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The Time Dimension in Risk Assessments

An evaluation of how the time dimension is considered in risk assessments, with possible recommendations for how it could have been considered

Author

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Preface

This thesis marks the conclusion of my Master of Science in Risk Analysis and Governance at the University of Stavanger. The thesis has been written between January and June 2022.

The topic chosen represents an interest in conceptual and foundational topics in Risk Analysis, which I discovered in the introductory courses. It has been a rewarding experience to complete this thesis. Along the road there has been obstacles and periods of frustration and doubt, but also the excitement of immersing myself deeply in a topic and a sense of accomplishment in the end. I want to say a special thank you to my academic supervisor, Associate Professor Anders Jensen (University of Stavanger), for your guidance and good discussions along the way. You pushed me from the beginning, always encouraging me to go further. Your keen interest in Risk Analysis was inspiring.

I also want to thank my fellow students for making the years studying Risk Analysis a rememberable and interesting subject to study.

Lastly, a warm thanks to my family, friends and especially my sister Hanne for all the support during these years.

Fredrik Nygaard, Stavanger 15/6-2022

Abstract

Considerations of time are already present in risk assessments. However, there is little formal guidance on how the time considerations can be explicitly stated in the analysis. Often, the judgements/considerations of time are made implicitly by the risk analyst, which in turn could make the decision basis for decision-makers unclear. By making considerations of time explicit and formalized in risk analysis, we could improve clarity in the risk assessment, and strengthen the decision basis for the selection of suitable risk management strategies.

Based on Logan et al. (2021), *this thesis will present a table for linking time considerations to risk management strategies, which can be used as a simple guide in the selection of risk management strategy, depending on the type of risk problem in the analysis.*

Both the time formalization and the table for evaluating the time dimension in risk assessments will be used to evaluate the time considerations in one case of the drilling of an exploration well, and one for considering earthquake risk in a Haitian village. The table will subsequently be used to suggest how time could have been considered in both cases.

The suggestions on formalization of the temporal dimension represent incremental improvements in the foundations for risk analysis, which can be considered as consisting of an applied part (A) and a generic part (B). The reasoning in this thesis is that we can strengthen the risk knowledge produced in the applied part by improving the concepts, theories, models and frameworks in the generic part.

There would be a need for future research to further investigate how the temporal considerations can benefit risk management strategies. However, risk analysis should benefit today from having a clear and formalized framework for how time considerations is considered.

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List of abbreviations

α	**Activity/system**
τ	**The time interval for an activity/system**
η	**The time horizon for consequences**

1 Introduction

1.1 Background

In recent years, there has been an increased focus on intergenerational risk problems such as climate change, sustainability, artificial intelligence, energy distribution, nuclear power/waste, population growth and environmental risks; (Ilag & Athave, 2019; IPCC, 2022; Tarbuck et al., 2017). One commonality in all these topics is that they include an element of time, or time horizons, that can stretch far into the future. This could be especially relevant for the field of risk analysis, where the treatment of time is already an important constituent (Aven, 2015, p. 14). However, a risk analysis is not always explicit in the considerations of time, possibly lessening the usefulness of risk assessments as a tool for decision-makers and decisions related to risk management strategies.

A common theme for the mentioned risk problems, is that the possible consequences involved could take decades to manifest themselves. This, in turn, could make it difficult to make accurate predictions regarding the adaptions and mitigations we put in place today, since the time horizons will be stretched over several decades, also with many interdependent variables (IPCC, 2022; Tarbuck et al., 2017).

From traditional risk assessments we are familiar with trying to answer the following questions: “What can go wrong”, “What are the consequences?” and “What is the likelihood?”. These questions stem largely from Kaplan & Garrick’s (1981) seminal work. It has been suggested by (Haimes, 2009) to also include the question of “Over what time frame?”. Moreover, by following Logan et al (2021), we can specify the temporal dimension further by considering:

(1) The period of time over which the activity is observed

(2) The length of time, after an event occurring, for which we evaluate the consequences of that event.

The first consideration~~s~~ seeks to clarify what activity or system we want to monitor in a risk context, and for how long period of time. We might consider an activity or system to be a production facility, a local community, an offshore installation operation or an ecosystem.

With the second consideration, Logan et al. (2021) puts an emphasis on the importance of how consequences are considered after an event. We can illustrate these considerations in different ways. The length of time over which an activity is observed could be the risk of an earthquake occurring, and the consequences the impact to a local community. We could observe the risk of an earthquake occurring over a period of e.g., 10 years. An important question then is to ask what about the possible long-term consequences that exceeds the 10-year period? In the case of natural disasters, this would be considered *secondary* or *tertiary* effects that stretches over long periods of time after an initiating event (Nelson, 2018). The secondary effects from the disaster could typically be fires, disruption of the electrical grid, the water and food supply or flooding. Tertiary effects usually have consequences that stretches even longer into the future, like the loss of habitat, crop failure or permanent changes in a river or permanent disruption of living areas (Nelson, 2018).

Logan et al. (2021) notes that time considerations have implications for how we compare and implement interventions related to long-term consequences. How do we compare interventions that have long term consequences? In the case of natural disasters, the way we prioritize e.g., short term interventions could be counterproductive for long-term development, and vice versa. After an earthquake, there would be a need for immediate humanitarian aid to the affected population (IFRC, 2015). But where and how do we draw the line between what is considered immediate aid and long-term development? The community would need to engage in a long-term development plan that in the future would make the community able to withstand catastrophes of similar or larger magnitudes. If not, the village/community will be equally vulnerable the next time a disaster occurs. This example illustrates how risk analysis could benefit from being explicit in how we refer to the temporal dimension in risk assessments, so that there is clarity on what consequences and time periods an analysis refers to (Logan et al., 2021).

This is not to say that risk analysis is not making clear judgements about time. In a risk assessment conducted for the Yucca Mountain High-Level Nuclear Waste Repository Site, time was an important and explicit factor (10 000 years) when estimating the recurrence rate and risk of a volcanic eruption related to possible disruption of a nuclear waste depository (Ho, 1992).

However, the main point is that judgements of time in risk analysis in many cases are made implicitly, and there is a lack of formal guidance explicitly showing how the attention to time has been considered (Logan et al., 2021). Some risk scholars argue that the lack of a formal framework for temporal considerations could be a cause for confusion for the role of Risk Analysis in relation to some risk problems (Logan et al., 2021). One example of this might be the divergence of the field of Risk Analysis and Resilience, after some world leaders have made "calls for a shift to resilience" to fight climate change (Aven, 2018; UNDRR, 2015). This call for a shift to resilience could be confusing in the sense that one might not think risk analysis is suited to tackle certain kinds of risk problems (Aven, 2019; Logan et al., 2021). One argument for diverging resilience analysis from risk analysis is that some view risk intervention as mostly concerned with reducing the immediate disruption (Logan et al., 2021). By using this metric, the temporal considerations are removed, and would suggest that risk analysis and risk informed decision-making is not interested in the recovery of a system or how the consequences are distributed over time (Aven, 2018; Logan et al., 2021). Both Aven (2019) and Logan et al. (2021) points to a need for a structured formalization on how we consider time in risk analysis to help resolve some of this confusion, and to strengthen fundamentals of the field of risk analysis.

The suggestions presented in the article from Logan et al. (2021) is to update the (*A,C,U*) perspective on risk with new nomenclature to include explicit considerations of time, both related to our concept and characterizations of risk. The suggested framework is presented in a logical and detailed way and builds upon the SRA glossary on risk, where risk is typically viewed as the consequences (*C*) of an activity (*A*), and its associated uncertainties *U* (SRA, 2018). In addition to formalizing the treatment of time in risk analysis to improve decision-making, one could also view explicit considerations of time as having implications for the risk management process. In the risk management process, questions such as "What can be done and what options are available?"; "What are the trade-offs in terms of all relevant costs, benefits and risks?"; and "What are the impacts on current decisions on future options?" are commonly asked questions in the process (Haimes, 2009). Based on Logan et al. (2021), and the three questions from Haimes (2009), this thesis will try to establish a link between how the considerations of time in risk assessments are related to the type of risk problem and risk management strategies and present this in a table.

One might argue that in the end, the risk assessment is a tool to help inform decision-making in the risk management process. By adopting this formalization, the risk analyst will be encouraged to clarify his or her considerations of time, which in turn could make risk analysis a more transparent and useful decision-making tool for risk analysts, decision-makers and the risk management process.

1.2 Problem formulation and structure

Problem formulation

This thesis will try to achieve the two following two things:

1) Conduct an evaluation of how time is considered in risk assessments,

and secondly,

2) Try to establish whether time could have been considered differently, with possible recommendations for how it could have been considered.

For the first point, a risk assessment for exploration drilling of has been chosen to conduct an evaluation of how time has been considered. The risk assessment is based on an environmental risk analysis report conducted from DNV GL, on behalf of Equinor, for drilling of the Stållull well in the North Sea (DNV GL, 2018). In this review, we will try to establish how the report considers aspects of time related to the activity of exploration drilling, and how it deals with time related to the consequences of a possible release of hydrocarbons to the sea.

For the second point, the thesis will try to give some possible recommendations on how time could have been considered on the backdrop of the suggestions laid out in the article from Logan et al. (2021), while also exploring implications for how time considerations can impact risk management strategies.

To further highlight the considerations of time in risk assessments, a second case dealing with an earthquake-vulnerable population in Haiti has been chosen. For this case, there does not exist much data in the form of formal risk assessments (at least to this authors knowledge), but research on related topics like disaster risk reduction/management, earthquakes, infrastructure development and vulnerability is readily available as a basis for the suggestions on how the temporal dimensions can be treated.

As will be shown, there is already explicit considerations of time in the exploration drilling case, whereas the Haiti case is more open to interpretation and guidance in a normative context. For both cases, however, possible areas for improvements are identified.

What will be central to the thesis, and discussion, is how the suggestions for how time can be considered has implications for risk management strategies for handling different types of risk problems. One could argue that clear considerations of time can aid the process of selecting the best suited risk management strategy, depending on the risk problem.

Structure of thesis

Chapter 2 presents relevant theory and concepts related to the research question and provides a risk perspective for how we can explicitly reflect time in risk assessments. The chapter will start by reviewing the A,C,U perspective in risk analysis, as this will be the foundation for the suggested updates in the A,C,U nomenclature related to the time considerations. We will then go through the suggested formalization of time considerations presented from Logan et al. (2021), for how time can be incorporated both in the conceptualization and characterization of risk. After this follows theory on risk management, where we will present a suggested table for the evaluation of time in risk assessments. With this table, we try to establish a link between the temporal considerations in risk analysis and the selection of risk management strategies depending on the type of risk problem. This table will form the basis for the subsequent evaluation and suggestions related to time considerations for the two cases.

Chapter 3 then starts our in-depth analysis and evaluation of the Stålull exploration drilling case. Here we will conduct an evaluation both on how time has been considered and suggest how it could have been considered based on the theory presented in the theory section, and by the use if our suggested table for how time considerations can be evaluated in risk assessments.

In chapter 4, we suggest how time could be considered in the context of a local village in Haiti, that is vulnerable to earthquake risk. For this case, there is no formal risk evaluation, so our attention is directed towards what normative guidance we can give for time considerations for this type of risk, and its implications for risk management.

After this follows a discussion in Chapter 5, dealing with the implications of how we can address time, both for the cases and the implications for risk analysis as a science. One key discussion point will be the implications different time considerations might have on risk management strategies.

Lastly, we sum up the main findings and recommendations in Chapter 6: Conclusions.

1.3 Approach of thesis

On a scientific basis, Aven (2019) divides risk analysis in two categories. The first category is applied risk analysis (A), which is when we conduct risk analysis and produce risk knowledge from real world activities. An example could be when performing a risk analysis for an offshore installation, a new health drug or an investment. The second category is generic risk analysis (B), which seeks to develop concepts, theories, frameworks, approaches, principles, methods and models in the risk science field (Aven, 2019, p. 29). Generic risk analysis is considered a science on its own, the same as for e.g., statistics. There is also a link between the two parts, in that the theoretical and conceptual work in generic risk analysis inform the way we conduct applied risk analysis. Similarly, knowledge gained from applied risk analysis support the generic risk analysis in such a way that it can influence changes and improvements in generic risk analysis based on the insights from real-world observations (Aven, 2019, p. 31).

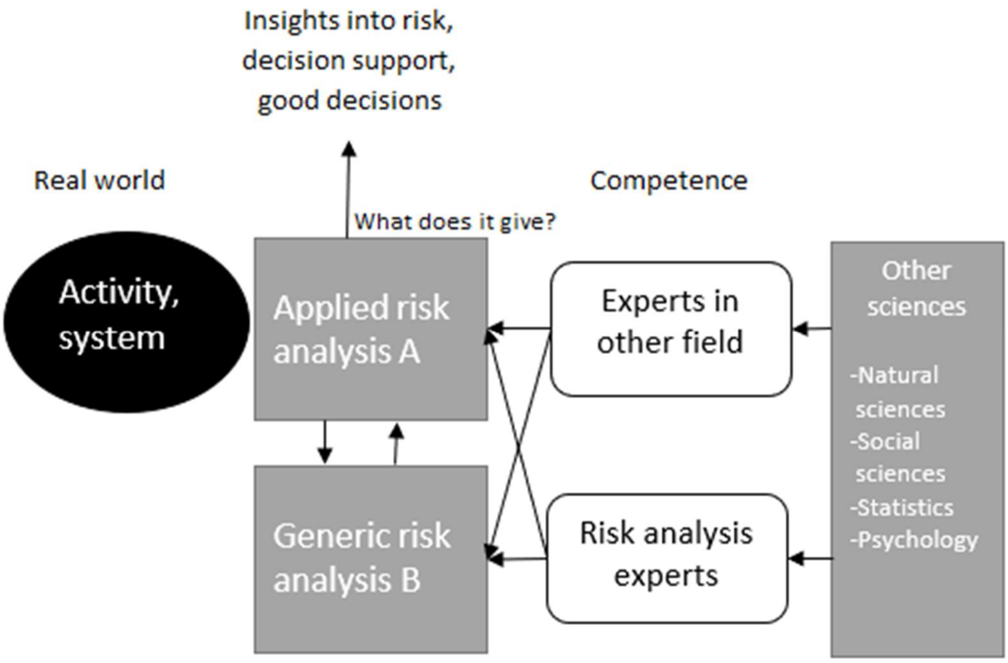

Figure 1: The relationship between applied (A) and generic (B) risk analysis and other sciences (Reprinted from Aven, 2019, p. 32).

Figure 1 shows how the A and B part of risk analysis interacts with risk analysis experts and experts in other fields. We also see that risk analysis interacts with other sciences, where risk analysis is commonly viewed as a supporting science (Aven, 2019, p. 30). The theory presented in this thesis stems from work in the generic part of risk analysis (B), but as figure 1 shows, the research going on in (B) can also be influenced by insights gained from applied risk analysis (A). Based on this, risk analysis can be argued to be both a science on its own right, based on the foundations and research going on in B, and/or be viewed as a supporting science for other sciences like natural sciences, medicine, social science etc (Aven, 2019, p. 30).

