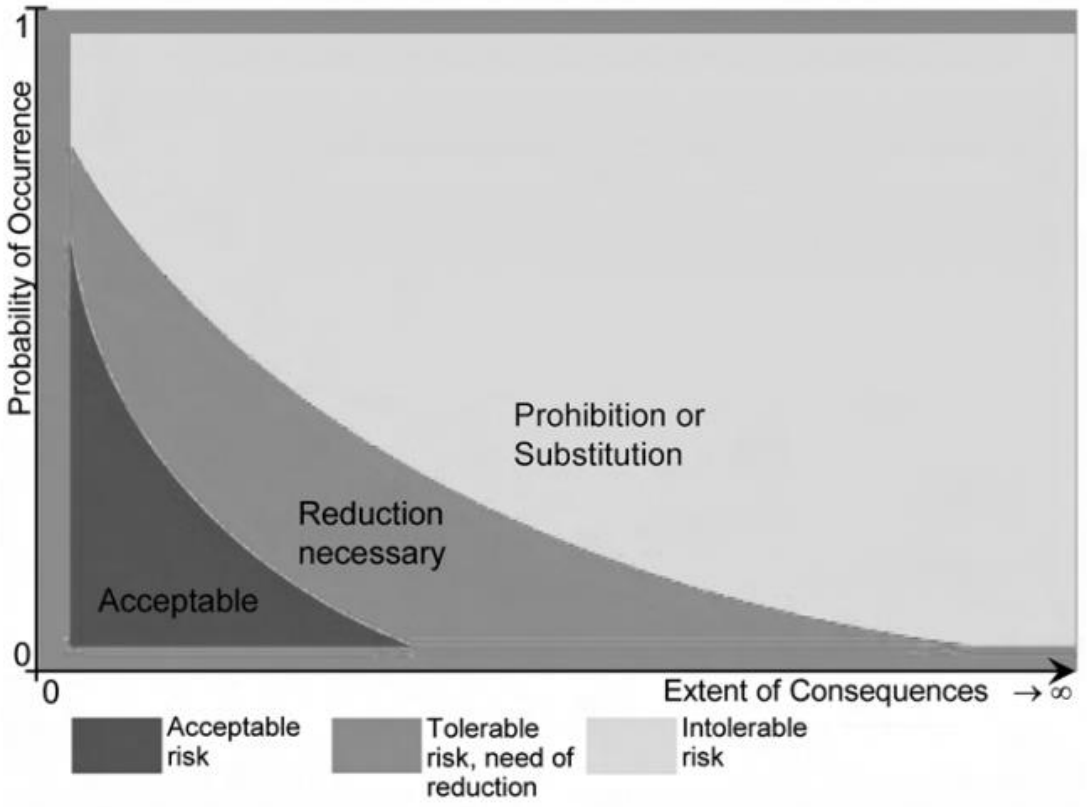

Figure 3 Acceptable, tolerable, and intolerable risks.

Source: (Bouder et al., 2007).

In the previous example used to illustrate the importance of assumptions and knowledge in the risk assessment, the situation could be described with high consequences since slipping on the doorsteps has the potential of causing serious injury. Those kinds of situation should be treated with cautious. However, in other situations, CBA (Cost-benefit analysis) is more suitable. Take as an example a case where the decision making is concerned about whether a light bulb should be changed once every year or until after failure. If the light bulb is used to light a non-critical place, the situation can be judged with low consequences. In this case a CBA can be used, and the light bulb should only be replaced after it fails as the cost of changing the light bulb once a year is higher than the gained benefits.

The above is a part of the ALARP (As Low As Reasonably Practicable) principle (Abrahamsen, Abrahamsen, Milazzo, & Selvik, 2018) that states the following:

"The risk should be reduced to a level that is As Low As Reasonably Practicable" (HSE, 2001)

The ALARP principle means that risk reducing measures should always be implemented given that it cannot be demonstrated that the costs are grossly disproportional to the benefits. This means that the ALARP principle is always leaning towards cautionary

principle with a potential of going to the other end of the spectrum and base the decision on expected values and CBA.

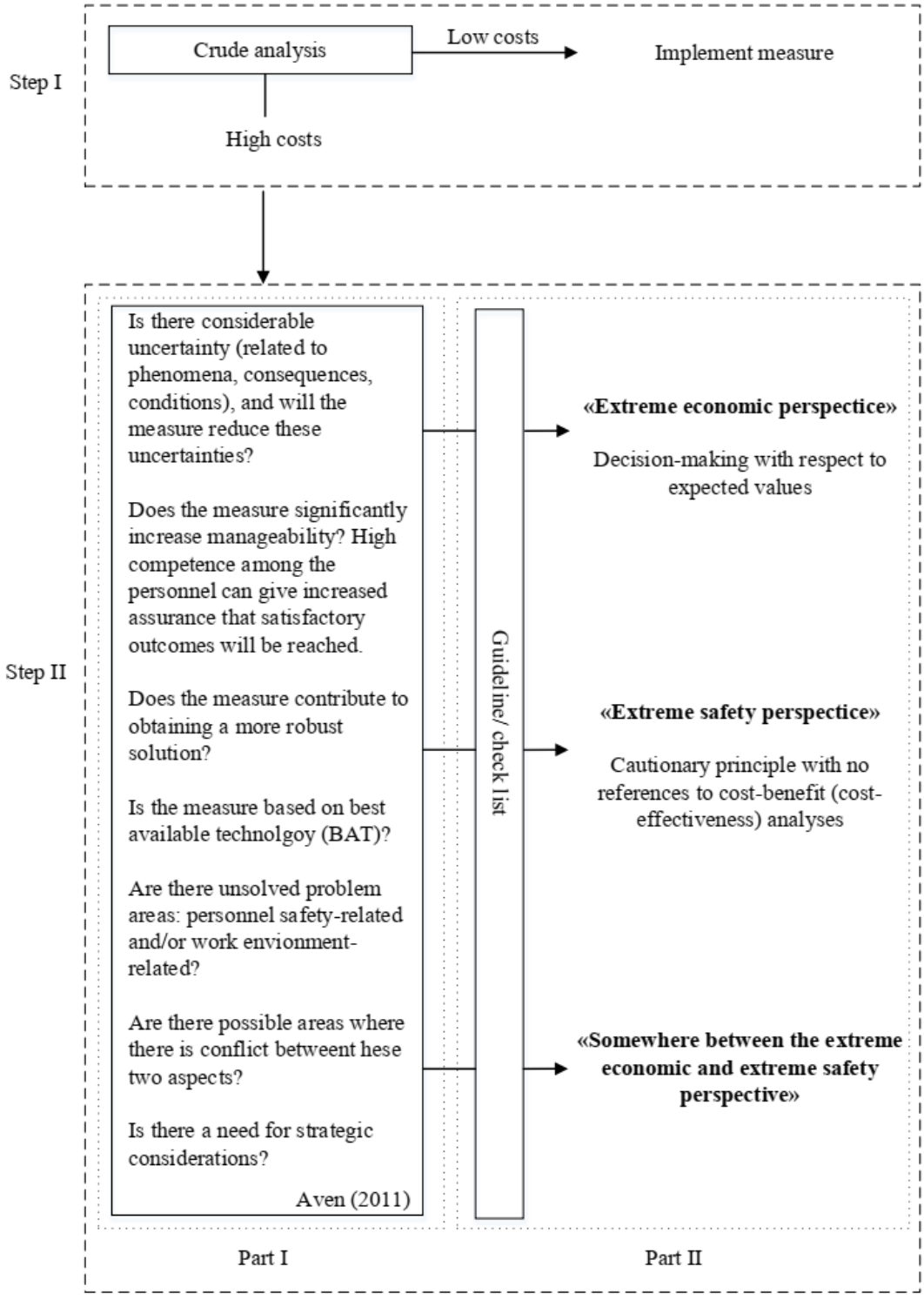

Figure 4 Layered approach for implementing the ALARP principle.

