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ABSTRACT

A decision-making taxonomy could provide a valuable framework for decision-makers and stakeholders in a variety of decision-making purposes. In this thesis, a system identification is done to identify the elements that constitute a decision-making rationale. These constituents are used to create a taxonomy of decision-making rationales.

The decision-making rationale taxonomy is developed by collecting and analyzing information acquired by expert elicitation and reviewing relevant literature across different sciences.

The influences between the elements in the taxonomy are identified and graphically represented in influence diagrams. From the system identification and influence diagrams, the hazards associated with the constituents within the decision-making taxonomy are identified and summarized in a table.

Lastly, a discussion regarding the implications and uncertainties of the findings within the thesis is done, and further work is suggested.

By signing this document, each member of the group confirms participation on equal terms in the process of writing the project. Thus, each member of the group is responsible for all the contents in the project.

System- & hazard identification of decision-making rationales

Master of Science and Technology in Risk and Safety Management

4th Semester

Aalborg University

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Preface

This master’s thesis was written by fourth-semester students completing their master's studies in Risk and Safety Management at Aalborg University. The authors are the following: Matias, with a BSc in Emergency and Risk Management and five years related experience in risk management and IT; Thor with a BSc in Biomedical Laboratory Science and seven years related experience.

We want to thank Linda and Michael for their support during the semester. The amount of time and effort provided by you was, once again, a surprise and a tremendous help, and much more than what we expected. Also, thanks to Lisa, our fellow student who peer reviewed parts of our thesis during the process of writing.

We, the authors, hope that this report can be a contribution towards a unified understanding of what constitutes a decision-rationale, and what hazards decision-makers and stakeholders should be aware of when engaging in the field of decision-making.

We hope you will enjoy your reading.
Matias and Thor.

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4 Danish summary

En taksonomi af beslutningstagningsrationaler kan være værdifuld for beslutningstagere og interessenter i forskellige beslutningstagningsformål. En systemidentifikation er udført med det formål at identificere de elementer, der udgør et beslutningstagningsrationale. Disse elementer er anvendt til at skabe en taksonomi af beslutningstagningsrationaler.

Taksonomien for beslutningstagningsrationaler er udviklet ved at indsamle og analysere information erhvervet ved ekspert rådgivning samt gennemgang af relevant litteratur på tværs af forskellige videnskaber.

Måden hvorpå elementerne i taksonomien påvirker hinanden identificeres og repræsenteres grafisk i indflydelsesdiagrammer. Fra systemidentifikations- og indflydelsesdiagrammerne identificeres og opsummeres farerne forbundet med elementerne i beslutningstaksonomien og disse opsummeres i en tabel.

Slutteligt diskuteres konsekvenserne og usikkerheden af resultaterne i specialet, og der gives forslag til fremtidigt arbejde.

5 Introduction

The motivation for this thesis is rooted in the authors' shared curiosity in understanding the nature of information: what it is; how it is created; and how it is applied in decision-making. The rationality of decision-making is subject to choices made by decision-makers. Such choices could follow from a formally defined (rational) model or could be a response to cognitively embodied mechanisms such as "gut feelings" as defined in the psychology and cognitive science literature. No matter what rationale is selected or on which basis, decision alternatives must be identified and weighed with respect to a decision context. In retrospect, it is possible to re-evaluate the decision-making objectives and the processes of identifying and weighing optional choices.

During the time the authors were enrolled in the master's program in Risk and Safety Management at Aalborg University, the decision-makers around the world have been dealing with the challenges arising from the covid-19 pandemic. During this time, collective decisions have been made by governing bodies on behalf of their populations. These collective decisions have impacted almost every individual in society. There has been debate on whether the preventative measures regarding the closure of borders, the wearing of protective masks, or the disallowance of social gatherings were proportional to the threat of the pandemic. Moreover, the information base used by decision-makers for justifying the implementation of preventative measures was/is based on uncertainty due to the novelty of the virus. When decision-makers decide on what to utilize as the information base behind their decision-making, the semantic terms (e.g., evidence-based, science-based, etc.), which normally justify valid knowledge, are filled with ambiguity, and are used differently across various domains. This deficiency in the use of terms questions the very basis of selecting the best suited rationale. If the constituents of the information base are perceived wrong, decision-making could be based on wrong information, and could pose a risk towards stakeholders. These considerations have sparked the authors' interest and curiosity in the field of decision-making.