Aven (2019, p. 27) then distinguishes between the following types of research methods: *descriptive vs analytical*, *applied vs fundamental*, *quantitative vs qualitative* and *conceptual vs empirical*. Both this thesis, and the main article it is draws its inspiration from, is largely operating in the *conceptual* sphere of research. This type of research mainly deals with abstract models, theories and ideas; where elements of identification, revision, delineation, summarization, differentiation, integration, advocating, refuting are important for the research (Aven, 2019, p. 27; MacInnis, 2011). For example, when discussing the 'call for a shift to resilience' earlier, the elements of *differentiation* and *integration* could become central points for the discussion, since it is a question of whether we, or the research, leads us to widen or decrease the gap between risk analysis and resilience analysis. We can also have situations where differing parties end up *advocating* their own views while at the same time *rebutting* the others. Aven (2019, p. 27) further notes that research usually is a mixture of different types of research methods, and that the mentioned elements are not constricted to one specific method.

Some authors note that empirical studies might have outgrown conceptual research in some fields, which could have a detrimental effect for conceptual advances in the given field on a longer term. In one case taken from the marketing field, McInnis (2011) expresses this view, noting that a lack of new conceptual ideas and research could cause the marketing field to miss important insights and new ways of thinking, which could turn marketing into a too narrow tool (MacInnis, 2011). Aven (2019) follows the same line of reasoning, advocating that conceptual research and the refining of our ideas, models and theories are important and needed for further advancement for the field of risk analysis.

Formalizing how time is considered, both related to the concept of risk and the risk characterization, can result in a strengthening in the generic part of risk analysis, which in turn impacts how applied risk analysis is conducted. The author of this thesis, and the suggested updates in the *A,C,U* nomenclature from Logan et al. (2021) supports the view that both generic and applied risk analysis would benefit from this conceptual strengthening, and that it could provide a viable path for future research and strengthening of risk analysis.

The suggested table for evaluating the time dimension in risk assessments in this thesis, represents an integrative approach seeking to strengthen the link between time considerations and risk management in risk analysis.

2 A risk perspective for explicitly reflecting time

2.1 The concept of risk

According to Aven (2019, p. 57), experience shows that it is hard for a scientific community to agree on universally understood terms and definitions of concepts related to risk. This in turn, creates a breeding ground for organizations and new frameworks, all trying to define the concepts differently. Even though there exist multiple risk frameworks, a common way to define risk is the following from Society for Risk Analysis (SRA):

> We consider a future activity [interpreted in a wide sense to also cover, for example, natural phenomena], for example the operation of a system, and define risk in relation to the consequences (effects, implications) of this activity with respect to something that humans value. The consequences are often seen in relation to some reference values (planned values, objectives, etc.), and the focus is often on negative, undesirable consequences. There is always at least one outcome that is considered as negative or undesirable. (SRA, 2018, p. 4).

By this we understand that risk is related to some future activity and its associated consequences, usually with regards to something humans value, where the focus is on negative outcomes. SRA (2018) further lists several qualitative definitions of the concept of risk. For illustrative purposes, two of them will be quoted as most of them are similar in nature in that they reflect uncertainty towards an activity and its consequences.

- Risk is the consequences of the activity and associated uncertainties.
- Risk is uncertainty about and severity of the consequences of an activity with respect to something that humans value. (SRA, 2018, p. 4).

The risk concept thus has two main components: consequences, which we write as C, and uncertainty, which we write as U (Aven, 2019, p. 58). Since both the consequences (C) and uncertainty (U) are depending on a initiating event, the risk concept can be expressed by the triplet (A,C,U), where A represents the initiating event (Aven, 2019, p. 58). An initiating event (A) could for instance be an earthquake, the consequences (C); the possible damage to something humans value (health, infrastructure, environment etc.,), whereas the uncertainty (U) relates to us not knowing whether an earthquake will happen or not. For simplicity, we can write the representation of risk as (C,U), since we understand that the consequences and related uncertainties depends on a preceding event. Further, depending on what goals and activities we might be interested in carrying out, this definition of risk allows us to specify both desirable or undesirable consequences (Aven, 2015, p. 15; Logan et al., 2021) . However, risk is often considered in the context of some specified activity or event where the focus is on some undesirable consequences, like loss of lives, the risk to a community or the health of a person (Logan et al., 2021).

2.2 Characterizing risk

Where the risk concept lets us to say whether we face risk, the risk characterization enables us to express how large the risk is. The risk characterization as defined by SRA (2018):

> A qualitative and/or quantitative picture of the risk; i.e., a structured statement of risk usually containing the elements: risk sources, causes, events, consequences, uncertainty representations/measurements (for example probability distributions for different categories of consequences – casualties, environmental damage, economic loss, etc.) and the knowledge that the judgments are based on.' (SRA, 2018, p. 8)

SRA (2018) states that risk characterization, or description, is a qualitative and/or quantitative representation of risk, where common elements are: a risk source, causes, events, consequences and their related uncertainty measurements, which depend on the differing categories of consequences and also the background knowledge. By referring to SRA (2018), some examples of risk descriptions/metrics are:

1) the combination of probability and magnitude/severity of consequences

2) The combination of the probability of a hazard occurring and a vulnerability metric given the occurrence of the hazard

3) The triplet (*si*,*pi*,*ci*), where *si* is the *i*th scenario, *pi* is the probability of that scenario, and *ci* is the consequence of the *i*th scenario, *i* =1,2,...*N*.

4) The triplet (*C'*,*Q*,*K*), where *C'* is some specified consequences, *Q* a measure of uncertainty associated with *C'* (typically probability), and *K* the background knowledge that supports *C'* and *Q* (which includes a judgment of the strength of this knowledge)

5) Expected consequences (damage, loss). For example, computed by:
a. Expected number of fatalities in a period of one year (Potential Loss of Life, PLL) or the expected number of fatalities per 100 million hours of exposure (Fatal Accident Rate, FAR)
b. *P(hazard occurring)*
x P(exposure of object | hazard occurring)
x E[damage | hazard and exposure]

i.e. the product of the probability of the hazard occurring and the probability that the relevant object is exposed given the hazard, and the expected damage given that the hazard occurs, and the object is exposed (the last term is a vulnerability metric).

c. Expected disutility

6) A possibility distribution for the damage (for example a triangular possibility distribution). (SRA, 2018, p. 4).

From these examples, we see that different descriptions for risk would be needed depending on different situations. For example, description (*1*) views risk as the combination of probability and magnitude of consequences. To exemplify this, we can estimate the probability of an earthquake to be very low by referring to frequentist probabilities. On the other hand, the possibility for catastrophic consequences in such disasters might lead us to view the risk as high. Similarly, we can assign the probability of being infected by a virus as high, but if the virus is known not to be dangerous to human life, we can view the risk as low.

When characterizing risk, we are generally led to the triplet (*C',Q,K*), which is shown in number (*4*) of the SRA examples. Here, we denote some specified consequences as *C'*, and choose a measure of the uncertainty which is denoted as *Q*. We also need to include the background knowledge *K* that supports both consequences *C'* and uncertainty measure *Q* (Aven, 2019). On the account of Aven (2019, p. 73), probability (*P*), or probability intervals, are the most common tools to express uncertainty, preferably used in conjunction with judgements about the Strength of Knowledge (*SoK*), supporting the probabilities. To assess *SoK*, different approaches are available, see for instance the assumption deviation risk approach, or the NUSAP system (Khorsandi & Aven, 2017; van der Sluijs et al., 2005).

Aven & Flage (2009) and Aven (2019, p. 129) presents some conditions that reflect either weak or strong background knowledge (weak assumptions denoted as w1, w2…, and strong assumptions as s1, s2…,):

Weak assumptions:

W1) The assumptions made represent strong simplifications.

W2) Data/information are/is non-existent or highly unreliable/irrelevant.

W3) There is strong disagreement among experts.

W4) The phenomena involved are poorly understood; models are non-existent or known/believed to give poor predictions.

W5) The knowledge *K* has not been examined (for example to unknown unknowns).

Strong assumptions:

S1) The assumptions made are seen as very reasonable.

S2) Large amounts of reliable and relevant data/information are available.

S3) There is broad agreement among experts

S4) The phenomena involved are well understood; the models used are known to give predictions with the required accuracy.

S5) The knowledge *K* has been thoroughly examined.

(Aven, 2019, p. 129)

Cases that fall between strong or weak assumptions could be classified as having medium strength of knowledge. Clarifying the assumptions reflecting the strength of knowledge is important for how we consider the uncertainties when $Q = P$, because a probability (P) alone is not able to tell the strength behind the probability (Aven, 2015, p. 25).

As a third example, we could consider risk to the marine environment from possible accidents on an offshore installation. If risk is defined according to SRA (2018), then risk has two dimensions: the consequences (C) of the operation on the installation (covering events A, which e.g., could be a blowout of hydrocarbons), their effects on the environment, and the uncertainty (U). Since we now have several decades of operational and accident data from offshore installation operations, we might say that we have strong historical data, or background knowledge, supporting the risk knowledge in this area. In other words, we might say that for a specified consequence (C'), our background knowledge (K) supporting C' and Q is considered strong. It is, however, important to note that some risk authors argue that strength of knowledge depends on the relevancy of the data/information available, the degree of expert agreement, availability of accurate models and how well the knowledge K has been examined (Aven, 2019, p. 128-129). Risk analysis is a tool that should give weight to the uncertainties, which means that emphasis should be placed on uncertainties, and the possibility for extreme events, e.g., like black swans, even though one might consider the background knowledge as strong and probabilities for the occurrence of such events as low (Aven, 2019, p. 77-78).

Figure 2: The relationship between risk assessment and characterization, and risk of an activity in the real world (Reprinted from Aven, 2019, p. 60).

Figure 2 shows how *C* and *U* is captured in a risk characterization for risk in real world activities. In the risk characterization, *C* is specified as *C'* and the uncertainty measure *Q* chosen to represent *U*. We also see how the background knowledge and judgements of the strength of knowledge supports *C'* and *Q*. We can also extend the framework presented in figure 2 to include risk sources (*RS*), which can be considered an element that either isolated or alone could give rise to an event (*A*), with some consequence (*C*). A risk source (*RS*) could for instance be a can of gasoline, which could start a fire (which could be event *A*) in case of ignition. The relationship between what is a risk source (*RS*) and/or an event (*A*) is relative and depends on what conditions we want to highlight (Aven, 2019, p. 123). In this sense we could also view the fire as a risk source (*RS*), and view the smoke development as the event (*A*). In this thesis, we use the suggested framework (*RS'*, *A'*, *C*, *Q*, *K*) when characterizing risk, but simply use (*A*) when referring to either events (*A*) or risk sources (*RS*).

2.3 Time in the risk concept

In this section we review Logan et al's (2021) suggested updates in nomenclature for explicitly reflecting considerations of time in the (*A,C,U*) risk perspective.

2.3.1 The activity/system

Logan et al's. (2021) suggestion for incorporating time in the risk concept builds upon the definition of risk presented by the Society of Risk Analysis glossary, which is mainly expressing that:

Risk is the consequences (C) of an activity and associated uncertainty (U) (SRA, 2018, p. 4).

From this definition, we know that risk can be conceptualized as its consequences (C) and uncertainty (U). We also understand that an event (A) would precede the consequences (C), and hence it would suffice to write risk as (C,U). What we are interested in when incorporating time in the concept of risk is the following:

i) The period of time over which the activity is observed.

ii) The length of time, after an event occurs, for which we evaluate the consequences of that event.

To account for the first consideration, Logan et al. (2021) suggest denoting the activity that is under observation as α. When an activity (α) is observed over a time interval $[0, \tau]$, we write this as α_τ. Thus, we can now denote how risk is related to an activity (α), over the time interval $[0, \tau]$, in the following way:

Risk = $(C,U)_{\alpha\tau}$ (Logan et al., 2021).

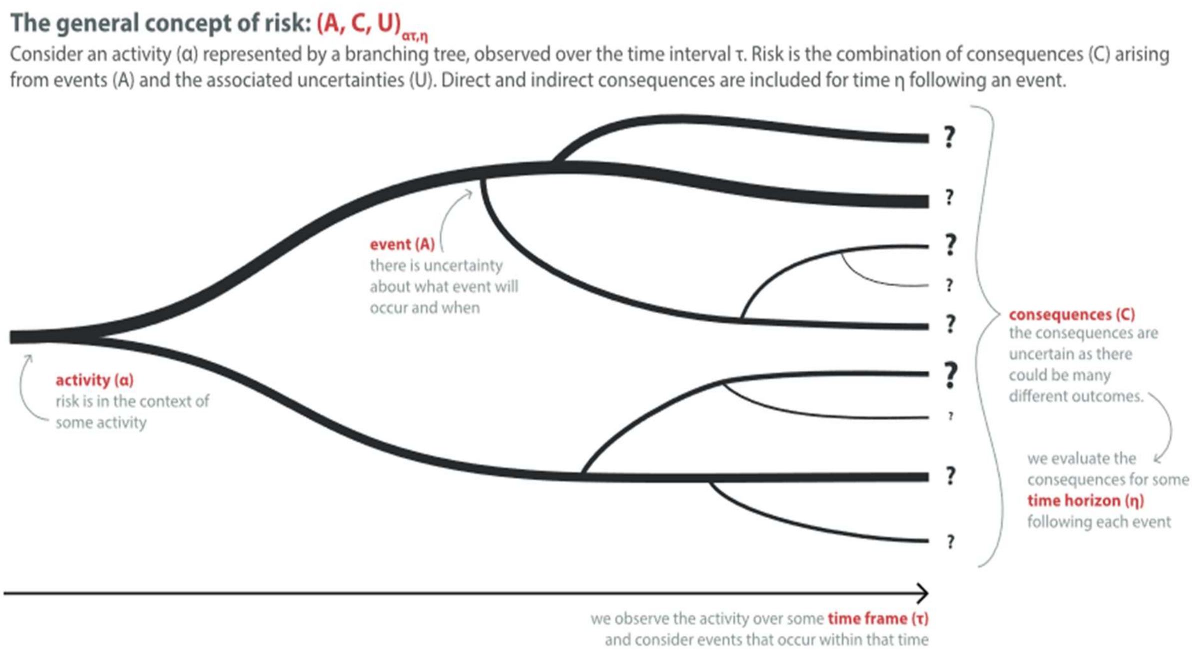

Figure 3: From left, were some activity (α) starts, to the right where we have the consequences which depends on the type of event (A) and its associated uncertainties. We also see that the time over which the activity is observed is (τ) (Logan et al., 2021).

In real life situations, the time interval ($[0, \tau]$) can be predetermined or depend on the activity and/or initiating event. We can use a few examples to illustrate different ways to consider the time frame of an activity (α):

- ***"Flooding risk"***: We can observe a village subject to flooding over a fixed period of time (T), in which case $\tau = T$.
- ***"Health risk"***: Observing a person over their lifetime, in which case τ is *unknown*.
- ***"Vulnerable system"***: We observe a production facility over a fixed time period (T), or until disruption happens at time T_e. If we have disruption at time T_e, we write $\tau = \min\{T, T_e\}$.
- ***"Resilience"***: If we consider the same facility over a fixed time period (T), and the production is disrupted at some point - we observe the facility until time $T + S$, before production is resumed as normal. (In this case S can be either unknown or specified). We write $\tau = T + S$. In case the production is normal at time T, S is considered to be 0, and then $\tau = T$.
- ***"Intergenerational problems"***: Observing a system for very long or infinite periods of time. Then $\tau = \infty$.