Source: (Abrahamsen & Abrahamsen, 2015).

Figure 4 shows how ALARP can be adopt in risk related decision making and how it can range from one extreme where decisions are made with reference to CBA to the other where cautious is adopted. In case of high consequences and high uncertainty situation, a cautionary principle should be adopted. While in situation judged with low associate consequences, the risk handling strategy should be based on a form of cost-benefit type of analysis.

Those principles are relevant when it comes to RBI. Since the RBI is a decision-making process centered around risk, it should adopt proper risk handling strategies depending on the level of uncertainties.

2.1.7 Managerial review and judgement

The risk analysis should always be seen in the light of used information. As the subjectivity of the assessment is inevitable, the background knowledge, the assumptions made, who assigned the probability numbers should always be considered before making a decision.

The managerial review and judgement is a step to put everything into perspective and make a decision. That is, to consider the available options in light of the assessment, knowledge and uncertainties and make a decision.

2.1.8 The possibility of surprise

Shortcomings of risk assessment have been linked to many events in the history. This is mainly due to the fact that risk assessment is usually not complete and ignoring the possibility of having surprises.

Surprise in risk assessment has been linked to accidents in many contexts such as the military (Handel, 1984), environment (Kates & Clark, 1996), and flood risk management (Merz, Vorogushyn, Lall, Viglione, & Blöschl, 2015).

The concept of black swans has been discussed in many scholarly articles. Taleb, the writer of the book “The Black Swan: The Impact of the Highly Improbable”, defines the concept of black swan as:

“First, it is an outlier, as it lies outside the realm of regular expectations, because nothing in the past can convincingly point to its possibility. Second, it carries an extreme impact (unlike the bird). Third, in spite of its outlier status, human nature makes us concoct explanations for its occurrence after the fact, making it explainable and predictable.” (Taleb, 2007)

The concept is illustrated by the example of the expedition that discovers the existence of black swans for the first time. The author goes on to explain that in order for something to qualify as a black swan, some criteria should be fulfilled. Those criteria are:

- rarity.
- Extreme impact.
- retrospective

The concept of black swan is of importance when it comes to the risk analysis field. As discussed earlier, some of the risk descriptions can hide uncertainties and therefore can cause some surprises in form of accidents. The concept of black swan shows the importance of considering surprises related to the knowledge used in the assessment.

In a risk context, black swans are defined as:

"A black swan is a surprising extreme event relative to the present knowledge/beliefs" (Aven, 2013).

And to differentiate between the types of black swans (depending on who has the knowledge), Aven (2015a) distinguishes between three different types:

- Known knowns: This type of events is known by everyone. But due to the low probability of occurring, the event is believed not to occur.
- Unknown knowns: This type of events comes as a surprise to some but not the others as they have the knowledge. This can be illustrated by the September 11 catastrophe. The victims on the airplane and the terrorists involved in the events knew about the event. However, the people in the two towers had no clue about what was coming for them.
- Unknown unknown: this type of events comes as a surprise for everyone as no one has the knowledge to foresee what is coming or what could happen.

While the concept of black swans is being defined and interpreted differently in many scholarly articles (Catanach & Ragatz, 2010; M. Yang, Khan, Lye, & Amyotte, 2015; Murphy, 2016), the purpose is somewhat still the same, to give highlight possible surprises. The concept is also getting popular and getting used in different context such as pandemics, economy, and cryptocurrency (Mishra, 2020; Rhee & Wu, 2020; Milovanov, Rasmussen, & Groslambert, 2021; Yarovaya, Matkovskyy, & Jalan, 2021). Other concepts such as grey swans, dragon kings, and perfect storms are also being used for the same purpose, to highlight the possibility of surprise (Glette-Iversen & Aven, 2021).

Sometimes, black swans are used an excuse to not spend money on safety measures (Ale, Hartford, & Slater, 2020), or to not take action to avoid those events. But they should be used as an opportunity to adopt a different thinking to avoid them. The following strategies can be adopted to reduce the probability of encountering a black swan:

- When it comes to an unknown-unknown type of black swan, resilience, warning signals, and knowledge generation are keywords.
- For unknown-knowns, improving the risk assessment to uncover those events along with improving the knowledge transfer to the relevant people performing the assessment are highlighted.
- Known-knowns can be tackled by acknowledging the fact that improbable events can still occur, understanding that probabilities are not enough to judge the risk, and adopting cautionary/precautionary principles.

2.1.9 Black swans in maintenance

Black swans also make sense in a maintenance context and therefore are important to be considered when performing RBI. This is proven by some maintenance related accidents. A study conducted by Okoh and Haugen (2014) where they investigated 183 major accidents in the process industry in Europe and the united states of America. Out of those 183 accidents, 80 (44%) were related to maintenance. The study also looked at different accidents' causes and concluded that 69% of those accidents were caused by deficient planning and fault diagnosis. The study states that two types of causes can be identified. Active and Latent. 34% of accidents were initiated by maintenance itself (Active). While 70% were caused by deficient risk analysis (Latent). The point made here is that the possibility of surprise is always present and the acknowledgement of that is important for reducing the probability of meeting one in real life.

Okoh and Haugen (2014) also discussed the causes of the accidents and linked them to two types. Active causes (or conditions) which are described as conditions having direct effect on the system, and latent causes or conditions which are described as being caused by the top decisions and are usually embedded in the work process (Reason, 1997). Table 2 summarizes their findings.

Table 2 Active and latent causes and their shares of being a cause to the accidents.

Active causes	Latent causes
▪ lack of barrier maintenance (50%) ▪ maintenance being an initiating event for an accident scenario (34%) ▪ maintenance error directly breaching barriers (21%) ▪ "maintenance introduces new hazards (15%)	▪ Deficient design/organization/resource management (85%) ▪ deficient risk analysis (70%) ▪ deficient documentation (51%) ▪ deficient implementation of requirements (44%) ▪ deficient monitoring of performance (23%) ▪ deficient management of change (21%) ▪ deficient learning (19%) ▪ deficient regulatory oversight (16%) ▪ deficient audit (11%) ▪ unbalanced safety and production goals (5%)

The acknowledgement of latent and active conditions is crucial to understand the potential causes of maintenance and inspection related accidents. Some of the identified causes in literature are human error (Hameed, Khan, & Ahmed, 2016) and probability of detection (Cronvall et al., 2012).

2.2 Risk based inspection and its weaknesses

2.2.1 Risk based inspection

Maintenance is an important activity of any industrial system. It is by which the system is assured to function and be available for functioning at any time. Maintenance contains many sub activities such as equipment checks, repair, and parts replacement when deemed necessary. Knowing when to perform the maintenance is tricky. As the resources are usually limited, the company seeking to perform a maintenance job is always looking for an optimal maintenance policy that balances the costs and benefits of the maintenance. This leads to maintenance optimization which has been around since early sixties (Dekker, 1996).

The literature points to many optimization models and polices (Garg & Deshmukh, 2006). Some of them are based on age, while some others are based on block repair policy, periodic repair policy, etc. Those policies are intended to reduce the costs of maintenance and the costs resulting from failures. It is acknowledged that some types of equipment are best to left run until failure such as lamps. Some other equipment can cause much damage or production losses if left run until failure.