Preferences, perception of the world, memory, time limitations, and stakeholder considerations are crucial parts of which decision alternatives seem to be the most attractive for a decision-maker. Stakeholders and decision-makers might not share a common goal in decision-making, and their perception of when a decision is considered to be effective might not be the same. In the present thesis, the authors want to categorize and develop a taxonomy based on what is identified as the constituents of decision-making rationales on a general level, and analyze the hazards related to these decision-making rationales.

5.1 Research question

The main objective of the thesis is to investigate the constituents of a decision-making rationale and propose a system identification and a related taxonomy of these constituents for the purpose of providing decision-makers with a pragmatic tool that encompasses the relevant aspects of decision-making rationales and highlight their related hazards. The system identification will serve as the foundation for a hazard identification where hazards related to the identified decision-making rationales are outlined. The questions answered in this thesis are the following:

What constitutes a decision-making rationale?

What hazards are related to decision-making rationales?

5.2 Definitions related to the research question

To answer the research questions, it is relevant to define how the words related to the research questions are used within the thesis.

Decision-making

Decision-making is the act where an individual or group must decide between at least two decision alternatives.

Rationale

A rational is a system of concepts and principles used as a basis for a specific purpose.

Decision-making rationale

A decision-making rationale is a system of concepts and principles utilized in order for an individual or group to decide between at least two decision alternatives.

Hazard

The potential source of negative consequences.

Hazards in decision-making

A hazard in decision-making can potentially cause negative consequences to the decision-making process and/or outcome.

5.2.1 Sub-Questions

To answer the main research questions, a set of sub-questions are asked. The sub-questions serve the purpose of answering the underlying elements of the main research questions.

To identify, and later categorize, the main branches of approaches in decision-making, the following question is asked:

1. *What are the principal approaches to decision-making?*

To understand how the conception of right and wrong influences decision-making, the following question is asked:

2. *What are the main branches of ethics related to decision-making?*

To understand how decision-makers and stakeholders preferences influence the decision-making process, the following question is asked:

3. *How can preferences be categorized?*

To understand how to conceptualize information and what conditions information can be subject to, the following question is asked:

4. *How can information be defined and categorized?*

To understand decision-makers perception of the system they want to manage, the following question is asked:

5. *What constitutes system information for a decision-maker?*

To understand how information is applied in decision-making contexts, the following question is asked:

6. *What are the main branches of the application of information?*

To understand where hazards are present in different parts of a decision-making process, the following question is asked:

7. *What are the general hazards in decision-making rationales?*
8. *How do the elements in the identified decision-making rationales influence each other?*
9. *What hazards can be derived from these influences?*

5.3 Introduction to core concepts: Information and memory

5.3.1 Introduction to 'information'

In a pragmatic decision-making context, 'a priori' truths derived from logic and definitions are not always relevant. What is relevant in a decision-making context is the way reality is perceived and how it pragmatically influences decision-making outcomes. As stated in (Legg, 2021) pragmatism is concerned with the practical application of philosophical topics. Pragmatist looks at ideas and thoughts as tools to put into use. Thus, the value of a proposition is correlated with its applicability. To further clarify, pragmatism is about meaning in context, i.e., conditional understanding/understanding of conditions. There are several branches of pragmatism; however, in this thesis, the term 'pragmatic' is used to describe a practical application of information rather than its theoretical consideration. This is why the consequentialist approach is utilized in this thesis, as it is only concerned with the information about the state of nature that makes a difference in decision-making contexts.