Table 1: Examples of how the time interval ($[0, \tau]$), for an activity (α), can be expressed in the suggested risk nomenclature for explicitly incorporating the time dimension in the risk concept.

Examples	**Specification of τ**	**Comment**
Flooding risk	$\tau = T$	Monitor risk for a fixed period of time (T).
Health of a person	τ is *unknown*	As long as a person is alive.
Vulnerability of a system	$\tau = \min\{T, T_e\}$	Monitor risk for a fixed time period (T), or until disruption at time (T_e).
Resilience	$\tau = T + S$	Fixed time period (T) and/or until system is back to normal operation after disruption time (S). If there is no disruption, then $S = 0$.
Intergenerational problems	$\tau = \infty$.	Observing a system for very long or infinite periods of time

These are some examples of showing how time can be specified when we view risk in the context of some observed or monitored activity and/or system. The important part is that the time interval is considered for each activity or case we are interested in observing, and that the ideas extends well with the *A,C,U* perspective. The examples in the table are not strictly linked to only one type of specification and could be specified depending on the needs of the risk analyst.

2.3.2 The consequences

In addition to clarifying the time interval (τ) over which we observe the activity (α), it is perhaps even more important to consider the time horizon for the consequences, which is highlighted in the second (ii) temporal consideration. The consequences can have far-reaching effects, and this is especially important when we discuss whether we face risk or not, pertaining to the risk concept. For example, let's say an investment manager manages a retirement portfolio over a period of 10 years. In this case, the activity α is managing the investment portfolio, and the time interval τ is 10 years. By the end of τ, referring to an event happening at the end of the timeline in figure 3, the stock market is hit by a major event, causing volatility and uncertainty in the markets. Surely, those that are close to retirement age would claim that they face risk, even though they are at the end of their investing period (α_τ). The consequences from the events induce uncertainty towards the portfolio-value for the next years when the retirees switch from actively saving to withdrawing funds from their accounts.

On the account of this, and by examples of similar thinking, it seems like there is a need to include a consequence dimension to the risk concept. By this, we can say something about how long into the future we consider consequences after an initiating event occurs. Even though we might have an event close to the end of the activity, like in our investment portfolio, the consequences might have far-reaching effects into the future which requires consideration. Logan et al. (2021) suggests letting η represent the length of time that we consider consequences after an event. Thus, we can express the concept of risk like this:

$$\textbf{Risk} = (\boldsymbol{C}, \boldsymbol{U})_{\alpha_\tau,\eta}$$

Now, the concept of risk accounts for both the time interval $[0, \tau]$, over which the activity is observed, and η, the time period over which we consider the consequences that follows from an event. We need to account for both α and η to be able to say when we face risk. Logan et al. (2021) further exemplifies how the consequence-dimension can be formulated for the risk concept in varying ways:

- We may want to know the risk of someone dying after being exposed to a toxin for a certain period of time. We could have a case of someone being exposed to a toxin for 1 year ($\tau = 1$), where we want to calculate the risk of the person dying within 5 years ($\eta = 5$).
- We consider consequences of an event over a fixed period of time after the initiating event. E.g., we can include direct and indirect consequences from a natural hazard 10 years after the disaster. This would include both the immediate damage to buildings and people as well as long term disruption to infrastructure and/or natural habitat. By specifying that $\eta = 10$, it also says that we will not consider consequences for longer than 10 years after the event.
- It could be helpful to allow for the fixed period over which we observe consequences to be different for separate events. In this case we would specify η as η_i, and as before, we consider consequences for η_i years after event i.
- We could also have instances where we only consider consequences until the end of (τ). Then $\eta = \tau$-t, where we understand t as the time of an event. As the previous point, we may have multiple events, which would lead us to write $\eta_i = \tau - t_i$, where t_i is the time when each event occurs.
- We consider consequences for several years after the observed activity have ended. If X is the time following the time interval $[0,\tau]$, then $\eta = \tau - ti + X$
- Lastly, we could have both τ and η running for very long periods of time, or even infinite. This could be relevant when conducting risk assessments concerning intergenerational impacts, with topics of e.g., sustainability or long-term development in vulnerable areas.

Table 2: Examples of how considerations of η can be formulated

Examples of how the time horizon η for the consequences can be specified in the suggested risk nomenclature for explicitly incorporating time	
Time interval η for consequences	Comment
$\eta = 5$	Calculate risk of dying within 5 years (after exposure of 1 year).
$\eta = 10$	Consider consequences from natural hazard(s) for 10 years after event.
$\eta = \eta_i$	Consider consequences for separate events i, for η_i years.

$\eta = \tau\text{-}t$	Consider consequences only until end of activity, the time interval $[0, \tau]$, after an event happens.
$\eta = \tau\text{-}t_i\text{+}X$	Consider consequences for X number of years beyond the period the activity was observed.
$\eta = \infty$	Consequences considered for long or infinite periods of time.

After this review of how considerations of consequences (η) pertain to the risk concept, we see that the time frame chosen for how we consider consequences could have big impacts on estimates of risk. For example, if η is too long in a natural crisis context, we could end up emphasizing long term development instead of other actions that could be more appropriate at the time, like e.g., immediate humanitarian aid. Considerations of η forces us to make judgements whether we should monitor consequences over the duration of the activity, or whether the consequences might extend for long periods of time after the activity ends.

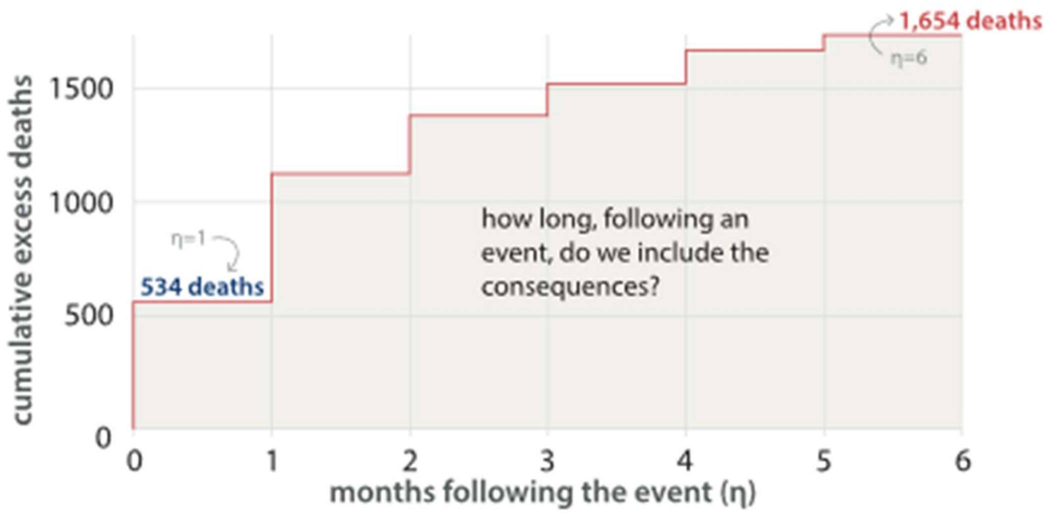

Figure 4: Example of the relationship between the time horizon (η) and the consequences (Logan et al., 2021).

For how long do we include consequences after an event? If the numbers in figure 4 represents the number of deaths rising in the months following an event, these could typically be caused by indirect causes like damaged infrastructure or the disruption of food and water supplies.

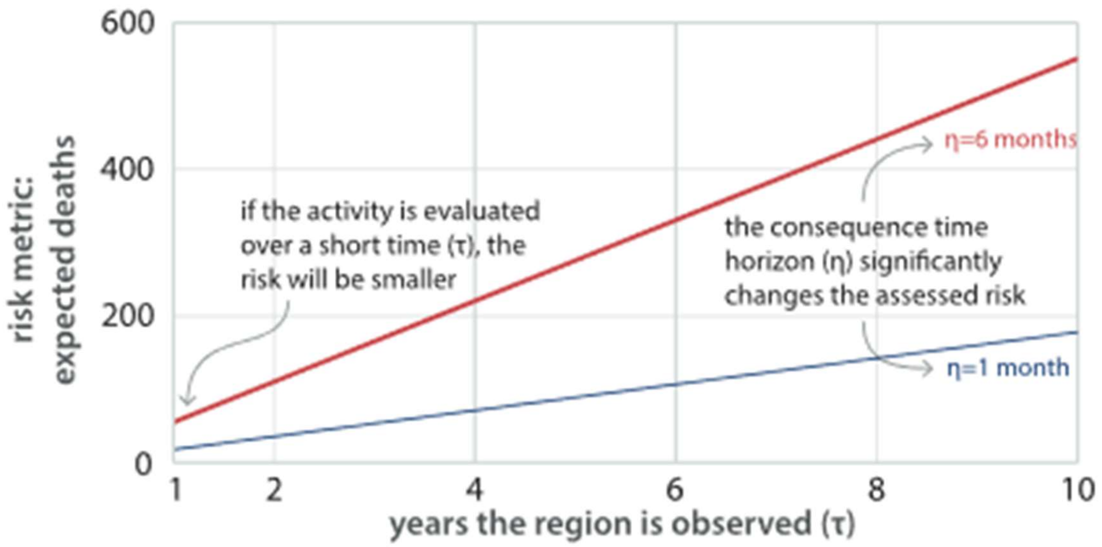

Figure 5: Shows how the choice of both η and τ could impact the assessed risk (Logan et al., 2021).

From figure 5, we see that if η is lower, then risk (expected number of deaths) is lower. The consequence horizon of η = 6 months gives higher risk than for η = 1 month. We also observe how the time over which we observe the activity τ impacts the risk assessment. The longer we observe, the higher likelihood that an event (e.g., an earthquake) will happen, and thus higher the risk.

2.4 Time in risk characterizations

Building on the previously used nomenclature for the risk concept, the risk description is written as (*RS', A', C', Q, K*), or by the simpler triplet (*C', Q, K*) (Aven, 2019). The problem here is the same as for the risk concept, in that time is not included in the description. Logan et al (2021) argue that both the time we observe an activity and the time horizon for the considered consequences after an event can have a major impact on determining the risk level. The authors therefore suggest to also include both the time interval of the activity (α_τ) we observe, and the time horizon of the consequences (η) into the risk description. Following that logic, the risk description could be written:

$$(C', Q, K)_{\alpha\tau,\eta}$$

Now, the risk characterization includes the time horizons both for the observed activity and the consequences. If we use an example of a vulnerable population, it is necessary to know over what time-period we observe the village, what kind of events (*A*) we are interested in monitoring (flooding, earthquakes, droughts etc.), the consequences (*C*) related to these events, and the time horizon (η) over which we consider these consequences. Remembering to include all elements of the risk characterization, it is also necessary to consider our measure of uncertainty *Q* (e.g., probability distributions or probability intervals) and judgements about the strength of the background knowledge *K* (Aven, 2019, p. 60).

In the next two sections, we give two brief illustrations of how risk can be characterized in one oil spill, and one flooding risk example. In the risk characterization, we first define the boundaries of the system (α_τ) we want to monitor, and the time horizon (η) for the consequences we are interested in considering. Secondly, we define the risk according to the (*A,C,U*) concept and characterize the risk according to the (*A',C',Q,K*) description. The reason for including these two examples is to show how the suggested updates in nomenclature for including time considerations would fit in the concept and characterization of risk when conducting a (simple) risk assessment.

2.4.1 Oil spill risk characterization example

We consider the risk from an oil spill from an offshore installation. To characterize risk, we first define the timeline and boundaries of the activity α_τ and the consequence horizon η:

α_τ: We observe the operations of offshore installation for a period of 6 months; then $\tau = 6$ months.

η: We assess the consequences to the marine environment over a period of 1 year after a potential oil spill occurs.

Following our concept for defining risk, we define risk as:

Table 3: Defining oil spill risk according to the (*A,C,U*) concept

Risk definition	
A	An oil spill occurs or not.
C	The consequences to the marine environment.
U	We cannot say whether an oil spill will occur or not

Now we characterize risk by the (*A', C', Q, K*) description:

Table 4: Characterizing oil spill risk according to the (*A', C', Q, K*) description

Risk characterization	
A'_1	An oil spill occurs within 6 months.
A'_2	An oil spill does not occur during the period.
C'	The impacts on marine life; seabirds, sea mammals and fish species from the oil spill, considered over a period of 1 year after the event.
Q	We use probability in combination with judgements of the strength of knowledge of the probabilities to express the uncertainties, for example by using the method suggested by Flage & Aven (2009).
K	*K* is the knowledge which $(A',C',Q)_{\alpha r,\eta}$ is based on.

In this case, we would monitor the activity over a period of 6 months and consider the consequences from a potential oil spill over a period of 1 year after the event. From a consequence viewpoint, we are interested in how pollution from an oil spill impacts the populations of marine life known in the region of the offshore installation. Oil spills are also known to spread over huge distances due to wind and ocean currents, meaning that the event could impact marine life at far away locations from the oil spill (Beyer et al., 2016; DNV GL, 2018). Perhaps a 1-year horizon for considering environmental impacts from oil spill hazards is not sufficient to cover all possible consequences in this risk assessment. One important thing is, however, that the two temporal considerations α_τ and η are clarified and explicitly stated in the analysis.

2.4.2 Flooding risk characterization example

We consider a village exposed to risk of flooding and want to characterize the risk. First, we define the timeline and boundaries of the activity α_r and the consequence horizon η:

α_τ: The time period over which we observe the community. In this stage, attention should also be paid to what components of the village that are of interest, e.g.: demographic, infrastructure, geographic limits and so on. In this example we will observe the inhabitants inside the village over a period of 5 years. Therefore, τ = 5 years.

η: For η there is several possible time horizons to consider. We could consider the consequences every day until the village returns to its normal state pre-disruption, or we can e.g., consider consequences as the number of cumulative deaths following the event, where η is specified to a period of 6 months or any other chosen time period. In this example we state η = 6 months.

Following our concept for defining risk, we define risk as:

Table 5: Defining flooding risk according to the *A,C,U* concept

Risk definition	Comment
A	The village is impacted by flooding during the 5 years, or not.
C	The consequences to the people in the village
U	We cannot say whether a flooding event will happen, nor know what the consequences will be over the time interval η.

Next we characterize risk by the (*A'*,*C'*,*Q*,*K*) description:

Table 6: Characterizing flooding risk according to the (*A',C',Q,K*) description

|Risk characterization	Comment
A'_1	The village is impacted by flooding within the 5 years.
A'_2	The village is not impacted by flooding within the 5 years.
C'	The consequences to the people expressed by the cumulative loss of lives.
Q	We use probability in combination with judgements of the strength of knowledge of the probabilities to express the uncertainties.
K	*K* is the knowledge which $(A',C',Q)_{\alpha_\tau,\eta}$ is based on.

As shown in figure 4 and 5 in chapter 2.3.2, we see that the level of risk depends on both how long we monitor the village (α_τ), and for how long we consider the consequences after an event (η). If defining our consequences as the loss of lives following a flooding event, a η longer than 0 allows us to consider both direct and indirect consequences from the event. We are 'free' to specify η depending on the events and situation at hand. For example, if we monitor health risk of a person, we might want to consider consequences over the entire lifetime of the person or for a specified period of time.