Two main types of maintenance can be found. The first one is corrective maintenance which is carried out after failure or after a fault is recognized. The second type is preventive maintenance and its objective is to keep a system functioning at a high reliability and/or with minimum risk. The way preventive maintenance works is by finding optimal intervals that enables the inspection of equipment before the reliability decreases to a certain level or the risk reaches a threshold (risk acceptance criterion). RBI is one of the tools used in preventive maintenance and it focuses on risk to determine when to inspect the equipment (Stenström, Norrbin, Parida, & Kumar, 2016). The development of the concept was initially motivated by the possibility of achieving tolerable risk levels (Khan & Haddara, 2004).

Despite the fact that reliability is already being used as a maintenance input in different industries, risk-based inspection provides a more solid decision tool for the prioritisation of the inspections and maintenance works. While a link can be established between reliability and risk (Singpurwalla, 2006; Finkelstein, 2008; Cox, 2008), high reliability does not necessarily mean low risk. Since measuring reliability does not give any indication of what type of consequences could result upon failure. Take for example a system that consists of one lamp in one room. The reliability of the lighting system can be improved by adding more lamps to the room so the probability of having no lights at all is small. However, having a low probability of having “no lights” has nothing to do with risk. If there is nothing to be affected and no consequences to be identified if all the lamps fail, the risk is simply not there. So, basing the inspection on the risk description provides a more solid ground for inspection scheduling.

The RBI can be done qualitatively, quantitatively, or using both approaches (DNV, 2010). The difference in those approaches are the way inspection intervals are produced. For

example, using a qualitative approach for RBI is easy and fast as it relies on expert judgement rather than calculations. However, updating the inspection data after an inspection is difficult and the use of risk acceptance criteria is not possible with qualitative RBI. On the other hand, a quantitative approach for RBI is more objective and allows to quickly update the inspection interval following an inspection using statistical modelling, Bayesian models, statistical simulation, and Markovian deterioration modelling (Garg & Deshmukh, 2006). A quantitative approach also allows the use of risk acceptance criteria.

The concept of RBI uses the level of risk to make a decision on how often the inspection should be performed. Two inputs are usually needed to perform an RBI, a measure of consequence of failure (Cof) and a measure of probability of failure (Pof). These inputs can be used in many ways to have a risk description. For example, many articles suggest that those inputs should be used in a risk matrix (Bertolini, Bevilacqua, Ciarapica, & Giacchetta, 2009), while others use them quantitatively (Khan & Haddara, 2003) and compare the product with a risk acceptance criterion. The probability of failure can be determined either from historical data or from expert judgement.

RBI programs seek to answer four questions (Faber, 2002): What, where, when, and how. And they generally start with a criticality analysis followed by a detailed analysis of medium to high risk equipment. The reason to follow such sequence is to eliminate low risk items in the initial phase and give priority to high risk items for a detailed analysis.

The inspection interval in an RBI depends on many inputs (Faber, 2002):

- The degradation of equipment
- Inspection quality
- Inspection times
- Inspection results
- Environment
- Safety
- Practical constraint
- Acceptance criteria

2.2.2 Shortcomings of the current approaches for RBI

It is not a surprise that a lot of RBI approaches are still based on short risk descriptions. Many approaches are still using expected values as their basis for describing risk (P. K. Dey, 2004; Prasanta K Dey, Ogunlana, Gupta, & Tabucanon, 1998; Reynolds & Aller, 1996). However, those approaches are not in line with the main motive of RBI. Since RBI is motivated by using risk levels to decide on the length of the inspection interval. This is demonstrated by past incidents in the history in which inspection was based on weak foundation.

The importance of considering other aspects and sources of risk are demonstrated by the crash of a Boeing 747 on flight JL 123. The crash occurred on the 12 of august 1985 with a registered 520 death and only 4 survivals (JTSB, 1987). The cause of the crash was due

to maintenance deficiency because of inspection difficulties. The part that was responsible of the crash was not accessible for visual inspection and therefore was skipped during inspection (Reason, 1997, p. 89).

Going back to the lamps example to demonstrate the effect of the assumptions behind the analysis in RBI. If the lamps are placed in an area with high humidity, the probability distribution of lifetime should have an expected value smaller that in cases where the lamps are placed in a location with low humidity. The example of placing the lamps in a humid place is also showing that the expected time until failure provided by the manufacturer should be used cautiously. As the time until failure provided by the manufacturer is also based on some assumptions that influence the probability distribution.

The above example shows that inspection can be a cause for major accidents. The example also show that the management should take into account those difficulties when making decisions about inspection intervals, especially for high risk items. This can be considered by introducing more inputs to the decision making process such as the probability of detection (Carboni & Beretta, 2007; Y. Yang & Sørensen, 2019) and human error (Hameed et al., 2016).

2.3 Research questions

In order to solve the problem, some questions are crucial to answer. The questions below are derived from the literature review. Two types of research questions should be answered. Primary questions which are the guiding compass for the research and sub-questions that deal with specific areas and help answering the primary questions.

Primary research questions:

- Is IKM's RBI approach perfect?
- If not, how can it be improved?

In order to answer the primary questions, the following secondary research questions should be answered.

- How IKM formulates and define the probabilities used in their RBI?
- How the set of consequences is formulated and used in the RBI?
- What are the sources of uncertainties in IKM's RBI?
- How the inspections are usually performed? Emphasis here is on the inspection methods as different inspection methods are more suitable than others to detect deterioration processes and hence increasing the probability of detection (POD)
- Are there any efforts to include the possibility of human error in the RBI?

The above research questions are the basis for the interview protocol.

3 Method

An important section of any research is the method section. It constitutes the main guide of the research in terms of what needs to be done and how to do it and it should address many issues that can rise during the research. This section discusses how the research will be carried out and how the validity and reliability is assured.

3.1 Methodology

The research methodology is decided based on the intersection of three choices. The first of these three choices is the philosophical assumption or research philosophy used in the research. The second thing is the research design. The third thing is the research method. The following sections explains the rationales for making such choices and how they should help to answer the research questions.

3.1.1 Choice of methodology

Starting by introducing the available research approaches first. Three research approaches exist. Qualitative, Quantitative, and mixed methods. The choice of either of them depends mainly on the goal of the study and what is the expected outcome of the study.

Qualitative research is of an exploratory nature and is suitable to understand and explore some social phenomena or problem. For example, if a study is looking to understand what factors influence the risk perception of a certain population, then a qualitative approach is justified and should be used.

Quantitative approaches are more suitable to test theories based on measured variables and performing statistical analysis on the data to make conclusions. For example, to decide whether there is causal link between distance learning during the covid-19 lockdown and depression among students, or whether there is a correlation between the unemployment rate the domestic violence.

Mixed methods involve the collection and combination of two types of data (qualitative and quantitative) to produce insights that cannot be produced by either of the former two approaches.

As will be shown and justified later, a qualitative approach is chosen for this thesis. some of its characteristics are given below (Marshall & Rossman, 2014; Hatch, 2002; Creswell & Báez, 2020):

- The researcher is the one deciding which data is relevant to the research and proceed to make a list of what kind of data is needed to complete the research. In the case of this thesis, a list of questions are developed from a body of relevant literature which are used later on as an interview protocol.
- Sources of data: In qualitative research, the researcher collects data from various sources to ensure the validity and reliability of data (Will be discussed separately) such as data from interviews, documents, images, videos, audios. Interviews

represent to perfect tool for qualitative research as they give the opportunity to collect much data through open ended questions.
- The participants point of view: in qualitative research the, the focus is on the point of views that the participants bring to the study about the problem and not the researcher's point of view.