5.3.2 Conditions of information

There are different conditions that can be applied to information that can influence the decision-making outcomes. As described by (Nielsen, Glavind, Qin, & Faber, 2019), these conditions may be categorized in the following way:

1. The information is relevant and precise.
2. The information is relevant but imprecise.
3. The information is irrelevant.
4. The information is relevant but incorrect.
5. The flow of information is disrupted or delayed.

The first condition, i.e., that the information is relevant and precise, is what should be aimed for in decision-making and cannot be considered a hazard. However, categories 2-5 could be hazards impacting decision-making processes and outcomes. How categories 2-5 will impact decision-making outcomes will depend on the system that is being managed in decision-making and how it is perceived. The system which the decision-maker intends to manage and how it is perceived will, in this thesis, be referred to as the 'decision context system' (see heading 10.1.1).

5.3.3 Individual memory

In general, there are two types of memory short-term memory and long-term memory. The two types refer to the amount of time a person keeps information in his/her mind before rejecting it or

storing it. The immediate rejection of information after a person has used it and thus forgetting about it is considered short-term memory. If the mind considers the information important to remember, it is ‘transferred’ into long-term memory for future use. The long-term memory type can be branched into other memory types, explicit memory, and implicit memory. Explicit memory is the action of active thinking, whereas implicit memory does not require active thinking.
The explicit memory is relevant when thinking back in time to remember specific information.
The implicit memory allows people to perform routine actions without thinking about them, e.g., walking, driving, etc.

As described in the chapter about Influence: Approach, see heading 10.1, memory is the cumulative knowledge and life experience a human has acquired through life. Moreover, this life experience and knowledge guide current behavior and lay the foundation for decision-making in the future (Klein, Robertson, & Delton, 2010).

5.3.4 Collective memory

The term collective memory had its origins in the 1920s when it was used by Maurice Halbwachs (Olick, 1999). Since then, there have been several propositions of how to understand the concept.

(Olick, 1999) proposes two main distinctions on the term collective memory, namely collected and collective memory. The former takes the notion that individuals are the only ones who can do the remembering, and as such, collected memory is the aggregated memory of individuals of a certain group. Consequently, the collected memory is influenced by the subjectivity of remembering aggregated in a group form.

The latter refers to the notion that collective memory is more than just the aggregation of subjective memory, and that groups have a memory of their own.

In this thesis, the latter standpoint is taken, i.e., collective memory goes beyond combined subjective individual remembering. By this, there is an inclusion of mnemonic technologies, such as cultural landmarks, historical objects, notes, paintings, and photographs, etc., from the past that goes beyond the capacity of remembering individuals. Thus, all information that has survived from the past that has been interpreted by society is part of the collective memory.

5.4 Semantic problems with knowledge framing

This section argues what decision-makers is using as knowledge framing to justify their decisions are often the terms “science-based”, “evidence-based”, “risk-based”, “resilience-based” and “sustainability-based”.

5.4.1 Uncertainties

One of the longest debated subjects in philosophy is the domain of knowledge (Lakoff & Johnson, 1999). Human knowledge is far from perfect, i.e., humans cannot predict future outcomes as it would be possible in a deterministic world. Because humans cannot perceive the world in a deterministic way, uncertainties exist. The uncertainties are in general split into two groups aleatory uncertainty and epistemic uncertainty. Because uncertainties exist, what one individual or group perceived as valid knowledge might not pass as valid knowledge for a different individual or group.

5.4.2 Aleatory uncertainty

The aleatoric uncertainties refer to values that change each time the exact same phenomenon happens. Because of the random nature or inherent variety of physical phenomena, aleatory uncertainty exists. Aleatory uncertainties are frequently related to observable quantities and are thought to be nonreducible since the value appears random each time the phenomenon happens (Faber M. H., 2007).