2.5 Risk Management

In this section we will explore some possible implications temporal considerations has for the risk management process. Risk management is in large part is about balancing development and protection (Aven, 2019, p. 169). An important part of risk management is concerned with finding an adequate level of protection and avoiding too high costs related to safety measures and risk reducing activities, while at the same time achieving an acceptable level of risk. Too high costs and risk reducing measures make business ineffective, while on the other hand, too little protection will result in mishaps and accidents (Reason, 1997). A risk assessment will be one of the tools to provide important information into this kind of decision judgements and to the risk management stage (Aven, 2019, p. 169).

The risk management process also includes a classification of the type of risk problem. As different types of risk problems need different responses and measures, it is important to understand the different classes of risk such that we can treat and mitigate them accordingly. For example, the International Risk Governance Counsil (IRGC) distinguishes between *simple/linear*, *complex*, *uncertain* and *ambiguous* risk problems (Renn, 2008b). *Simple/linear* risk problems would be those that are straightforward to assess, like the health-related effects of smoking or traffic risks. *Complex* risk problems are those with more complicated structures, making it hard to predict how a system might behave (Aven, 2019, p. 220). An example of this could be electrical infrastructure grids, health care systems or the movements in financial markets. *Uncertain* risk problems would be those were we struggle to predict the outcome or occurrence, like for a terrorist attack, where the consequences could be severe. *Ambiguous* risk is when we have different views on the scientific evidence and/or what values we want to protect (Renn, 2008a). An example of ambiguous risk could be nuclear energy and the question of whether we should use it or not, which have been a debated topic due to the involuntary exposure of risk to populations (Löfstedt, 1996).

A system for the classification of risk problems, in conjunction with a selection of appropriate tools for managing the risk might be useful for decision-makers and risk analysts in solving real world risk problems. One system for managing risk according to this line of thinking might be to follow risk management strategies that are classified as *routine based (linear)*, *risk informed*, *cautionary/precautionary* or *discursive* (Aven, 2019, p. 168; Renn, 2008a, p. 178-179). Table 7 below shows this relationship between the type of risk problem, the suggested risk management strategy, and their related instruments for handling risk.

Table 7: Risk characterization and its implications for risk management

Knowledge characterization	Management strategy	Appropriate instruments	Stakeholder participation
1 Linear risk problems	*Routine-based* (tolerability/acceptability judgement) (risk reduction)	→ Applying 'traditional' decicion making • Risk-benefit analysis • Risk-risk tradeoff • Trial and error • Technical standards • Economic incentives • Education, lbaelling and information • Voluntary agreements	Instrumental discourse
2 Complexity-induced risk problems	*Risk-informed* (risk agent and causal chain)	→ Characterizing available evidence • Expert consensus-seeking tools - Delphi or consensus conferencing - Meta-analysis - Scenario construction etc. • Results fed into routine operation → Improving buffer capacity of risk target through: • Additional safety factors • Redundancy and diversity in designing safety devices • Improving coping capacity • Establishing high-reliability organizations	Epistemic discourse
3 Uncertainty-induced risk problems	*Precaution-based* (risk-agent)	→ Using hazard characteristics such as persistence and ubiquity as proxies for risk estimates Tools include: • Containment • ALARA (as low as reasonably achievable) and ALARP (as low as reasonable practicable) • BACT (best available technology), etc.	Reflective discourse
	Resilience-focused (risk-absorbing system)	→ Improving capability to cope with surprises • Diversity of means to accomplish desired benefits • Avoiding high vulnerability • Allowing for flexible responses • Preparedness for adaption	
4 Ambiguity-induced risk problems	*Discourse-based*	→ Application of conflict-resolution methods for reaching consensus or tolerance for risk evaluation results and management option selection • Integration of stakeholder involvement in reaching closure • Emphasis on communication and social discourse	Participatory discourse

Reprinted by the author from Renn, 2008a, p.181.

In table 7, we see examples of how one could link the type of risk problem to a suited management strategy for handling risk. Each type of risk problem has a distinct management strategy and some associated instruments for handling the risk. For example, for complexity-induced risk problems, it is suggested to the use the *risk-informed* strategy to handle risk problems bound to that category. Here, some common instruments to manage risk is by the use of expert consensus, ALARA/ALARP (*As Low As Reasonably Achievable/ As Low As Reasonably Practicable*), safety design, redundancy, improved coping capacity and/or establishing a high reliability organization. It is also relevant to adjust the stakeholder participation depending on the risk problem/management strategy, as can be seen in the right-hand side of the table.

By suggestion of the author of this thesis, our perspective on how to consider the time dimension in risk assessments could perhaps be 'integrated' with the table for risk characterization (Table 7) with its implications for risk management. The reasoning behind this "integration" is that the considerations of the time dimension could help inform decision making on what risk management strategies is most suitable for the risk problem. Next, we adapt a simplification of table 7 to also include the relevancy of time considerations for the risk problem taxonomy, and present this relationship in table 8:

Table 8: Classification of risk problem, management strategy (and its appropriate instruments) and the relevancy for time considerations.

Classification of risk problem	**Management strategy**	**Appropriate instruments (simplified)**	**Time dimension relevancy**
Linear/simple	Routine-based	Technical standards and requirements, Risk-risk tradeoff, Risk-benefit analysis, Economic incentives	Low
Complex	Risk-informed Robustness-focused	Characterize risk, Expert consensus, Improve coping capacity, Reduncancy, High reliability theory	High
Uncertain	Precaution-based Resilience-focused	ALARA/ALARP (as low as reasonably achievable/as low as reasonably practicable), Containment, Improve capabilities to cope, Flexible and adaptive responses	High
Ambiguous	Discourse-based	Expert consensus, Involve stakeholders, Social discourse	Depends on the risk problem. E.g., exclusion of nuclear power, climate change risk, sustainability topics

In table 8 we have classified the relevancy of time considerations from low to high according to the risk problem taxonomy. Each category is explained more in the following.

Linear/simple risk problems: The relevancy of the time dimension is generally judged low for this category. To solve these problems, standard types of decision making like statistical analysis or technical standards, risk-risk tradeoff, risk-benefit analysis, economic incentives etc., is commonly used, and typically does not require deliberate time considerations. Some problems might, however, be subject to temporal considerations in this category too. One could subject health risk from smoking to temporal considerations, since e.g., exposure-time is an important factor that increases the risk of disease (Logan et al., 2021). Most of these problems are however solved by standard modes of decision making.

Complex risk problems: The relevancy of the time considerations can be judged as high for this category. For these risk problems, the major input for risk management is provided by scientific characterization of risk (Renn, 2008a, p. 178). In this category, some common tools for characterizing risk are e.g. expert consensus, improving capacity to withstand, cost-benefit analysis (CBA) and cost-effectiveness analysis (CBE), which provide methods to find a balance between opportunities and risk (Aven, 2019, p. 173; Renn, 2008a, p. 178). For cost-benefit analysis, time is an important factor since long term/future consequences are transformed to monetary values and discounted, which could influence policy creation today and/or determine the levels of investment in risk reducing measures.

Uncertain risk problems: Time relevancy is also judged as high for the category of uncertain risk problems. Some common risk problems in this category require precaution-based approaches, using instruments like BACT (best available technology) or ALARA/ALARP where e.g., cost benefit analysis based on expected values is commonly used (Aven, 2019, p. 177). Also, problems dealing with vulnerability, resilience, adaption and/or robustness falls under this category. Considerations of time for uncertain risk problems could be highly relevant when studying a vulnerable system, like a community exposed to natural disasters.

Ambiguous risk problems: The relevancy of time considerations in this category depends on the type of risk problem. Whether to use nuclear power when the nuclear power plant is located near densely populated areas, or when the population is opposed to it, is a debated risk topic where the tolerability of risk versus benefit, different stakeholder views could conflict with judgements of values and priorities (Löfstedt, 1996; Renn, 2008a, p. 180) Similarly, risk assessments of artificial intelligence risk could be considered an ambiguous risk problem, and considerations of time could be an important factor both for the monitoring (α_τ) of the technology (activity) and the possible consequences and the time horizon (η) over which they are considered (Ilag & Athave, 2019). Typically, in this category we often find intergenerational topics like sustainability, nuclear power, climate change risk etc., where the temporal considerations could be highly relevant. By clearly stating considerations of time, we can help increase clarity on what kind of risk problem we face, which in turn means that time considerations can be a guidance in the process of selecting the best suited management strategy for a certain risk problem.

2.6 A table for the evaluation of the time dimension in risk assessments

After reviewing how time can be explicitly stated in the concept and characterization of risk in chapter 2.3 and 2.4, and by using the classification system for managing risk problems in table 7 and table 8 in chapter 2.5, we now arrive at what is a suggested template that can be used for the evaluation of time considerations for the Stålull drilling case and the Haiti earthquake case. The steps outlined for arriving at this template are illustrated in figure 6 below:

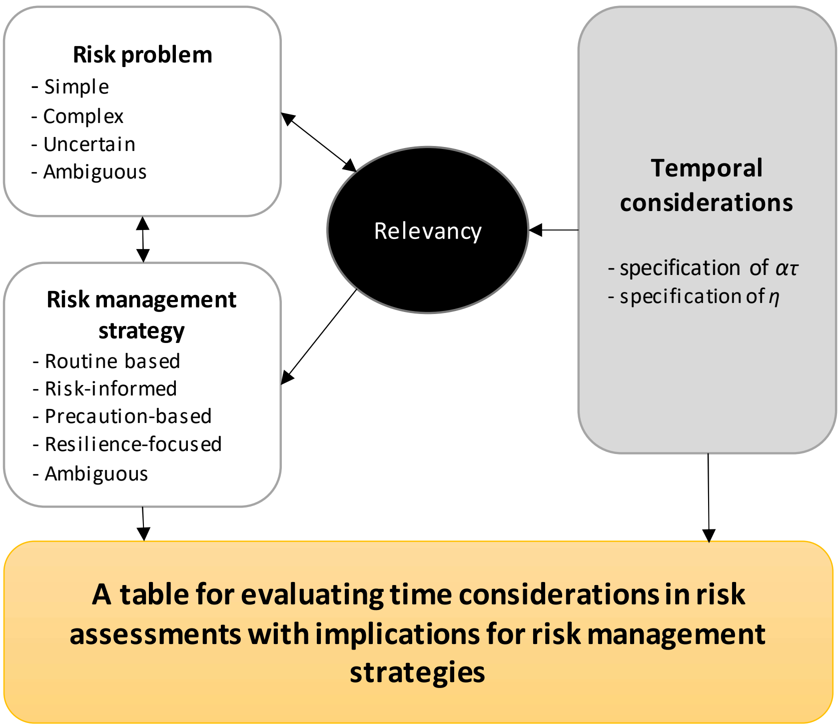

Figure 6: The relationship between the temporal considerations and risk management strategies

In figure 6, we see how the relevancy of the temporal considerations interact with the type of risk problem classification and risk management strategies, to result in a table for the evaluation of the time dimension in risk assessments. The template only represents a suggestion from the author of the thesis and is not meant to be a definitive guide. It could be thought of as a simple tool to perhaps increase clarity on the connection between time considerations and the selection of appropriate risk management strategies, depending on the risk problem. One note to keep in mind, is that there is not necessarily a strong connection between the specifications of τ and η on each line/example. For each specification of τ, the consequences η can be considered in a variety of ways. Next follows the suggested template:

Table 9: A table for the evaluation of the time dimension in risk assessments

The monitored activity/system α_τ					•	The considered consequences and time horizon η			
Examples of activity α	**Specification of τ**	**Comment**	**Risk problem**	**Risk Management Strategy**	•	**Time interval η for consequences**	**Comment**	**Risk problem**	**Risk Management strategy**
"Flooding risk"	$\tau = T$	A fixed period of time (T).	Linear/simple, Complex Uncertain	Routine based, Risk-informed, Precaution-based, Resilience-focused	•	$\eta = X$	Consider consequences for X number of days/months/years after an event occurs.	All types could apply	All strategies could apply, depending on risk problem
"Health risk"	τ is unknown	As long as a person is alive.	Uncertain Ambiguous	Resilience-focused, Precaution-based, Discourse-based	•	$\eta = \tau - t_i + X$	Consider consequences for a X number of years beyond the period the activity was observed, and ti is the occurrence time of any event.	Complex Uncertain Ambiguous	Risk informed, Robustness-focused, Precaution-based, Discourse-based
"Vulnerable system"	$\tau = \min\{T, T_e\}$	Fixed time period (T), or until disruption at time (T_e).	Complex Uncertain	Risk-informed, Robustness focused Precaution-based, Resilience-focused	•	$\eta = \tau - t$	Consider consequences only until end of activity, and time interval [0, τ], where t is the time of the event.	Linear/simple Complex Uncertain	Routine based, Risk-informed, Precaution-based, Resilience-focused
"Power grid failure (resilience)"	$\tau = T + S$	Fixed time period (T), if system is functioning normally at time T, or observed until time T + S, where S is an unknown or fixed time until the system resumes normal function. If there is no disruption, then S = 0.	Complex Uncertain	Risk-informed, Precaution-based Resilience-focused	•	$\eta_i = X_i$	Consider consequences for separate events i, for an Xi period of time after an event.	Complex, Uncertain	Risk-informed, Resilience-focused
"Intergenerational topics"	$\tau = \infty$	Monitor activities or systems over long intergenerational time periods	Uncertain Ambiguous	Precaution-based, Resilience-focused, Discourse-based	•	$\eta = \infty$	Consequences considered for very long or infinite periods of time.	Uncertain Ambiguous	Precaution-based, Resilience based, Discourse based
Stålull drilling case					•				
Haiti earthquake risk					•				

The different specifications of α_τ and η in table 9 provide a quick view into how the time considerations are linked to both the type of risk problem and the suitable risk management strategies. The different specifications of time are represented by examples to illustrate some typical cases where the specifications could be used. As for the first line in the table, we use the example of "*Flooding risk*" as an example, where $\tau = T$ (a fixed period of time), which could be *one* suitable specification on how to monitor flooding risk. Similarly, specifying the consequence horizon as $\eta = T$, allows us to consider the consequences for a fixed period of time after the flooding event. As for this example, there is a lot of options on what is a suitable risk management strategy since the risk problem falls in the categories of linear/simple, complex, uncertain.

For some other specifications of τ and η, the guidance on risk management strategies can be more clarifying. E.g., specifying τ and η for very long periods of time (or infinite) for example, is a specification that points us in the direction of an uncertain and/or ambiguous risk problem. To handle these kinds of risk problems, the suggested instruments would be precautionary, resilience-focused and/or discourse based for the risk management. We also observe that the specification $\eta = \eta_i$, has been classified as a *complex* risk problem in the table, pointing to complexity caused by several separate events and possible consequences related to the events.

In the bottom of the table, two blank rows have also been added for the Stålull and Haiti case to illustrate that the template will be used for the evaluation and suggestions on how time can be considered in the cases, and what management strategy that might be suited to handle the risk. In the next chapter we start the evaluation and suggestions on time considerations for the Stålull exploration drilling case.

3 Case 1: An evaluation of how time is reflected in the risk assessment for the Stålull exploration well

In this case we evaluate an environmental risk analysis done for an exploration well in the North Sea. Specifically, it is a report from Det Norske Veritas (DNV), made on behalf of Statoil ASA (referred to as *Equinor* hereafter, after the 2018 name change) for drilling the exploration well 35/10-4 Stålull in block PL630. The report was delivered 14/02-2018 (DNV GL, 2018).