3.1.2 The research paradigm

This section is consecrated to explore the four most popular research paradigms, or philosophical worldviews as referred to in some books, and then deciding which one should be used based on the goal of the research.

The first research paradigm is the postpositivist which is usually performed using quantitative approaches. Sometimes called scientific method. This worldview is concerned about challenging the idea of absolute truth (Phillips & Burbules, 2000). In this paradigm, the researcher looks to identify causal links to some specific outcomes using experiments and to test hypothesis using measurable variables and statistical analysis.

The second worldview is the constructivist. The approach is mainly done using qualitative approach. In this paradigm, the research is looking to understand the participants' views about the real world by gathering as much data as possible. This is done by adopting an inductive approach rather than a deductive one using open ended questions. The participants in this paradigm have the opportunity to share their thoughts and view in a non-limited way such as in close ended questions.

The third worldview is the transformative paradigm. This paradigm is similar to the postpositivist paradigm, but it is a result of the idea that postpositivist paradigm is not a good fit for marginalized individuals or issues such as power and discrimination (Creswell & Creswell, 2018). The group of researchers adopting this paradigm includes feminists, critical theorists, etc.

According to Mertens (2014), transformative paradigm is suitable for cases when:

- The studies population is marginalized.
- The focus is on inequities such as the ones based on gender, sexual orientation, race, disability, ethnicity, socioeconomic class.
- Trying to Establish a link between political and social actions and the above inequities.

The fourth and last paradigm is the pragmatic. This paradigm is concerned about what works to answer a research question. Unlike the other paradigms, being pragmatic is about employing all the necessary means to answer a question. For example, being a postpositivist generally points towards a quantitative approach to challenge a theory and make conclusion using statistical analysis. While being a constructivist means employing qualitative approach to understand and exploit a social phenomenon, being pragmatic is about combining both approaches rather than siding with one approach. For example, the researcher can focus on a small population first to identify relevant variables to some

phenomenon using interviews, then work on a bigger population and collect more data using surveys to measure those variables and perform statistical analysis.

Although the pragmatic paradigm looks appealing in terms of its flexibility, the chosen paradigm for this study is the constructivist. This is justified by the fact that the research is performed to understand a population (IKM) rather than performing any sort of quantitative analysis.

3.1.3 The research design

Choosing the methodology of research is not just about picking a paradigm or the research approach (qualitative, quantitative, or mixed), but also about choosing a research design.

Research design are types of enquiries that constitute the main guide to answer the research questions. The choice of a specific research design should be justified by the objective of the study.

Many research designs can be identified in literature. When trying to establish a causal relationship between some inputs and outputs, an experimental is suitable. However, when trying to describe the experience of induvial with a certain phenomenon, the experimental design is not suitable.

Within the qualitative approaches, there exist several research designs (Tesch, 2013; Wolcott, 2008). Narrative research is a design that is suitable for studying the lives of individuals. Grounded theory is another research design that is popular in sociology in which the researcher is looking to establish a general theory from the collected data.

When the researcher is studying a specific population or looking to perform some sort of evaluation of a program or an activity, the case study design is appropriate to follow. This type of study design is suitable for this thesis as the goal is to evaluate IKM's approach for RBI.

3.1.4 The research method

Among the available data collection methods, the choice of one of them should also be justified by the nature and the objective of the research. This thesis is concerned about exploring and understanding IKM's RBI. For that purpose, the choice of data collection method is through open ended interviews. The interview protocol is presented in appendix A.

Open ended interviews are common in qualitative research as they enable the researcher to gather a lot of information from a specific and not-so-large population. However, in some cases, the researcher might also rely on other source of data in order to ensure the validity of the researcher. This will be discussed in detail in the "validity and reliability" section.

According to Miles and Huberman (1994), the selection of participants should be justified based on four criteria:

- Setting: the nature of the study and data needed is not linked to the physical being in the company. The data was collected by interviews through Microsoft teams as the Covid-19 situation did not allow for physical meeting with the participants.
- Participants: the participant of this study are two out of three employees that are involved in the developing of the RBI program. The reason for the small sample is because only those employees are involved in the making of the program and involving other participants with little to no knowledge about the program would just reduce the quality of the data.
- Number of participants: 2.
- Data to be collected: interviews and a document explaining IKM's RBI.

Creswell and Creswell (2018) suggest the use of a systematic approach to analysis the data (See Figure 5). The approach comprises 5 steps:

- Step 1: preparing the data of the analysis. Transcribing and importing different documents to the software.
- Step 2: going through the data to gain some sense of what story the data is telling.
- Step 3: Start coding relevant sections.
- Step 4: Generate descriptions and themes.
- Step 5: Represent the description and themes.

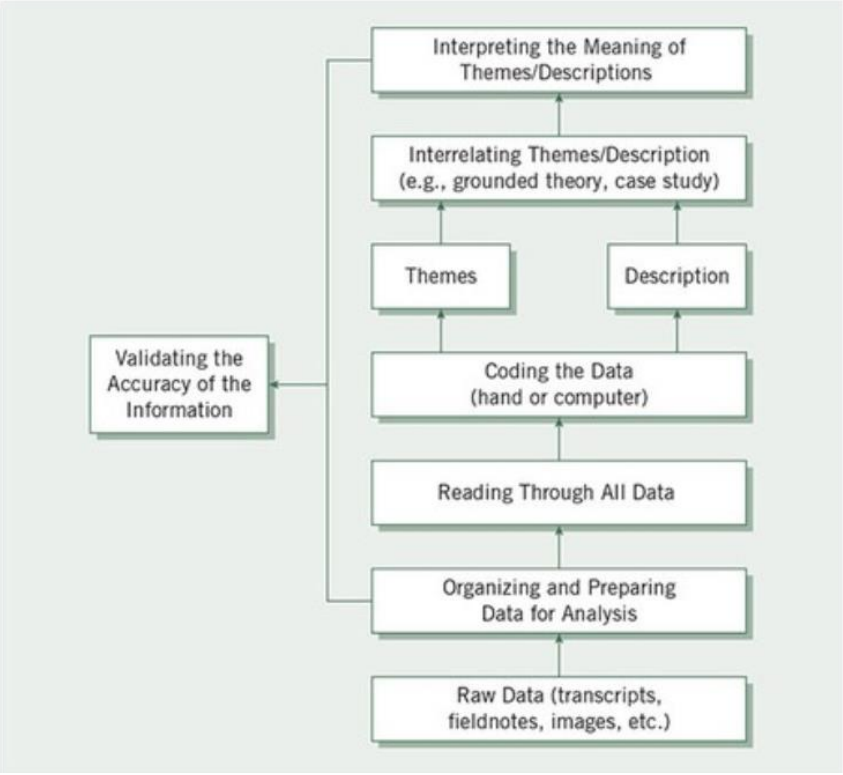

Figure 5 Data Analysis in Qualitative Research.

Source: (Creswell & Creswell, 2018).

Löfgren (2013), Braun and Clarke (2006) suggested a similar approach. The approach is called “thematic analysis” which is presented below.

- Step 1: Familiarization with the data.
- Step 2: Coding.
- Step 3: Generating initial themes.
- Step 4: Reviewing themes.
- Step 5: Defining and naming themes.
- Step 6: Writing up.

The analysis approach used in this thesis is a combination of both approaches presented above. An inductive and descriptive coding approach was adopted. The researched, however, acknowledges that some codes were generated deductively because of previous knowledge about the field.