After the evaluation, we will provide suggestions on how time could have been considered based on Logan et al. (2021) article. The table for the evaluation of the time dimension in risk assessments in chapter 2.6 will be used both for the evaluation and suggestions on how time can be considered in both cases.

3.1 Background

The Stålull well is located in the northern part in the North Sea, 67km from the shore outside Utvær in Sogn og Fjordane. The water is fairly deep at the well location with a depth of 366m. The main objective of the report is to estimate possible consequences from a potential blowout during the drilling operations that could harm marine life, both at sea and at the coastline.

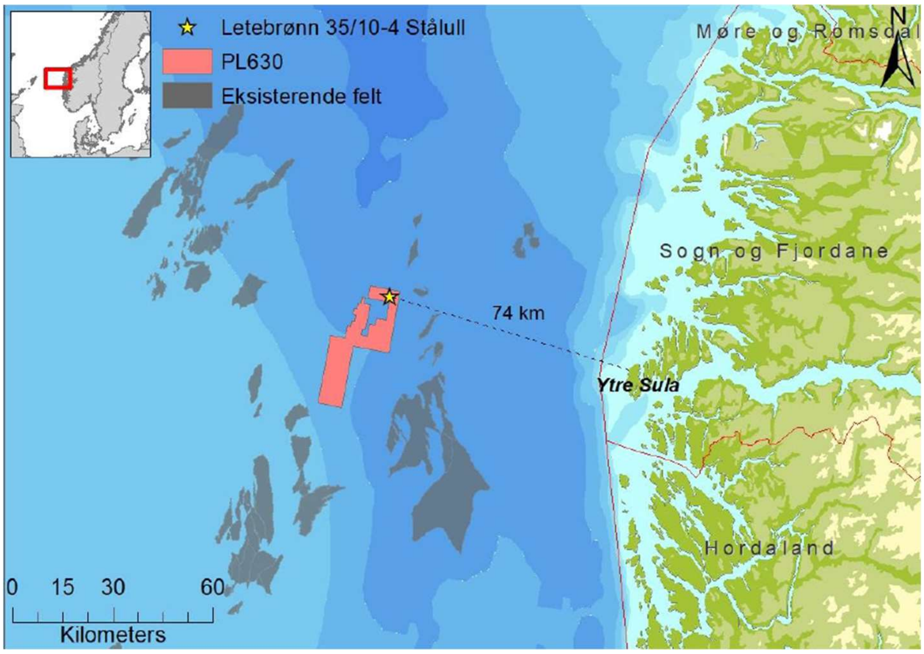

Figure 7: The location of the Stålull well in the northern part of the North Sea in PL630 (DNV GL, 2018).

A blowout can be defined as an uncontrolled release and flow of hydrocarbons (oil & gas) to the sea and atmosphere (Andersen, 1998). Further, blowouts might be considered the most dreadful, dangerous and costly event that can happen on offshore drilling rigs. In addition to potential damage to humans and property, a blowout also poses high risk to the environment (Andersen, 1998). In 2010, the Deepwater Horizon blowout in the Gulf of Mexico resulted in the largest marine oil spill ever recorded. In this disaster, the drilling rig Deepwater Horizon lost control of a well in the Macondo prospect during operation, where several events in combination with barrier failures, caused a blowout when the blow out preventer (BOP) located on the seafloor failed to operate as expected (Pallardy, 2022). The consequences of the blowout were catastrophic. 11 people were killed, the rig capsized and sank, and hydrocarbons were flowing freely from the well into the sea at estimated rates of 1000-60 000 barrels per day for almost 3 months. Eventually, the oil escaping from the well created an oil slick covering 149 000 square kilometres of sea in the Gulf of Mexico, with major consequences for marine life and seabirds in the affected areas (Pallardy, 2022; Beyer et al., 2016). More than a decade after the event, there is still evidence of the damage done to marine life, and the long-term consequences still remain unknown (Beyer et al., 2016).

In the environmental risk analysis for the Stålull well, the main objective is to investigate the possible risk to valued eco-components like seabirds, sea mammals and fish species. The report, however, points out the difficulty of quantifying environmental risks. DNV (2018) stresses that all numbers and figures are based on parameters that contain higher or lesser degrees of uncertainty. For example, in environmental risk analysis it is important to have a sufficient dataset and knowledge related to the population and habitat of different species to be able to make estimations of risk (DNV GL, 2018; Beyer et al., 2016). The Stålull report has been criticized from Miljødirektoratet (2018) for avoiding dealing with risk for several species known to be present in the location of the Stålull well. DNV GL, on the other hand, argues that there simply does not exist enough data on these species to create meaningful estimations on risk.

In their risk analysis prior to drilling operations on the Norwegian continental shelf, Equinor uses standardized risk accept criteria that would be customized according to the location and the type of species and populations present (DNV GL, 2018). The acceptance criteria contain both the vulnerability and restitution time of the potentially affected species and habitat (DNV GL, 2018). Equinor further highlights that ".. nature should to the greatest possible extent remain untouched by the company's activities", meaning that Equinor's risk management is actively making efforts to limit possible harm to the external environment (DNV GL, 018, p. 8). Table 10 shows the operational specific acceptance criteria Equinor operates with in relation to environmental damage.

Table 10: Equinor's operational specific accept criteria for pollution.

Environmental damage	Restitution time	Operational specific criteria
Minor	1 month – 1 year	$< 1 \times 10^{-3}$
Moderate	1-3 years	$< 2{,}5 \times 10^{-4}$
Significant	3-10 years	$<1 \times 10^{-4}$
Severe	> 10 years	$< 2{,}5 \times 10^{-4}$

Reprinted by the author (DNV GL, 2018, p. 8)

In table 10 we are introduced to considerations of time, both related to operational specific acceptance criteria and the restitution times of species in the report (DNV, 2018). Equinor further classifies the degree of damage in the range of *minor*, *moderate*, *significant* to *severe*, depending on the restitution time and operational criteria. We also observe that Equinor classify a restitution time of more than 10 years to be most severe, while a duration of 1 month to 1 year is classified as having a minor impact on the environment. Further, the operational specific criteria establish probabilities/frequencies for each classification of accept criteria. The probability decreases as we go from the small impact ($< 1 \times 10^{-3}$) to the most severe impact ($< 2{,}5 \times 10^{-5}$). For example, we see that Equinor estimate a moderate impact to have a probability of $< 2{,}5 \times 10^{-4}$, which means they believe an incident like this will happen once every 4000 years.

A potential blowout from the Stålull well would be regarded as a defined hazard and accident situation (DSHAs) by Equinor, meaning that it has a major accident potential (DNV GL, 2018). For the Stålull well, Equinor have defined the blowout risk to have a probability of $6{,}35 \times 10^{-5}$, which translates to an estimation of 1 blowout for every 15 748 exploration wells drilled. The planned drilled section and formations are well known from other wells in the area, the risk for a blowout is reduced by 50 percent compared to a generic probability of a *wildcat* exploration well (DNV GL, 2018). Since the well will be drilled with the blowout preventer located at the seafloor, a potential blowout would most likely happen on the seafloor level (DNV GL, 2018). Equinor estimate that there is a 75% probability for a potential blowout to happen at the seafloor level, compared to 25% probability for a surface blowout. This has implications for how oil from a blowout will be dispersed in the sea compared to a surface-blowout. Both Andersen (1998) and Beyer et al. (2016) notes that a blowout at surface level most likely will create a larger oil sheen compared a blowout on the seafloor, which in turn would be more damaging to the coastal areas and the associated marine life. However, a seafloor blowout would have other damaging implications, i.e. that more oil will disperse onto the seabed and impact marine life differently than in a surface blowout. There are e.g., reports explaining that massive amounts of oil from the Macondo oil spill are still present on the seafloor more than 10 years after the disaster (Beyer et al., 2016; Pallardy, 2022). Next, we will conduct an evaluation of the time considerations related to the drilling activity of the Stålull well.

3.2 An evaluation of time considerations for the drilling activity

The activity (α) we are interested in monitoring is the drilling operation, as this is the activity related to the potential blowout disaster that is described in the report (DNV GL, 2018). The report further distinguishes between two key operations related to the drilling, namely drilling of the first (*initial)* well, and a possible second (*relief*) well in the case of a blowout during the first well. If the drilling operations for the initial well would go according to plan, with no blowout, there would be no need for drilling of the relief well.

The time estimate for drilling of the relief well is 63 days, and that includes mobilization of rig, drilling into the reservoir and killing the blowout (DNV GL, 2018). The consideration of time is therefore explicit in the time estimate of the relief well, but there is no notion on what time is planned for the initial well. If we call drilling of the initial well α_1, and the second well α_2, we have established the activities to consider, but we lack a time frame for the first activity. We can illustrate the two main activities and their notions of time in table 11:

Table 11: Evaluation of time considerations related to the drilling activity α_1 and α_2

Evaluation of the monitored activities for the Stålull Well				
Activity (Stålull)	**Specification of τ**	**Comment**	**Risk problem**	**Risk Management Strategy**
Initial well α_1	τ is *unknown*	Unknown. No mentioning of the planned time for the first well in the report	Uncertain Ambiguous	Resilience-focused, Precaution-based, Discourse-based
Relief well α_2	$\tau = T$	A fixed period of time (T). The relief well has a time interval, $[0, \tau]$, of 63 days	Linear/simple, Complex Uncertain	Routine based, Risk-informed, Precaution-based, Resilience-focused
α_i	…	…	…	…

In the DNV GL (2018) report there is no specific notion of the time frame (τ) considered for the drilling of the first well (α_1), but it is explicitly stated to be 63 days for the relief well (α_2).

The included α_i in table 11 is there to indicate that we also could have an *i-th* number of activities or systems we want to monitor in our analysis.

The first specification is related to the initial well, where there is no mentioning of time considerations. This is an τ = *unknown* specification. The problem with not specifying the time interval for this activity is that it becomes unclear what this means for the risk management, and/or what kind of risk problem we are faced with. As we have mentioned earlier, r = *unknown* would perhaps be a suitable specification related to e.g., a persons health, since his/her life time is unknown. For the drilling case, it becomes a question of whether it is helpful with such a specification. Can the drilling case be considered an uncertain and/or ambiguous problem, and are the associated risk management instruments applicable to the drilling risk? We will come back to some possible 'solutions' in section 3.5 for the suggestions of how time could have been considered.

The second specification in table 11 is for the relief well, in case of a blowout. Here, we are presented with an explicit statement of consideration of time, where the drilling of the relief well is expected to last 63 days ($\tau = 63$). This is a $\tau = T$ specification, where we are pointed to a risk problem classification that lies in the simple/complex/uncertain category. Here, the available management strategies are multiple. By referring to table 9 and 11, some of the risk management instruments are standard decision making, economic incentives, expert consensus, the ALARP principle, containment, risk informed and/or resilience based. Some of these risk management strategies (instruments) are widely used in the oil industry. For example, the ALARP principle supports that a safety measure shall be implemented unless one can demonstrate that the costs are disproportionately large to the expected benefit, where cost-benefit analysis is a commonly used tool to verify ALARP (Aven, 2019, p. 177). The precautionary principle is also extensively used, for example when designing the offshore living quarters to be fireproof on the basis that fires might occur on offshore installations (Aven, 2019, p. 180). $\tau = T$ is all in all a suitable specification, but there could also be other suitable specifications that we will look into in the suggestions on how time can be considered for the activity.

3.3 An evaluation of the time considerations for consequences

The consequences from a potential blowout in the Stålull case are closely linked to the time it takes to drill the relief well to stop the uncontrolled release of hydrocarbons. As previously noted, the estimated time for drilling of the relief well and killing the blowout is 63 days, which means that this is also the estimated duration for the uncontrolled release of hydrocarbons to the environment. The environmental risk considered in the report deals with risks to seabirds, sea mammals and fish species, where the vulnerabilities between different species differ, and their restitution times will be affected (DNV GL, 2018). As we saw in the introduction, Equinor uses four main categories for classifying restitution times (consequences):

- Minor (< 1 year)
- Moderate (1-3 years)
- Significant (3-10 years)
- Severe (> 10 years)

The environmental damage is expressed as the time it takes for a given species to recover to 99% of its pre-event levels. A time interval of more than 10 years for a species to be recovered to 99% of its pre-event population is therefore the most severe classification according to Equinor, as per the classification in table 10. By stating η to be in the range of months or years, depending on the severity of consequences, Equinor is effectively considering consequences for a fixed period of time after an event occurs. In table 12 below, we use our table for evaluating the time-dimension in risk assessments to see how the consequence time-horizon has been considered:

Table 12: Evaluation of the time horizon (η) for the consequences for the Stålull well

Evaluation of the time horizon (η) for the consequences				
Type of specification of η	**Time interval η for consequences**	**Comment**	**Risk problem**	**Risk Management strategy**
$\eta = X$	η = from *1* month to more than *10* years	Consider consequences for up to *1* year after a blowout occurs.	All types could apply	All strategies could apply, depending on risk problem

$\eta = X$ is a pretty simple and straightforward specification, where the consequences are considered for a specified period after an event occurs, and is effectively the specification type used in the report. In the report, the consequences are considered for a certain period of time from 1 month to more than 10 years, which fits this type of specification.

We also see that the $\eta = X$ specification applies to all types of risk problems and the related risk management strategies. This could be an issue when selecting risk management strategy, and there would be a need to accurately define the boundaries of the system being monitored;

the possible consequences, and their related time horizons to get meaningful decision information for selecting the best suitable risk management strategy.

3.4 Suggestions for how time could be considered for the observed activity α

In this section we will provide some suggestions on how time could have been considered, both for the drilling activity and the consequences in the Stålull case, based on the table for evaluation of the time dimension in risk assessments.

***The drilling activity α*:** For our purposes, we are interested in monitoring the drilling operations from the start, throughout a possible blowout scenario, and until the drilling operations again are back to its pre-disruptive state. This means that even though the report distinguishes between the two drilling activities α_1 and α_2, we in effect should treat both as one activity (α), as they are linked together.

The report only state explicit time frames for the second *relief* well. This could have to do with the fact that the premise for drilling of the relief well would be to have a blowout event during the first well. If operations go without a blowout during drilling of the initial well, there will be no need for a relief well (and monitoring). However, for purposes of clarification, it would be recommended that explicit time considerations should also be stated for the first well.