For the data analysis process to take place, the interviews had to be transcribed first. The transcription was done using an online tool named “OTTER.IO” that provides transcription services. After the transcription was done, a coding process took place to label relevant sections of the transcript with a relevant code.

The transcripts were checked after the tool was done with the transcription process to make sure that the text file matches the audio file. A sample of the transcription is presented in appendix B with an example of the coding used. The analysis was done by NVivo which is a software for analyzing qualitative data.

3.2 Data and sources

This thesis needs multiple sources of information to be completed. The first source is IKM as a provider of their internal procedure for RBI. In addition to that, standards governing the procedures of RBI are used as a guide to better understand the company’s RBI approach. And finally, the body of literature review that acts act as the guiding arrow to answer the research questions.

Two interviews were performed. The first one was around 30mins while the second one was around 60mins. Table 3 shows the participants’ functions and how much time spent on the interviews.

Table 3 interview participants' functions

Participant	Function	Time spent on interview
1	Senior technical integrity engineer	30 mins
2	Chief technology officer	60 mins

3.3 Validity and reliability

The validly and reliability of research are important to have some sense of the quality of the research. The methods used to ensure the reliability and validity as suggested by Creswell and Creswell (2018) are presented below.

To ensure the validity:

- Data triangle: data from interviews and a document were used to make sure the diversity of data.
- Use a rich, thick description to convey the findings
- Clarify the bias the researcher brings to the study: this is tackled in the reflexivity section.
- Modifying information: All the data used is at its pure state. The researcher used both the negative and positive sides of the data.
- Use an external auditor: The research was reviewed by a fellow student to see if there is anything that could be improved to make the research more valid and reliable.

To ensure the reliability:

- Checking transcripts: after the transcription process was done by the software, all transcripts were checked to see if they match the audio file used.
- checking codes and data: codes were checked to make sure that they actually represent the data.

3.4 Ethical issues

As in many research projects, the involvement of other human beings and the collection of data from them is inevitable. And because of that, the research must adhere to some ethical considerations. The following list suggested by Creswell and Creswell (2018) is used in order to address the ethical issues that can rise before and during the research. Many steps are discussed in (Creswell & Creswell, 2018) in details. However, not all of them are relevant to this thesis.

- Prior to conducing the research:

Necessary permissions: the researcher should obtain the necessary permissions to have access to the participants. This is ensured by the agreement signed with IKM.

Profit from research: the researcher should seek and select a site (IKM in this case) without any benefit, profit, or interest. The nature of this thesis and the research performed does not allow for such thing. Since there is no influence or power from IKM’s side on the research performed.

- At the beginning and during the research:

Objective of research: it is advised to identify a research problem that is beneficial to the participants. This is ensured by the fact that the thesis is being done with a goal to improve IKM's RBI.

Pressuring participants: although the more data is collected from the participants the better, the participation was voluntary, and no participant were pressured to participate in the study. Therefore, two out of thee engineers were the only source of data collected from interviews.

Respect the privacy: No identity disclosure was done. In qualitative research where interviews are the methods of data collection. It is difficult to have any sort of privacy as the researcher knows the participants. But their privacy is ensured by not disclosing any of that information to any person.

Harmful data collection: The nature of the research does not involve the collection of any information that could be harmful to the participants, as the research is not concerned about any personal data.

3.5 Other considerations and comments about the research methodology

3.5.1 The audience

The audience to whom this thesis is written consist of the staff of IKM, professors and students from the risk management and risk analysis and governance programs, and the other professors from other departments as well.

The choice of the research methodology is done by considering the audiences discussed above. Professors from the university are familiar with most research approaches. However, the qualitative approaches are more common within the risk analysis field. The field looks into many issues related to risk. One of those issues is the way risk is being described and characterized. The study of those issues is done using a qualitative approach rather than a quantitative one.

Moreover, students of the university of Stavanger have different backgrounds. The choice of the method was done taking the different backgrounds into account. A technical student may find it easy to understand quantitative approaches rather than a qualitative one. But he/she can also understand qualitative approaches. However, for a student from a non-technical study background such as societal safety, qualitative approaches are more suitable.

3.5.2 Winnowing the data

The author is aware that the data gathered is rich with information. However, the use of that data is dependent on the goal of the research and interest of the researcher. For example, the same set of data gathered in this thesis can be used to performed other research under other topics. The reason this is mentioned is because there is a process called

"winnowing the data". It means that the researcher will only look at parts of data while ignoring other aspects because of non-relevancy.

3.5.3 The reflexivity

In qualitative research, the researcher has an interpretative role. This means that the same set of data can be interpreted differently base on the intertest of the researcher and the research problem. Not like in quantitative research where the data is mostly being analyzed and discussed objectively by the mean of statistical analysis. The result of the discussion ana analysis of data is preconditioned on many things. This is called reflexivity and it might shape the data analysis and discussion process. Reflexivity mainly depends on the educational background and experiences of the researcher.

3.6 Expectations

The expected result of the thesis is to have a new framework for RBI that reflects uncertainties in a better way by focusing on the potential causes of uncertainties and addressing them in a new framework.

3.7 Limitations

While risk-based inspection programs can be improved from different perspectives such as models to calculate inspection interval or degradation processes modelling, this thesis is limited to the analysis of IKM's RBI in terms of potential uncertainty sources and how they can be integrated in their framework rather than doing calculation and modelling for different processes of degradation.

The researcher also acknowledges the small sample size that consists of two employees and 1 document from IKM about their RBI. That being said, the nature of the study allows for small sample size. Any attempt to make the sample larger will result in too much irrelevant data as the focus here is IKM's RBI.

IKM's RBI is in development process. This also limits the potential of the study, as only the work done so far by the company was considered in the study.

4 Results

A total of 33 codes were generated. But only relevant codes were used to make a map showing the connection between them. Figure 6 represents the codes used and the connections between them.