Let's explore what guidance we can give for the possible specifications of τ in the Stålull case in table 13 below by using our table for evaluating the time-dimension in risk assessments:

Table 13: Suggestions for specifications of α_τ for the Stålull case:

The monitored activity/system α_τ				
Examples of activity α	**Specification of τ**	**Comment**	**Risk problem**	**Risk Management Strategy**
«Flooding risk»	$\tau = T$	A fixed period of time (T).	Linear/simple, Complex Uncertain	Routine based, Risk-informed, Precaution-based, Resilience-focused
«Health risk»	τ is unknown	As long as a person is alive.	Uncertain Ambiguous	Resilience-focused, Precaution-based, Discourse-based
«Vulnerable system»	$\tau = \min\{T, T_e\}$	Fixed time period (T), or until disruption at time (T_e).	Complex Uncertain	Risk-informed, Robustness focused Precaution-based, Resilience-focused
«Power grid failure (resilience)»	$\tau = T + S$	Fixed time period (T), if system is functioning normally at time T, or observed until time T + S, where S is an unknown or fixed time until the system resumes normal function. If there is no disruption, then S = 0.	Complex Uncertain	Risk-informed, Precaution-based Resilience-focused
«Intergenerational topics»	$\tau = \infty$	Monitor activities or systems over long intergenerational time periods	Uncertain Ambiguous	Precaution-based, Resilience-focused, Discourse-based

$\tau = T$ (“Flooding risk”specification): This specification is regarded as suitable for the Stålull drilling case. With $\tau = T$, we specify the time interval for the activity we want to monitor to a fixed period of time. Since the drilling operation is limited in is duration, this could be a suitable choice for the specification of τ. The **specification** does not, however, account for possible delays in the activity. What if T is specified to e.g., 100 days, but the activity exceeds this time horizon? The specification does not account for possible delays in the monitored activity.

τ = unknown (“Health risk” specification): This is not a meaningful specification for the Stålull case, as it does not provide any specified timeline to monitor the drilling activity. The specification would fit well in cases related to personal health, as a person’s life span is unknown. Further, it does not provide definitive guidance on the selection of risk management strategy without a clear definition on what the boundaries of our system in consideration are.

$\tau = \min\{T, T_e\}$ (“Vulnerable system” specification): This could be a viable specification for the Stålull case in some respects. With this specification, we monitor the drilling activity for a fixed period of time (T), or until disruption occurs at time (T_e). Still, one needs to be aware that this is also a fixed time specification of τ, where monitoring stops when/if disruption happens at time (T_e). The problem one runs into is that the specification does not allow for the monitoring of the system throughout a disruptive state and back to its pre-disruptive state. Since the Stålull case is related to a hydrocarbon blowout, the time considerations and related risk management strategies should be concerned with the recovery of the system, not just the immediate disruption.

$\tau = T + S$ («Power grid/resilience” specification): This time specification monitors the drilling activity for a fixed time period (T) in case of no disruption, or until the system is back to normal operation after $T + S$ time. This specification fits the Stålull case well, since it allows for a fixed time specification for the monitored activity, while additionally accounting for any disruptive event and the monitoring of the activity until it resumes its pre-disruptive functionality. In the Stålull case, we would be interested in this kind of specification as it supports risk management strategies that are risk informed, precaution-based and resilience-focused. Some related instruments used in these strategies could be characterizing risk, expert consensus, improving coping capacity, safety factors and design, ALARA/ALARP, BACT, reducing vulnerability, adaptive measures and allowing for flexible responses.

$\tau = \infty$ («Intergenerational topics» specification): This specification is less useful in the Stålull drilling case. The time period for monitoring the activity with this specification are stretched for very long, or infinite, time horizons which is impractical for the needs of the drilling case. It also refers the risk management strategies to those that are pre-caution-based, resilience-focused and discourse based, where the last one might be considered as having little relevance for this kind of risk (depends on the problem). In any case, the drilling activity would be much more restricted in time than what this specification is suited for.

In the end, our main suggestion for how the drilling activity α_τ should be monitored will be the following specification:

$$\boldsymbol{\tau} = \boldsymbol{T} + \boldsymbol{S},$$

With this specification, we effectively allow for the system to be monitored for a fixed period of time T, and/or until the system is back to normal operation after a disruptive event. The time until the system is back to normal operation is S, and could be either unknown or predetermined. This specification therefore allows us to monitor the risk until the uncontrolled release of hydrocarbons is back under control/containment. In our table for the evaluation of the time dimension in risk assessments, this specification relates to complex and uncertain risk problems, where risk-informed and resilience-focused risk management strategies are tools that can be used to handle the risk.

3.5 Suggestions for how time could have been considered for the consequences

The report presents some explicit operational criteria used by Equinor, where the consequences are ranked from minor to severe depending on the impact and restitution times for seabirds, fish and sea mammals. To see how we might consider specifications for the time horizons related to consequences, we use our table for the evaluation of the time dimension in risk assessments. Every listed specification in table 14 below is evaluated and discussed to see what specification(s) is best suitable for the Stålull case. In the end, two specifications for the consequences will be recommended.

Table 14: Suggestions for the consequence horizon η for the Stålull case:

Suggestions for the consequence horizon η			
Time interval η for consequences	**Comment**	**Risk problem**	**Risk Management strategy**
$\eta = X$	Consider consequences for X number of days/months/years after an event occurs.	All types could apply	All strategies could apply, depending on risk problem
$\eta = \tau - t_i + X$	Consider consequences for a X number of years beyond the period the activity was observed, where t_i is the occurrence time of any event.	Complex Uncertain Ambiguous	Risk informed, Robustness-focused, Precaution-based, Discourse-based
$\eta = \tau - t$	Consider consequences only until end of activity, and time interval $[0, \tau]$, where t is the time of the event.	Linear/simple Complex Uncertain	Routine based, Risk-informed, Precaution-based, Resilience-focused
$\eta_i = X_i$	Consider consequences for separate events i, for an Xi period of time after an event.	Complex, Uncertain	Risk-informed, Resilience-focused
$\eta = \infty$	Consequences considered for very long or infinite periods of time.	Uncertain Ambiguous	Precaution-based, Resilience based, Discourse based

η = X: This specification applies to the Stålull drilling case since the consequences in the report is considered over a fixed period of time (X) from 1 month to over 10 years. It might still require consideration on how to choose a suitable length of η in light of the risk problem. As seen in the Stålull report, the most severe consequences might last for 10 or more years in the case of a release of hydrocarbons to the environment. Since there is uncertainty related to how long the consequence horizon should be considered, the risk management strategies related to risk problems that are uncertain and ambiguous might be helpful for managing the risk.

$\eta = \tau - t_i + X$: This specification allows us to consider consequences for a fixed period of time (X) after an event occurs at time t_i, after the end of the observation period. Similar to the $\eta = X$

specification, this specification allows us to specify the interval over which we consider consequences as the risk analyst regard as purposeful. This specification includes the direct and indirect effects occurring within X years after the event.

$\boldsymbol{\eta = \tau\text{-}t}$: This specification considers consequences only until the end of the activity, and time interval [0, τ], after an event happens. For the drilling case, this specification of consequences will miss to capture the long-term (indirect) effects to the environment, instead directing attention to the immediate and short-term consequences. It is not a recommended nor a used specification to consider long term environmental consequences in the Stålull case.

$\boldsymbol{\eta_i = X_i}$: This specification allows us to consider consequences for separate events for an X_i period of time after any event. The Stålull case is only considering one event; the uncontrolled release of hydrocarbons to the sea, so this is not a specification used in the report. It would however be a useful specification in cases where there could be several initiating events to consider.

$\boldsymbol{\eta = \infty}$: This specification considers consequences over very long or infinite time periods, and is in some ways a viable specification for the Stålull case. In the case, we are concerned with the long-term consequences to the environment, although maybe not for infinite periods of time. The Macondo oil spill accident in 2010, has shown that the consequences from oil spills warrant considerations of consequences that can last for decades. It is however not explicitly stated anywhere in the report how long consequences might impact the environment, only that a recovery time for a species of more than 10 years is classified as the most severe. This specification points to risk problems that are uncertain or ambiguous in nature, which could be appropriate classifications for risk problems (consequences) that have long-term effects on the environment.

Finally, we arrive at the suggested specification of η, for considerations of consequences in the Stålull case. Our preferred specification of η will be the:

$\boldsymbol{\eta = X}$ specification,

or alternatively the

$\boldsymbol{\eta = \tau\text{-}t_i\text{+}X}$ specification.

Both these considerations of η specifies the time over which the consequences are considered over a fixed time period after an event occurs. This is also what has been used in the report, where the time horizon of consideration of the consequences ranges from 1 month to more than 10 years. However, what is somewhat unclear in the report, is how long environmental risk should be considered. A time-period of 10 years could be considered a viable period for monitoring of consequences, but when there is evidence of longer reaching impacts on the environment from oil spill disasters, this might encourage the use of participatory discourse and the involvement of different stakeholders to seek a consensus on what is a suitable time horizon for this type of environmental consequences.

The suggested specifications for the consideration of consequence horizons are, however, not necessarily very clear in terms of what guidance it can give to risk problems/management for the drilling activity; other than the general “all strategies could apply”. In cases like this, there would be a need to accurately define the boundaries of the system under observation to find suitable risk managements strategies and the appropriate instruments.

The Norwegian petroleum industry now has several decades of historical data related to accidents and impacts on the environment, and this can then be used as a basis for defining the boundaries in the case of exploration drilling activities.

4 Case 2: How time should be reflected for earthquake risk in Haiti

Haiti is a country that is vulnerable to several types of natural disasters. In this case we will see what guidance that could be given for considerations of time related to earthquake risk for a village in Haiti, based on the suggested formalization and evaluation of time considerations in risk assessments.

4.1 Background

Geographically, Haiti is located in the Caribbean Sea at the Hispaniola Island, which is also shared with the Dominican Republic. The country is located in the middle of a hurricane belt, often experiencing severe tropical storms and droughts in periods throughout the year. Further, natural hazards like earthquakes and flooding also pose serious threats to the inhabitants (Næverdal et al., 2022). Most of the population is located by the coast, which also makes Haiti exposed to sea level change and tsunamis (G. Granvorka & Saffache, 2010).

Due to low economic diversity, the Caribbean countries are also highly vulnerable to economic shocks and disturbances in industries like tourism and import/export of commodities. One single natural disaster could therefore have a measurable negative impact on GDP in these countries, which would cause strain on socioeconomic institutions and long-term development of infrastructure (Granvorka & Saffache, 2010).

Figure 8: A geographic overview of Haiti. We can see the country's long coastline and is proximity to the Dominican Republic. (Source: https://www.travelinghaiti.com).

In 2010, one of the biggest earthquakes in recent years struck near Port-au-Prince in Haiti. The impact from the earthquake had catastrophic consequences, killing an estimated 230,000 people and destroying 300 000 homes (Tarbuck et al., 2017). One of the findings after the 2010 earthquake was reports of insufficient building techniques, where the building materials were too weak and lacked the necessary reinforcements to withstand the lateral shear forces from earthquakes (Caldwell, 2018; Daniell et al., 2013).

The numbers of reported deaths are however contested, and there exist discrepancies between numbers released by the government and analysis done by external organizations (Daniell et al., 2013; Reardon, 2021). On january 12th 2021, exactly one year after the earthquake, the prime minister Jean-Max Bellerive updated the number of deaths to a total of 316 000 from the earthquake, an increase of 86 000 of total deaths, thus accounting for 236 bodies measured or found every day since the earthquake (Daniell et al., 2013). Multiple reports believe this updated number to be exaggerated, albeit at the same time noting that the post-event number is likely to increase with time due to the indirect effects from the earthquake. Nelson (2018) classifies the effects of natural hazards in three different categories; *Primary*, which are the direct effects from the event like building collapse, landslides. The *secondary* effects stem from the primary, and could be e.g., fires created from the primary event, disruption of electrical power and/or water supply. The *tertiary* effects are long term effects, also resulting from the primary event, like loss of habitat, physical changes of landscape, crop failure etc (Nelson, 2018). In risk analysis, one might also use a simpler classification of effects from events, such as *direct* for the immediate consequences and *indirect* for the long-term consequences (Logan et al., 2021).

In the aftermath of the 2010 earthquake an effort called *Build back Better* was launched to improve building technique and housing resilience in Haiti (Caldwell, 2018). Approximately 70% of the damaged infrastructure was related to housing, which has increased the focus on resilient building techniques to withstand disasters (Hendriks & Stokmans, 2020; Wisner et al., 2012). There has, however, been challenges in the rebuilding of infrastructure, where the choices of building materials have been affected by economic factors and possible mismatches between local construction knowledge and the availability of materials (Audefroy, 2011). Haiti is also argued to be the poorest country in the western Hemisphere, with over half the population living under the poverty line, leaving this socioeconomic class extra vulnerable to disasters (Daniell et al., 2013; Labrador & Roy, 2021).

On 14th of august 2021, Haiti was again struck by a major earthquake, this time killing 2200 people and affecting 800 000 people. The earthquake left many in need of immediate aid, water, food and medical supplies (OCHA, 2021). Additionally, the new earthquake revealed that the housing infrastructure was still weak. A major part of the newer housing could not withstand the earthquake, in effect leaving much of Haiti's infrastructure just as bad as it was after the 2010 earthquake. There is evidence, that despite a heightened global humanitarian focus towards sustainable development, especially related to Haiti, the government attention is primarily focused on solving immediate urgencies (IFRC, 2015). This could have a detrimental effect for the long-term development in the country (Granvorka & Saffache, 2010).

Next, we will go through a brief risk characterization example considering earthquake risk to a village in Haiti, before suggesting how time can considered for both the activity α and the consequence horizon η.

4.2 Considering risk for a village threatened by natural hazards

We consider the risk to a village in Haiti that is exposed to risk from earthquakes. Disasters like flooding, landslides, droughts etc., would be similar in nature but our considerations are restricted to earthquake risk. There exists no formal risk assessment forming a basis for the evaluation in this case, so the suggestions on time considerations could be considered more as normative guidance.

4.3 Risk characterization example of a village exposed to earthquake risk in Haiti

First, we need to define the boundaries of the activity α we want to monitor, and the time interval specification ($[0,\tau]$) for how long we observe the activity.

$\boldsymbol{\alpha_\tau}$: We observe a village in Haiti that are vulnerable to earthquake disasters in the context of weak housing and electrical power grid infrastructure. Our area of interest is confined to the outer limits of the village, and we monitor the entire population in the village. Since we are free to choose our time interval $[0, \tau]$, we could choose to monitor the village over a period of say; 2 years. This number might be rather arbitrary, and there exist reasons for increasing τ to more than 2 years, since there have been recorded earthquakes in the region over several decades (Witze, 2021). This could e.g., warrant monitoring for longer time periods, or even letting τ run infinite. From figure 5, we have seen that increasing the time interval $[0, \tau]$, also increases the risk, since it is more likely that an earthquake will occur. However, by specifying τ to 2 years, we characterize the risk for the community for the following two years. In this case our time-period is fixed, and $\tau = T$.

$\boldsymbol{\eta}$: How we choose to specify η will impact the risk level. By referring to table 2 we can choose η depending on the situation. As noted previously, if choosing a short time interval for

η, we risk not capturing long term consequences by instead focusing the attention on direct consequences, like immediate deaths. Similarly, choosing a too long η could put our emphasis away from allocating resources to immediate interventions like humanitarian aid. Secondly, our specification of η impacts whether we capture primary (direct) or secondary and tertiary (indirect) consequences from an event. η needs to run longer for us to be able capture the all the long-term effects. In the Haiti case, one consequence of interest is the number of cumulative deaths from the disaster, where we need to account for the direct and indirect effects from the event.

Now we define and characterize risk to the village.

Defining risk to a local community in Haiti

A: The village is impacted by an earthquake or not within the 2 years.

C: The consequences to the people in the village, and the impacts on electrical infrastructure until the village return to its pre-disruptive state.

U: We cannot say whether an earthquake will happen or not.

Characterizing risk

A'_1: A major earthquake occurs during the 2 years.