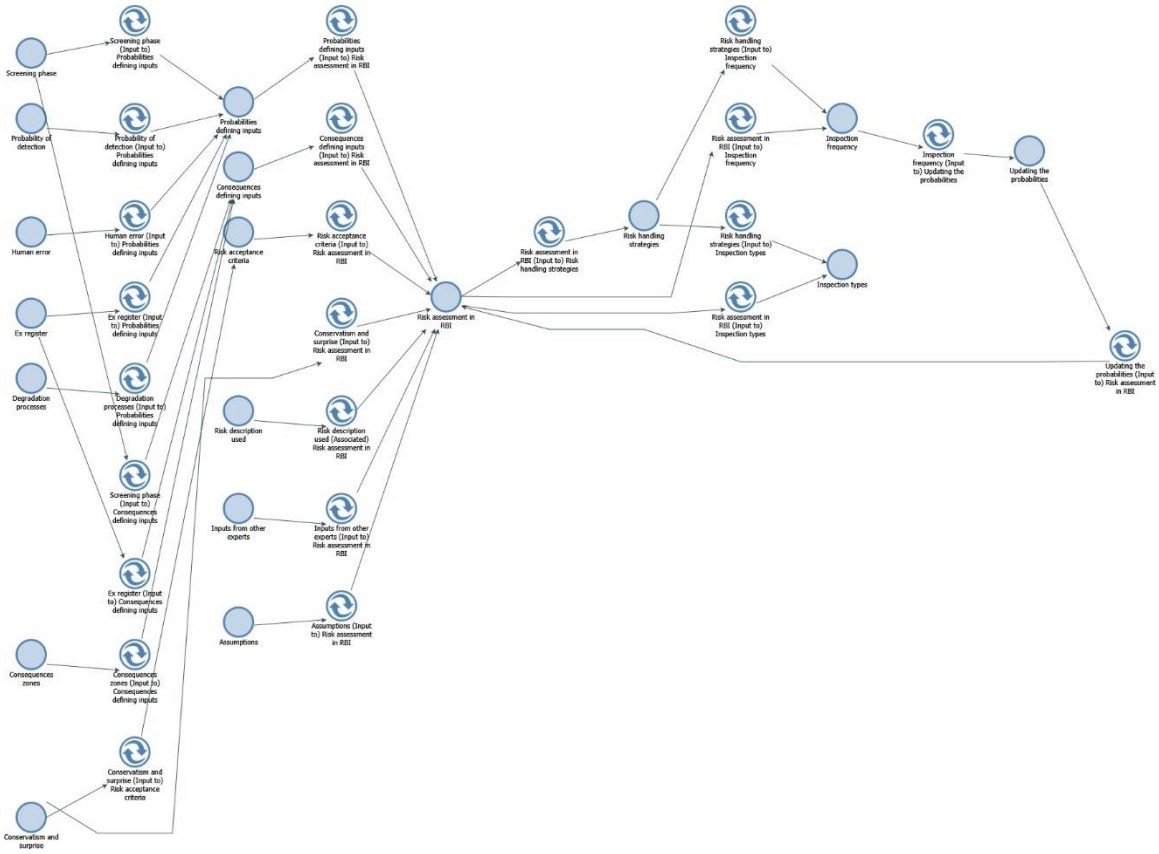

Figure 6 Codes used from NVivo and the connection between them.

4.1 Probability of failure inputs

The approach suggested by IKM is to assign probability numbers based on "best guess". The assignment of probability is, however, not totally subjective, or arbitrary. Many inputs are used to say something about the probability of failure such as the exposure of equipment to harsh environment, material, protection type, exposure to chemicals, and mechanical load. Those information are initially sent by the client company to IKM so an initial RBI can be done.

The initial probability assignment is done to ensure the completion of the initial risk assessment and have a starting point. After the inspections are starting to take place and more data is emerging, the probabilities get updated based on historical failure data.

The program uses 5 Pof classes: Very unlikely, unlikely, possible, likely, and very likely. Figure 7 shows the Pof levels with their explanations.

4.2 Consequences and risk factors.

The set of consequences used in the RBI program contains 5 levels. Starting from negligible up to very high. The levels are shown and explained in Figure 7.

The magnitude of consequences is affected by the following risk factors:

- The zone in which the equipment is placed: three high risk zones exist which are susceptible to have flammable gases and are labeled by zone 0,1, or 2. The fourth zone is called “safe area” in which no flammable gases exist. The three hazardous zones are described as follow (E2S, 2013):
    - 0: Explosive atmosphere present continuously.
    - 1: Explosive atmosphere likely to be present in normal operation.
    - 2: Explosive atmosphere not likely to be present but may be present for short periods.
- Protection type: equipment have different protections again various types of ignition. Each ignition type is only capable of resulting in a fire or an explosion when specific conditions are present such as flammable substance type and flammable gas concentration in air (Kuchta, 1986).

RISK MATRIX			HAZARD SEVERITY				
			LOW		MEDIUM	HIGH	
			Negligible (1) Negligible consequence	Slight (2) Minor consequiense requiring	Moderate (3) Failure leading to a LTA	High (4) Involving single death/serious injury	Very High (5) Multiple Deaths
Likelihood of Occurrence	L	Very Unlikely (1) A freak combination of factors would be required for an failure to result	LOW	LOW	LOW	LOW	LOW
		Unlikely (2) A rare combination of factors would be require for an failure to occur	LOW	LOW	LOW	MED	MED
	M	Possible (3) Could happen when additional factors are present	LOW	LOW	MED	MED	HIGH
	H	Likely (4) Not certain to happen but additional factors may result in a failure	LOW	MED	MED	HIGH	HIGH
		Very Likely (5) Almost inevitable that a failure would result	MED	MED	HIGH	HIGH	HIGH

LOW	MEDIUM	HIGH
5 year visual inspection (Typical 20% anually) and 2% detailed inspection anually	3 year visual inspection (Typical 33,3% anually) and 5% detailed inspection anually	1 year visual inspection and 10% detailed inspection anually

Figure 7 IKM's RBI risk matrix

Source: retrieved from the document share by IKM.

4.3 Human error

Although it was acknowledged that human error exists, there are no efforts from IKM’s side to include human error in their RBI. This is due to the fact that the inclusion of human error can be time and resources consuming and will only make the workflow more complicated. Some comments from one employee indicated that the human error is being

addressed by using a digital inspection system that uses a tablet as an input. The stated reason for not taking human error into consideration is because of the abundance number of tags to be inspected. However, the inspector is encouraged to make correction if he/she sees that something onsite is not corresponding to the information on the tablet.

The digital system uses a tablet to make a systematic inspection routine. This has been done to not miss any tag without inspection.

4.4 Risk handling strategies and conservatism

The data suggest that the company has a neutral attitude towards risk. The result from the risk assessment are treated without showing any risk aversion behavior.

The results obtained from the risk assessment are inserted in a risk matrix without referring to any risk averse handling strategies or introducing tighter risk acceptance criteria as an act of conservatism.

4.5 Probability of detection

While the human error has been already mentioned in the findings above, the probability of detection is not the same as human error. Probability of detection is related to the difficulty of noticing an ongoing degradation process.

Based on the interviews, the probability of detection is not considered in the RBI program.

4.6 Assumptions in the program:

The data from the interviews states that some assumptions are made in order to make the workflow better and to reduce the amount of work the company has to do.

The company assumed that the data received from the client company is correct. The data correspond to an excel sheet with information about all the tags on the installation. The data contains the type of equipment, what it is made of, the state of the equipment in terms of degradation, and the zone in which the item is placed.

An initial risk assessment is usually performed on all the tags where the assignment of probability is made by “best guess”. The company assumes that the risk assessment is correct.

4.7 Risk ranking and risk acceptance criterion:

The program uses a risk ranking that is based on expected values. The risk is being calculated by multiplying the consequence class (Cof) by the probability class (Pof). The product is to be to be compared with risk acceptance criterion in order to classify the item in question. Table 4 Shows an example of the risk score calculation.

Items are classified as:

- Green: if the risk score is at most 6.
- Yellow: if the risk score is at least 7 and at most 12.

- Red: if the risk score is at least 15.

Table 4 examples of the risk calculations done by IKM

Risk Description	Risk Evaluation	Probability Class	Consequence Class	Risk Score & Category (color)	Consequence/description
Risk of corrosion beyond design limits	-installed in climate controlled areas. -produced in non corrosive materials. -surface treatment by design	1	3	3	Corrotion of the equipment will have impact of the Ex integrity.
Risk of external impact destructing the equipment and mechanical damage	-no lifting activities -no forklift activities -no heavy mechanical activities -sheltered areas	1	3	3	The level of impact force will have a degrading effect on Ex integrity.
Risk of moisture or water ingress in equipment	-installed in climate controlled areas -no exaggerated use of water	1	2	2	Moisture or water will have a minor impact of the Ex integrity.
Risk of exposure to Chemicals or Solvents	-no use of chemicals or solvents -equipment materials withstands chemicals or solvents normaly used during service and maintenance	1	1	1	Chemicals or solvents will have a minor impact of the Ex integrity.
Risk of accumulation of dirt or dust	-installed in climate controlled areas -periodic service and cleaning -no generation of dust and dirt	1	1	1	Dust or dirt will have a minor impact of the Ex integrity.

4.8 Inspection intervals and types of inspection:

The RBI program constitute three different classes or categories to rank the equipment based on the risk level. The first category of items belongs to a low risk category. Items in this category are inspected once every 5 years. The way this is done is by inspecting 20% each year and after 5 years all of the tags should have been inspected. The second category is medium risk items. This category is inspected once every three years and the way they perform this is by inspecting 33% of the tags each year and by 3 years all of the tags should have been inspected. The third category is the high-risk category. Items in this category are inspected once every year.

All of the three categories are inspected mainly by visual inspection. However, 2% of the items in the first category get detailed inspection. While the second category gets 5% detailed inspection. The third category gets 10% detailed inspection.

Visual inspection is the most used form of inspection and it does not involve any case opening or anything complicated. Close inspection is not used in IKM's RBI. While detailed inspection involves opening the casing and checking the item thoroughly.

4.9 Degradation processes modeling

The approach followed by IKM does not involve any degradation modeling. The degradation modeling means how the probability of failure changes with time. This gives some indication on when the Pof will reach a specific level. Instead of the degradation

processes modeling, the company performs a form of qualitative assessment to check the state of the item in question. As mentioned before, the qualitative assessment is done by either a visual or detailed inspection.

4.10 Seeking outside expertise when needed

The interviewed employees said in situation where it is difficult to interpret or understand an inspection result, they seek more expertise outside the RBI team. However, the expertise they seek is from inside of the company.

4.11 Screening phase

A document produced by DNV suggests that the RBI process should include a screening phases to highlight items with medium to high levels of risk (see Figure 8). Items with low consequence and probability scores are given a low risk score while items with at least a medium level of either Pof or Cof are given a medium or high-risk score. The screening phase is done to reduce the amount of resources spent on not-so-important items.

The same procedure is mentioned in the document shared by IKM, but it is not followed when performing RBI.

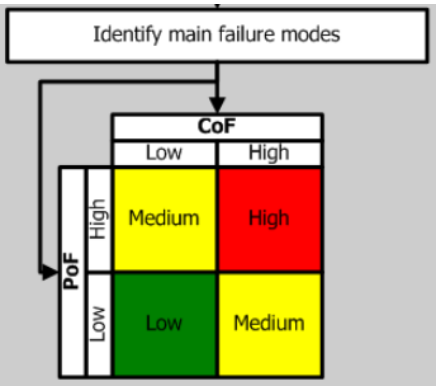

Figure 8 Screening phase matrix

Source: (DNV, 2010).

4.12 Risk assessment

A traditional form of risk assessment is being used to give a value to the risk of failure for different tags. Using a scoring system from one to five, the risk is described by multiplying the consequence score and the probability score.

5 Discussion and recommendations

As shown by the collected results, the RBI program is still at the development phase. Although the company has a document explaining the RBI approach followed, answers from the two employees evolved in the development of the RBI stated that the program is far from complete and many aspects are still needed to have a complete RBI program. this has limited the discussion to the amount of data collected and also has some implications on the way the program is criticized and improved.

The categories below are recognized from the generated codes in the results section.

5.1 Assumptions

The data suggests that the company has some assumptions in the RBI program to simplify and improve the workflow.

The assumptions stated are usually not the only assumption used in reality. And because the program is not complete yet, more assumptions are possible to emerge. The assumptions are usually a huge uncertainty point and could possibly lead to a weakly made inspection program which can translate to accidents.

One of the found assumptions is the use of data from the client company to have the initial risk assessment in place. The initial risk assessment is the used to make an initial inspection program which will be used for inspection until more failure data is registered. This approach seems reasonable, but it has some drawbacks. The suggested solution is to highlight the items in high consequence zones and make sure the data is reliable for those items. This comes at a low cost since most of the items are placed in low consequence zones, and it has to be done only for the initial risk assessment.

In addition to that, Tacit assumptions are always present and should be uncovered if possible as they usually hide uncertainties. Kingston (2012) suggests a process to capture tacit knowledge. The company is advised to follow a similar process.

5.2 Sources of uncertainty

Uncertainty is a part of any assessment. The question is how large those uncertainties are. The interview data pointed out to some important uncertainty sources:

- The probability of detection: the company does not take into account the probability of detection into account. This can be included in the decision process as an input to the RBI program. Although it is difficult at the beginning when no data is available, the company could use historical data to highlight which types of equipment has a low probability of detection. Those equipment can have a close or detailed inspection instead.
- Human error: while some measures have been introduced in the way inspection are performed to reduce the possibility of human error, more actions can be taken to make it easier for the inspector to focus on important inspection parameters. The

document shared by the company shows that many types of data are collected during the inspection. And according to the interviews results, huge part of the data is not needed. For example, the company uses the zone and the protection type to say something about the possible consequences. Inspectors may focus only on those parameters to reduce the possibility of committing a mistake when entering inspection data. The same thing can be done for Pof.

- Knowledge: As will be shown later, knowledge in the RBI should be given some attention as it may result in deficient inspection programs. Recommendations on how to address this are given in "Improving the knowledge" section.

5.3 Risk description and ranking

The risk description used by the company is somewhat based on expected values. The process of RBI involves giving Cof and Pof values from 1 to 5. The risk score equals the product of those values (See Table 4). The company also uses a risk matrix to rank different equipment (Figure 7).

Apart from having issues with this kind of description, there are some inconsistencies in the way risk is described. For items characterized by Cof of 1 and Pof of 5, the risk score is 5. The risk score should be similar to items with a Cof of 5 and Pof of 1. Both of those items should be characterized with low risk. However, the risk matrix in Figure 7 does show some inconsistencies since items characterized with a Cof of 1 and a Pof of 5 are labelled as medium risk items while they should be low risk items.

Moreover, Cof and Pof should be explicitly described. The risk matrix shared by the company shows some issues in terms of the descriptions of what it actually means to have a specific Cof or Pof score. For example, a Pof of 2 is described as "a rare combination of factors would be requiring for a failure to occur". That statement can be understood differently by different assessors. Changing the assessor in this case means changing the result of the RBI. This points to a validity problem in the assessment. The same thing could be said about Cof as well. Humans judge things differently. What is perceived as high by one person might be perceived as low by someone else (Slovic & Peters, 2006). This leads to the importance of having explicit Cof and Pof descriptions.

The literature review section pointed to issues related to the use of expected values as a risk description. Some of those issues are the non-inclusion of the knowledge dimension. This can be improved by addition a knowledge dimension to the risk description. The knowledge dimension can have inputs such as the reliability of data used, assumptions made, and probability of detection. This is inspired from the strength of knowledge ranking system suggested by Flage and Aven (2009). Table 5 shows an example of Sok scoring system based on reliability of data, assumptions, and probability of detection.

Using a Sok judgement system is important since the company relies on data from outside the company to make the RBI assessment. The company has no control over who does the inspections and how they perform them. This can be addressed by adding a Sok dimension in the RBI matrix. The Sok judgement should make it possible to have some sort of

understanding of the existing uncertainties. If the company makes sure that the data is reliable, the assumptions are reasonable, and the probability of detection is high, then Sok can be classified as strong, and the uncertainties related to the knowledge dimension can be considered small. In this case, Pof and Cof constitute the main inputs to the RBI assessment. However, in the other two cases where Sok is judged by medium or weak, Pof and Cof should be seen in the light of the knowledge in hand. This can be solved by introducing conservatism and by being cautious.