A'_2: A major earthquake does not occur during the 2 years.

C'_1: The number of excess deaths from the earthquake, illustrated in figure 9 further below.

C'_2: Consider the decrease in electrical power grid functionality over the course of time where the system might be degraded as a result from the earthquake, until resuming its normal functionality. Figure 9 (further below) illustrates the loss of electrical power grid functionality from the pre-event until the recovery of the system. As can be seen from the figure, it resembles a recovery/resilience curve.

Q: We express the uncertainty by using probability and accompanied judgements of strength of the background knowledge supporting the probabilities. A classification scheme for judging *SoK* such as suggested from Aven & Flage (2009) might be useful.

K: Is the knowledge that $(A,C',Q)_{\alpha r,\eta}$ are based upon.

By briefly characterizing risk in this example, we have specified some consequences, C'_1 and C'_2, that serve as useful boundaries when considering possible specifications of η for the Haiti case in the next sections. Similarly, by defining our activity of interest (α), we have defined some boundaries that are useful also in the considerations and suggestions on specification of τ.

4.4 Suggestions for how time could be considered for the observed activity α

First, we define the activity we are monitoring, which is very similar to the example above, but this time only the time consideration nomenclature will be used in the examples, and no explicit numbers (years).

$\boldsymbol{\alpha_\tau}$: We observe a village in Haiti that are vulnerable to earthquake disasters in the context of weak housing and electrical power grid infrastructure. Our area of interest is confined to the outer limits of the village, and we monitor the entire population in the village. We are free to choose our time interval $[0, \tau]$, and choose to monitor the village over a period of η years, depending on our preference. This length of τ is subject to debate, but there exist valid reasons for increasing $[0,\tau]$ to long intervals, since there have been recorded earthquakes in the region over several decades (Witze, 2021). This could e.g., warrant monitoring for longer time periods, or even letting τ run for infinite periods of time. From figure 5, we have seen that increasing the time interval $[0, \tau]$, also increases the risk, since it is more likely that an earthquake will occur. One possible problem in the specification of τ, is if an event occurs at the end of the observable period. How do we capture risk that falls outside the observable window? We use our table for evaluating the time dimension in risk assessments to discuss and suggest what specifications of τ that could be suitable for the village exposed to earthquake risk:

Table 15: Suggestions for specifications of α_τ for a Haitian village:

Suggestions for specifications of α_τ				
Examples of activity α	**Specification of τ**	**Comment**	**Risk problem**	**Risk Management Strategy**
"Flooding risk"	$\tau = T$	A fixed period of time (T).	Linear/simple, Complex Uncertain	Routine based, Risk-informed, Precaution-based, Resilience-focused
"Health risk"	τ is unknown	As long as a person is alive.	Uncertain Ambiguous	Resilience-focused, Precaution-based, Discourse-based
"Vulnerable system"	$\tau = \min\{T, T_e\}$	Fixed time period (T), or until disruption at time (T_e).	Complex Uncertain	Risk-informed, Robustness focused Precaution-based, Resilience-focused
"Power grid failure (resilience)"	$\tau = T + S$	Fixed time period (T), if system is functioning normally at time T, or observed until time T + S, where S is an unknown or fixed time until the system resumes normal function. If there is no disruption, then S = 0.	Complex Uncertain	Risk-informed, Precaution-based Resilience-focused
"Intergenerational topics"	$\tau = \infty$	Monitor activities or systems over long intergenerational time periods	Uncertain Ambiguous	Precaution-based, Resilience-focused, Discourse-based

$\tau = T$ («Flooding risk" specification): This specification would be considered as suited for monitoring natural disaster risk. It allows us to specify a fixed time period over which we observe the activity or system of interest. This specification covers linear/simple, complex and uncertain risk problems, and allows the use of several different appropriate instruments to handle the risk. Interestingly, some authors note that regularly recurring natural disaster risk belongs in the linear/simple risk problem category, which is a type of risk problem this specification covers (Renn, 2008a, p. 178). One possible issue with the specification is the question of what happens if a natural disaster occurs at the end of the observed period? Should we then stop monitoring the risk if we are at the end of our observation period, like the example in figure 3?

τ = unknown («Health risk" specification): Similarly as for the Stålull case, this specification could be considered unclear for the purposes of monitoring natural disaster risk, and is perhaps better suited to cases e.g., related to health. Since the τ = *unknown* specification (only) covers uncertain and ambiguous risk problems, we could also miss suitable risk management strategies that is covered by the linear/simple risk problem instruments for handling the risk. This specification is considered to have low applicability for the Haiti case.

$\tau = \min\{T, T_e\}$ ("Vulnerable system" specification): With this specification, we monitor the village over a fixed period of time T, or until disruption at time T_e. This could be a suitable specification for the earthquake risk, but only in some respects. Since we stop monitoring the activity at time T or T_e, we miss to capture aspects of the risk picture where the recovery of the system/activity is of interest. If some of our specified consequences is concerned with the loss of functionality of critical infrastructure, we might need a specification allowing for monitoring of the system throughout the pre-disruptive state.

$\tau = T + S$ («Power grid/resilience" specification): This time specification monitors the activity for a fixed time period (T) in case of no disruption, or until the system is back to normal operation again after a $T + S$ time period. This is considered a preferable specification for how the earthquake risk is monitored for the village, because it allows us to monitor the activity through a disruptive state until the system regains its normal functionality. As seen from the evaluation table, this specification covers complex and uncertain risk problems and risk management that are concerned with risk-informed, precaution-based and resilience focused strategies. Figure 9 below illustrates how the degradation and recovery of an electrical power grid in the village might occur:

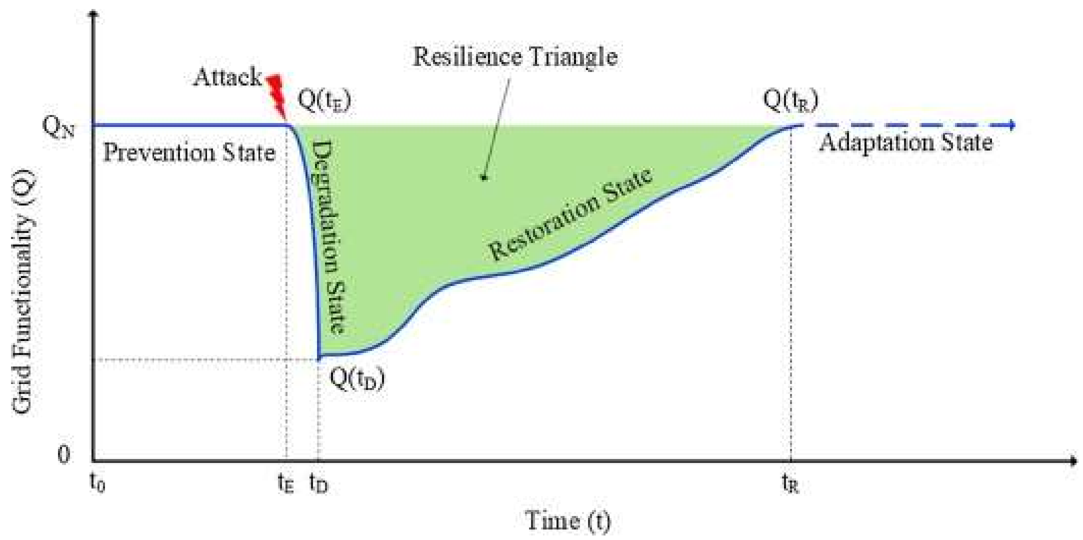

Figure 9: A resilience/recovery curve for a power grid failure. Reprinted from Jufri et al., 2019.

In figure 9, we observe that there is a steep loss of functionality at the time $Q(t_E)$ of the event, and then a gradual recovery until the critical functionality regains the pre-event level at time $Q(t_R)$. The $\boldsymbol{\tau = T + S}$ specification ensures that we monitor the system throughout the degraded state of the system and back to its normal functionality.

Regarding consequences, we could also specify that we are concerned with the consequences that occur during the disruptive state of the system, exemplified by specification C'_2 in the risk characterization section 4.3. This puts an emphasis on risk handling strategies that support adaptive and transformative measures to increase the speed of the recovery of the system.

$\boldsymbol{\tau = \infty}$ («Intergenerational topics» specification): By classifying earthquakes as a recurring event, having τ run for very long periods time could prove a viable option for monitoring risk in the village. This specification could be due to the fact that it covers intergenerational aspects of risk, meaning that it can consider impacts on future generations in Haiti. This warrants the use of discourse-based risk management strategies covered by ambiguous risk problems, and/or pre-caution-based and resilience-focused risk management strategies covered by uncertain risk problems. With this specification, risk management would be focused on long term development, and decreasing vulnerabilities for the Haitian people.

In the end, the recommended specification of how earthquake risk in the village should be monitored will be the

$$\boldsymbol{\tau = T + S}$$

specification, which allows us to monitor earthquake risk to the village for a fixed period of time, and throughout a disruptive event until the system reaches its pre-disruption state again. This specification supports the use of adaptive and transformative measures for handling the risk which supports increasing the speed of the recovery of the system, which would be pertinent in a case where a village or population potentially loses vital functions in their community like the access to water, food, medical care or electrical power.

4.5 Suggestions for how time could be considered for the consequences

How we choose to specify η will impact the risk level. By referring to table 2 we can choose η depending on the situation. As noted previously, if choosing a short time interval for η, we risk not capturing long term consequences by instead focusing the attention on direct consequences, like immediate deaths. Similarly, choosing a too long η could sway our attention away from immediate interventions like humanitarian aid. Secondly, our specification of η impacts whether we capture primary, secondary and/or tertiary consequences from an event. η needs to run longer for us to be able capture the all the long-term effects. In the Haiti case, one consequence of interest is the number of cumulative deaths from the disaster, where we need to account for the direct and indirect effects from the event. We use our table for evaluating the time considerations in risk assessments to suggest how η can be specified in table 16 below:

Table 16: Suggestions for specifications of η for a Haitian village

Suggestions for specifications of η			
Time interval η for consequences	**Comment**	**Risk problem**	**Risk Management strategy**
$\eta = X$	Consider consequences for X number of days/months/years after an event occurs.	All types could apply	All strategies could apply, depending on risk problem
$\eta = \tau - t_i + X$	Consider consequences for a X number of years beyond the period the activity was observed, where t_i is the occurrence time of any event.	Complex Uncertain Ambiguous	Risk informed, Robustness-focused, Precaution-based, Discourse-based
$\eta = \tau - t$	Consider consequences only until end of activity, and time interval $[0, \tau]$, where t is the time of the event.	Linear/simple Complex Uncertain	Routine based, Risk-informed, Precaution-based, Resilience-focused
$\eta_i = X_i$	Consider consequences for separate events i, for an Xi period of time after an event.	Complex, Uncertain	Risk-informed, Resilience-focused
$\eta = \infty$	Consequences considered for very long or infinite periods of time.	Uncertain Ambiguous	Precaution-based, Resilience based, Discourse based

η = X: This specification of consequence horizon η applies to the Haiti case. With this specification, we can account for both short-term and long-term effects from the earthquake, depending on how long η is specified. However, one needs to be aware that if η is set to very long time periods, this might put the focus toward long-term consequences. If one considers the short-term consequences more important, n should be set to a shorter time interval to direct the risk management to more immediate measures. The case of earthquake risk in Haiti can be considered complicated, since it demands the consideration of both immediate humanitarian aid and long-term development of infrastructure. As was mentioned in the background, the number of deaths was highest in the immediate aftermath of the earthquake, but 1 year after the disaster the number had risen with 86 000 more deaths, from 230 000 to 316 000, possibly due to indirect effects from the earthquake and/or more reliable information from both external and government reports. We see that all types of risk problems and management strategies apply to this specification, meaning that the definition of the boundaries related to n (and α) is important to aid selection of the most suitable risk management strategies for the risk.

Figure 10 below illustrates the consequences for the village expressed as the cumulative number of excess deaths after the earthquake, for the following 12 months after the event ($\eta = 12$ months). In the risk characterization we did in section 4.3, this is the specified the C'_1 consequence.

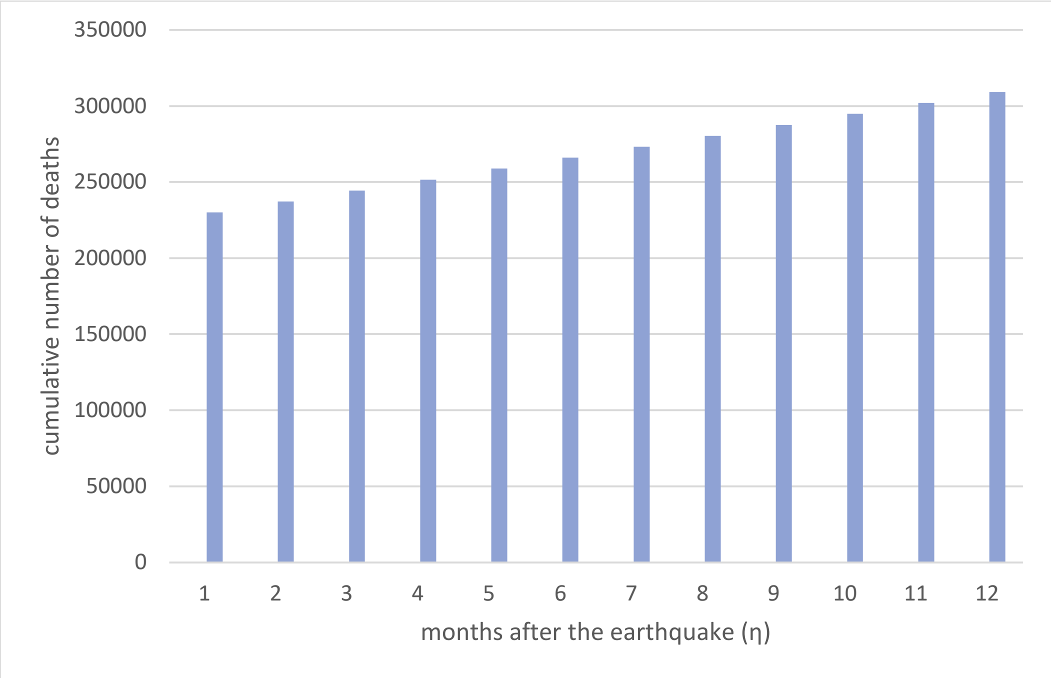

Figure 10: Illustration of the cumulative excess deaths in the months following an event

The number of recorded deaths will be highest immediately after the disaster, but as time goes by, the numbers continue to increase due to the secondary and tertiary effects from the earthquake. The increase in cumulative excess deaths in the following months (years) might be due to disruption and shortages of e.g., medical supplies, power, food and water.

$\boldsymbol{\eta = \tau - t_i + X}$: This specification allows us to consider consequences for a fixed period of time (X) after an event occurs at time $\boldsymbol{t_i}$, after the end of the observable period. Similar to the $\eta = X$ specification, this specification allows us to specify the interval over which we consider consequences as the risk analyst would regard as purposeful. This specification is useful for the Haiti case and allows the risk analyst to consider the consequences from the event over a chosen period of time.