Table 5 Example of Sok judgement system

Conditions	How many conditions check?		
Data is reliable	all of them	Only two of them	One of them or non
Assumptions are reasonable			
High probability of detection			
Sok judgement	Strong	Medium	Weak

The following ranking suggested by Aven and Flage (2018) can be used instead of the one dimensional matrix used:

- Very high risk: potential for extreme consequences, relatively large associated probability of such consequences and/or significant uncertainty (relatively weak background knowledge).
- High risk: potential for extreme consequences, relatively small associated probability of such consequences and moderate or weak background knowledge.
- Moderate risk: between low and high risk. For example, the potential for moderate consequences and weak background knowledge.
- Low risk: no potential for serious consequences

Risks ranked as very high or high can have a one-year inspection interval. Medium risk can have three years inspection interval. While low risk can have five years inspection intervals.

5.4 Improving the knowledge

According to Flage and Aven (2009), four elements constitute the knowledge dimension. To strengthen the knowledge, the company should aim at:

- Having good models
- Making good assumptions,
- Having experts' agreement
- Ensuring the reliability of data

IKM should include employees from the client company as they have some knowledge that need to be transferred to the people performing the assessment. This is important to uncover black swans of type unknown-knowns. The employees from IKM stated explicitly that probability levels are determined initially by best guess. So, the subjectivity of the

assessment is present. What the company does to reduce the level of subjectivity is crucial, especially for medium or high-risk items.

Another issue to highlight is the oversimplified work methods. In decision making processes, accuracy and simplicity are rivals (Bohanec & Bratko, 1994). Improving the workflow has its costs and benefits as it saves resources but also reduces the accuracy of the assessment. Even though simplification is needed in practical settings, it should be done with care. Simplification should help to reduce human error in RBI. However, important parameters should not be abandoned in the decision-making process. This can be overcome by bringing more expertise with actual experience in RBI from outside the company and agree on which factors are important to describe risk and perform the RBI. The other factors can be ignored without compromising the level of accuracy.

5.5 Risk handling strategies

The results indicate that the company has no risk averse strategy in their RBI. This can come costly in some situations. Since some of the equipment are placed in high risk zones and are more likely to cause damage if a failure happens, the company has to adapt its strategies based on the level of uncertainties.

The knowledge dimension is linked with uncertainties. Those uncertainties can be reduced by following the recommendations given earlier. However, in cases where the knowledge is still weak and uncertainness are high, the cautionary principle should be introduced in the decision-making process. This induces stricter behaviour towards risk.

IKM initially receives an excel sheet from the client company. The excel sheet is used for an initial RBI when no historical or inspection data are available. The company assumes that the data received from the client company is good for use. This might not be a good approach for medium or high-risk items. While being conservative all the time is impossible because of the induced costs, some risk aversion behaviour and being cautious is crucial to have a safe installation. The following measures are recommended for the initial RBI:

- The company is advised to assure the reliability of the data. This can be done for medium and high-risk items. The document shared by the company indicates that most of the items are labelled as low risk while no item is labelled as high risk. This means that the existence of medium risk items is limited. Performing an additional check on the data in this case should not induce high costs. And even if the costs are not acceptable, double checking the data and compare it with what is actually on the platform is justified by the cautionary principle.
- An alternative solution is to be more conservative in terms of the inspection interval length. Most of the items are low risk items while the rest is medium risk item. The company may choose to treat those medium risk items as high risk items. this should induce a more frequent inspection interval (once a year) such as the one reserved for high risk items. This can serve as a temporary solution until more data is registered. Then historical data can be used if appropriate.

5.6 managerial review and judgement

Risk analyses are never perfect. The above suggested improvements are not always possible and will not always be followed. This motivates an additional step in the RBI process to put everything in a broader perspective and make sure that the weaknesses of the methods used are taken into account before making decisions about inspection intervals. This can be done under a managerial review and judgement step.

6 Conclusions and answering the research questions

Question one: Is IKM's RBI approach perfect?

If the answer to this question is yes, then IKM's RBI approach should be a role model when performing RBI. Unfortunately, according to science, no such thing like perfect exists. As science is linked with time, what is perfect today might not be perfect tomorrow. That being said, the theoretical part on how to improve risk related decision-making processes is available. However, putting those improvements in a practical setting is more challenging than it looks like.

To answer the question, the company's approach for RBI is not perfect.

Question two: If not, how can it be improved?

In theory, any risk analysis procedure can be improved. The body of literature in the risk field is enormous, and methods for improving the way risk is described and managed are emerging every day.

To answer the question, the process can be improved by following the next steps:

- The company should update their risk matrix to include Sok judgement.
- The risk ranking system used by IKM is not valid. It is advised that the company uses a ranking system that has uncertainties as the main element.
- Human error should be considered by reducing the amount of data to be collected during inspections and by focusing on parameters that affect the RBI results. non-important parameters can be ignored.
- Although simplicity is beneficial when reducing human error, it should be done with care as the accuracy of the assessment is negatively affected.
- The company should include the probability of detection in their program.
- The knowledge dimension should be strengthened.
- The company should attempt to uncover tacit assumptions.
- The company should adopt some risk averse strategies and introduce conservatism when necessary.
- Include a managerial review and judgement step in the process.

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8 Appendices

8.1 Appendix A: interview protocol

Introduction at the beginning of the interview: This interview will investigate the RBI approach used by your company. The goal of this investigation is to locate uncertainty issues in the program and suggest possible improvements if possible.

Opening questions:

- Are you involved in the development of the RBI?
- What's your role and relation with the RBI

Body questions:

- How you define and formulate your probabilities?
- How you define and formulate your consequences?
- How you assure the reliability of data used in the RBI?
- Are there any assumptions in the RBI process?
- Do you use any models to predict the degradation process? If so, are they known to give good predictions?
- Do you take inputs from other experts in the field?
- How do you consider the possibility of surprises? This question is related to the possibility of having an accident due to long inspection interval.
- How do you consider the possibility of human error in your process?
- How do you consider the probability of detection (Pod) when performing the RBI?

Closing the interview: I want to thank you for your time spent on this interview and for your responses. We will end the interview at this point but if you have anything you want to add, please send me an email. After the study is done, the results will be shared with you.

8.2 Appendix B: An example of the coding system used

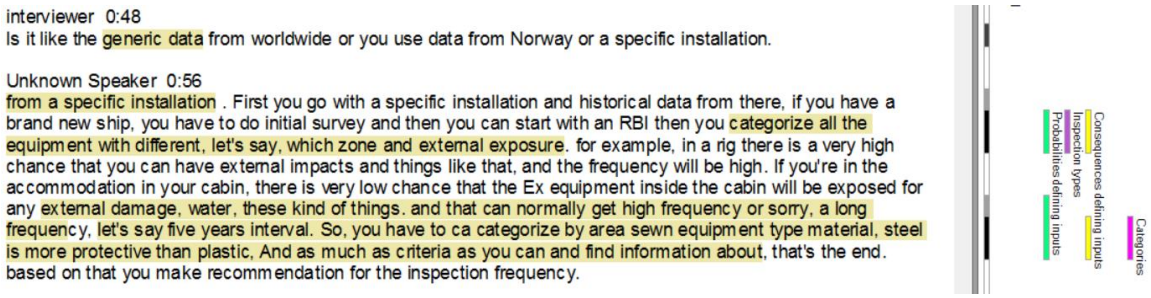

Figure 9 Example of the transcription and coding used in NVivo.