$\eta = \tau\text{-}t$: This specification considers consequences only until the end of the observed activity, the time interval [0,τ], after an event happens. For the Haiti case, this specification of consequences will miss to capture the long-term (indirect) effects, instead directing attention to the immediate and short-term consequences. This is actually in line with some reports stating that the Haitian government mostly concerned with strategies for providing immediate aid (Granvorka & Saffache, 2010). It is a good specification for capturing the immediate (direct) consequences, which would result in reducing the immediate effects from the disaster. It does not, however, allow us to consider long term consequences, and the potential long-term development of infrastructure, or loss of habitat which could increase future vulnerability for the population.

$\eta_i = X_i$: This specification lets us consider consequences for separate events for an X_i period of time after any event. The Haiti case is only considering an earthquake event and the consequences from that event. However, since Haiti is exposed to many types of natural disasters (flooding, hurricanes, drought etc.,). This would be a good way to specify the consequence dimension if the risk analyst is not restricted to analysing only one type of disaster. This specification covers complex and uncertain risk problems, which should be able to capture the a complex relationship between several types of disasters/events and their consequences.

$\eta = \infty$: This specification considers consequences over very long, or infinite, time periods, and in some ways is a viable specification for the consequence horizon in Haiti. If one considers earthquakes as recurring events, the $\eta = \infty$ specification might be regarded as covering the consequences indefinitely. It does however strongly emphasise the long-term consequences, and this could be detrimental to immediate humanitarian aid efforts that also would be needed in earthquake disasters.

As a final recommendation to how η could be specified, we suggest the use of the

$\eta = X$, or alternatively the ***$\eta = \tau\text{-}t_i\text{+}X$*** specification

to specify the period over which the consequences from an earthquake disaster should be considered. Both these specifications allow us to consider consequences for a fixed period of time after the initiating event. The difficulty for the Haiti case is knowing what consequence horizon is adequate for capturing both immediate and long-term consequences from a disaster.

The Haitian government needs to be aware of the risks of not improving housing construction in the long term. As was evident since the 2010 earthquake, the measured improvements in buildings' ability to withstand a new earthquake was considered low when the 2021 earthquake occurred. The government have reportedly been more concerned with solving immediate urgencies from the disasters, which could have a detrimental effect on long term development and reducing the future vulnerability of housing infrastructure (Caldwell, 2018). As reported from the 2010 Haiti earthquake case, 75 percent of the deaths from the earthquake is related to the collapse of buildings, highlighting the need for improvements in housing construction (Daniell et al., 2013).

Considerations of the time horizon for monitoring the activity and the consequence horizon can be helpful tools to achieve a balance whether to focus on immediate aid or long-term development. Especially the time horizon for consequences is important since natural disasters can have consequences reaching far into the future.

It is not only the immediate effects (number of deaths) from earthquake disasters that might be of interest to the risk analyst (where η is specified for shorter time intervals). Haiti is vulnerable to flooding, droughts, hurricanes and sea-level change, which all could have long term consequences for Haitian communities. Crop failure might be the result of periods of drought, or change of habitat as a result from flooding, both potentially disrupting food production, natural habitat etc. (Nelson, 2018). As these consequences would be caused indirectly from the primary event, it is pertinent that η is considered for sufficiently long enough periods to account for these longer reaching effects.

Also, by specifying the consequence dimension η according to these types of consequences we can direct the appropriate risk management strategies according to the type of risk problem

Depending on what consequences we specify for the Haitian village, we also might be interested in considering the consequences as those that occur during e.g., disruption of the electrical power grid, or access to food stores etc. In this case, the risk analyst would be interested in monitoring the system throughout the disruptive phase, and until the system again reaches its pre-event functionality. Our suggested specification of $\tau = T + S$ allows us to monitor the system throughout the period where the system is in substandard state after the event.

Since the housing infrastructure in Haiti is considered weak, and there exist a large vulnerable socio-economic class, we could be inclined to consider consequences for longer time periods, putting the emphasis on increasing robustness and/or resilience for the local communities to withstand future earthquake (natural) disasters. It must, however, not come at the cost of considering the immediate consequences from a disaster.

5 Discussion

Foundational implications for risk analysis

Making considerations of time explicit in the conceptual definition and characterization of risk has implications for the foundations in risk science. By adopting the view that risk analysis is considered a science based on its own foundations of principles, concepts, models and ideas, the suggested ideas from Logan et al. (2021) on a formalization of the temporal considerations represents an extension and delineation of the already existing (A,C,U) perspective in risk analysis. In effect, the suggestions represent conceptual work in the generic part (B) of risk analysis, which is dealing with concepts, theories, frameworks and models for understanding and conceptualizing risk. Similarly, the foundational work on temporal considerations has implications for how risk knowledge is generated in the applied part (A) of risk analysis, because the improvements in generic risk analysis changes how risk knowledge is produced from real-world activities.

Consideration of consequences

One key implication for making time explicit in the conceptual definition and characterization of risk regards the length η chosen to consider consequences. By explicitly having to state considerations of η, the risk analyst is encouraged to consider risk problems that have long term consequences like sustainability, long-term development, climate change risk, nuclear power/waste, artificial intelligence, environmental risk and similar topics where the consequences have intergenerational impacts (Ilag & Athave, 2019; IPCC, 2022; Tarbuck et al., 2017). Since these issues can have far reaching effects into the future, time considerations should be explicitly stated in risk analysis to provide the best possible information basis for decision makers. Addressing these long time-horizons is also pertinent in the decision(s) of the level of investment in long term adaptive measures and risk treatments (Logan et al., 2021). In issues where the time horizons are long, like in e.g., the problems of environmental impacts and long-term consequences from natural disasters, discounting of consequences might be a point of discussion. Discounting consequences over many years, might lead to low levels of investment in adaptive measures (Logan et al., 2021).

Monitoring time

Having clear considerations of the time interval τ over which we monitor an activity α could be helpful for decisionmakers and other risk professionals when reviewing risk assessments. It also raises important questions for how we should view risk. For example, when monitoring health risk to a person or a community, risk is known to increase with the exposure time to a toxin (Cox, 2011). If we view the activity (α) as the time a person is exposed to a toxin, the time period has a direct relationship to the consequences which would be developing disease. So, knowing the exposure time makes us able to say whether face risk, but it does not able us to say when the person will develop the disease. The suggested framework for incorporating time considerations explicitly in risk assessments could help clarify this in future analysis. By also linking the temporal decisions to the type of risk problem and their related risk management strategies, we can increase and/or clarify the information produced in risk assessments.

The Stålull drilling case

For the Stålull drilling case the considerations of η is highly important, as large oil spills could have devastating impacts for the environment, seabirds and fish species for many years or even decades into the future. As evident from the Macondo oil spill disaster in 2010, there are reports stating that there are still huge amounts of oil present on the seabed, more than 10 years after the event. This calls for perhaps a re-evaluation for the length we consider consequences for oil spills, since the released hydrocarbons might have a negative impact on marine life for decades following such events. As in the Stålull report, a consequence dimension of more than 10 years might be considered ambiguous and warrant a discussion whether even longer consequence horizons should be considered and included in environmental risk analysis. One could argue that a suitable suggestion is consider the consequence dimension for time periods lasting several decades. Since society constitutes different stakeholders, with different values, beliefs and judgements, risk analysis can be a helpful tool in balancing concerns and opportunities related to risk management. A balance needs to be struck between protecting the environment and pursuing the opportunities which also contain benefits for society.

As for the monitored drilling activity, it seems preferable to specify the observable period in a way that allow us to influence the speed of recovery of the system, to reduce the consequences to the environment. This means that the risk handling should be oriented towards reducing the time span of the release of hydrocarbons as much as possible, to reduce the impact on the environment.

The Haiti case

As seen in the Haiti case, there is no straightforward answer to how resources should be prioritized between immediate disaster aid and long-term development of infrastructure. Immediate humanitarian aid is needed to reduce the direct consequences from natural disasters, and long-term development and increased robustness and resilience is needed to withstand future events and long-term impacts (IFRC, 2015). Striking a balance between the two might prove difficult and requires careful judging between the information provided by the risk assessment and different values from stakeholders. Explicit considerations of time could be a tool providing useful information and clarification for the decision-makers and stakeholders involved in natural disasters. Explicit considerations of time could also prove insightful information on the selection of best suited risk management strategy for a risk problem. By using the table for evaluating time considerations in risk assessments suggested in this thesis, one can link time considerations to type of risk problem and risk management strategies.

By specifying the time period τ over which we monitor earthquake risk, we decide whether risk is monitored for long or short periods of time. The specification also helps clarify how risk is monitored at the occurrence of an event. We can have specifications that end the observable period at the onset of an event, but then again, this specification will not allow us to monitor risk throughout the disruptive face and back until the system regains its functionality again. As was seen in the Haiti case, a specification of $\tau = T + S$ effectively allows us to monitor until the system is back to its pre-event state, which could be a suitable specification when we consider consequences like e.g., power grid failure, disruption of food, water and medical supplies. For these consequences the risk management would be concerned with the increasing the speed of the recovery of the system, and not just reducing the immediate consequences from the disruptive event. As we saw when using the suggested table for evaluating and suggesting how time can be considered in risk assessments, the $\tau = T + S$ specification is linked to complex and uncertain risk problems, where risk management strategies that are risk-informed, precaution-based and resilience-focused are suggested as suitable tools.

When defining consequences e.g., as those that occur from the time of disruption until the village is back to normal operation, risk analysis can be a tool that allows for the pursuit of interventions and mobilization of capacities to increase the speed of recovery. This is in contrast to a common belief that risk handling is mostly concerned about reducing the immediate disruption of a system (Logan et al., 2021).

We could also specify the time period over which an activity is observed for a fixed period of time (e.g., $\tau = T$), and in this case we need to set the time interval ($[0, \tau]$) for an appropriate period of time and make sure we don't stop to monitoring risk too early in case of an event occurring at the end, or after the observable time period.

The way consequences are defined has implications for the temporal specifications of η. For example, if we are concerned with immediate deaths from the earthquake, we e.g., set $\eta = \tau$, meaning that we are considering the immediate consequences at the occurrence of the event.

By specifying η for longer periods of time (e.g., 5 years) our focus shifts to account for the secondary and tertiary effects from the disaster.

One tool that can be helpful for risk management in cases of long-term development or for cases where consequences stretch out for long time periods is cost benefit and types of analysis. It has been suggested as a viable tool for directing development in Haiti by several authors (Granvorka & Saffache, 2010). It must, however, be used with an understanding of its possible shortcomings. Converting non-material values to monetary value entails ethical and value judgements which are in no way standardized. Secondly, care must be used with cost benefit analysis in the regard that it does not take the possibility for extreme events into account (Aven, 2019). By understanding the limitations of this type of analysis, and by subjecting the results to sensitivity analysis, it can still be and informative tool for risk management (Aven, 2019). One complication that might arise when using cost benefit analysis is that the discounting of consequences over time might lead us to invest too little in adaptive measures and risk treatments (Logan et al., 2021).

Risk Management

As was mentioned in the introduction, the risk management process tries to answer what can be done related to a risk problem, and with what options? What are the trade-offs in terms of costs, benefits and risk? And what are the effects of current decisions on future options?

Explicitly, stating time in risk analysis and risk assessments can provide important for the decision makers in this context. The temporal considerations could help clarify what risk management strategy is suited to tackle a certain risk problem, whether it is *simple*, *complex*, *uncertain* or *ambiguous*. By building on the idea that specifications of time can be linked to the type of risk problem, we can point to suitable risk handling strategies for handling the risk problem. The table for evaluating the temporal considerations presented in this thesis tries to accomplish this. However, it is only meant to function as *one* possible tool in reaching decisions for the risk management. In some cases, at least, the time considerations could give a good indication of what type of risk management strategy is best suited for a problem. Like for the mentioned intergenerational risk problems, where the time horizons might stretch out far into the future, a $\tau = \infty$ specification would refer us to uncertain and ambiguous risk problems, where the risk management strategies that are resilience-focused and discursive might be recommended for those risk problems. Similarly, if we are more concerned with the immediate consequences of an event, we specify the consequence horizon η for shorter time intervals, to effectively capture and emphasize the immediate consequence reduction measures in the risk management.

It is pertinent to show that risk analysis is a suitable tool for long term risk management, and not automatically refer to e.g., resilience analysis for those types of risk problems (Aven, 2019; Logan et al., 2021). We have e.g., seen that depending on how we specify η, risk analysis is not just a tool concerning reduction of the immediate disruption, but that it also allows for interventions and adaptions that influence the speed of the recovery of systems. In many ways, this relates to resilience and robustness, and the view of the author of this thesis is that there exists no major need for the field of risk analysis and resilience analysis to diverge in light of the "call for a shift to resilience" (Aven, 2019, p. 196). Aven (2019, p. 12-13) advocates for an integrative approach between the two fields, where an important point is that both the camps of resilience analysis and risk analysis acknowledges the existence and benefits of the other 'field'. By having the fields diverge, important information from either perspective might be missed, which could cause foundations in both fields to weaken. Aven (2019, p. 190) points out that there is a need for resilience analysis, but that it is still lies within the domain/scope of the risk analysis field, therefore suggesting a unified approach between the two fields instead of a further separation.

6 Conclusion

This has been a review and evaluation of how temporal considerations can be considered and explicitly stated in risk assessments and risk analysis. Based on Logan et al. (2021) it is suggested to include the two temporal considerations:

$\boldsymbol{\alpha_\tau}$: the time we monitor an activity or system. This could be a production facility, natural habitat, community or any other system defined by the risk analyst, where τ is the specified time interval ($[0, \tau]$) the system monitored.

$\boldsymbol{\eta}$: the length of time over which we consider consequences following an event. We specify the length of η based on the type of situation and risk problem. It could be specified as days, months or years.

On the basis of the (A,C,U) perspective for understanding and expressing risk, we denote the concept of risk the following:

$$\textbf{Risk} = (\boldsymbol{C}, \boldsymbol{U})_{\alpha_\tau,\eta},$$

where risk is understood as a combination of the consequences (C) and related uncertainty (U), while also accounting for the temporal considerations of the activity α_τ and consequences η in the nomenclature. Similarly, we also update the nomenclature for risk characterization as follows:

$$\textbf{Risk description} = (\boldsymbol{C'}, \boldsymbol{Q}, \boldsymbol{K})_{\alpha_\tau,\eta},$$

such that considerations of time related to the monitored activity and consequences are explicitly stated when characterizing risk, where C' is some specified consequence, Q a measure of uncertainty and K the knowledge upon which C' and Q is based.

The main contribution from this thesis is the suggested table for the evaluation of the time dimension in risk assessments, which can be used as a simple tool for supporting the selection of suitable risk management strategies depending on the risk problem.

These updates can yield a positive effect of increasing the clarity in risk analysis and provide improved information basis for both risk analysts and decision-makers. It also supports the view that risk analysis is suited to tackle many kinds of risk problems and are not necessarily a field mostly concerned with decreasing the immediate disruption of a system. Depending on the situation, the temporal considerations allow us to consider interventions and risk reduction strategies that reduce future consequences through adaption and transformation. Instead of diverging risk analysis from resilience, the updates support a unification the two fields, and shows that an integrative perspective could be advantageous for both fields.

A future field of research could be to further investigate how the temporal considerations can benefit risk management strategies. However, risk analysis will benefit today from having a clear and formalized framework for how time considerations is considered.

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