5.4.3 Epistemic uncertainty

Epistemic uncertainties refer to values that could be known but are not known; this could be due to the imprecise character of information or lack of knowledge. Non-observable quantities or observable with doubt are frequently related to epistemic uncertainty. The epistemic uncertainty is thought to be reducible since more knowledge can be collected and quantified (Faber M. H., 2007).

5.4.4 Semantic problem terms

As pointed out by (Nielsen & Faber, 2021), decisions for long-term societal development must consider society, the environment, and the economy. When decision-makers consider a specific decision problem, they must be able to explain to their stakeholders how this decision relates to the society, environment, and the economy. Facing this task, the decision-makers must ask the right questions to acquire relevant knowledge in the field of the decision problem.

(Hessami, 2011) argues that the management of risk is a key element for decision support and states that the concept is utilized for decision support on various levels (industry, governance of states, etc.). (Nielsen & Faber, 2021) points towards specific terms used within the concept of risk, i.e., “science-based”, “evidence-based”, “risk-based”, “resilience-based” and “sustainability-based”. These terms (non copiose) form the basis for what can be known as accepted knowledge for decision-makers.

The above-mentioned terms could be used to promote products, causes, policies etc. The usage of these terms for promotional purposes indicates that what is being done is supported by evidence or science. These terms do, however, cover a wide range of different evidence that can be visualized in the hierarchy of evidence, see Figure 1. (Doleac, 2019) argues that it is critical to recognize that some research yields more accurate estimates than others and that research results should be weighted based on where the study fits into the hierarchy of evidence. The pyramid is an example as to incorporate the quality of evidence accessible from each type of research design and the degree of evidence predicted from specified designs in a qualitative way. The amount of accessible evidence decreases with each level. In general, study designs at higher levels of the pyramid provide higher quality evidence and lower risk of bias. At higher levels, trust in causal relationships grows (Yetley, et al., 2017). However, relying on a scientific model like this may or may not have anything to do with the degree of relevance or scientific rigor in these categories.

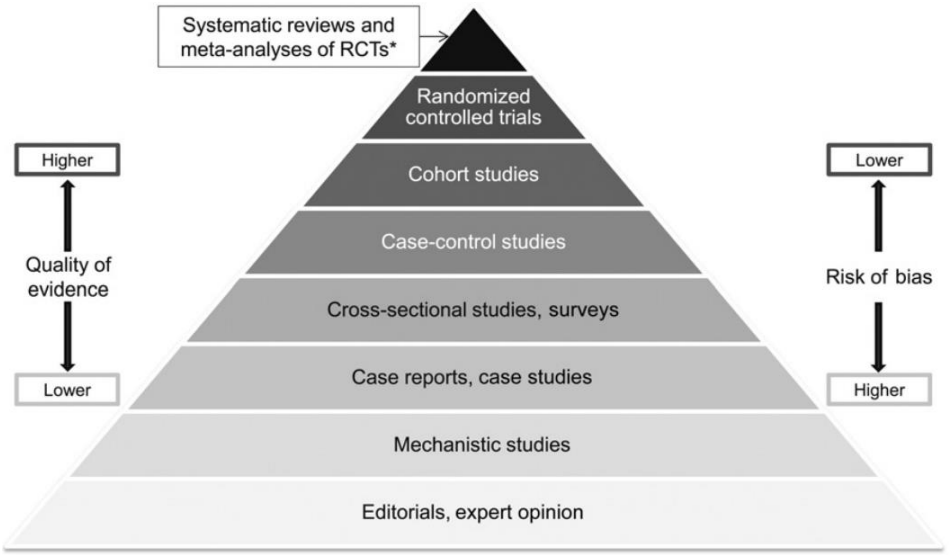

Figure 1: The hierarchy of evidence (Yetley, et al., 2017)

The decision-maker's basis for their decision is thus often based on one of these terms. To get a better understanding of these terms, the thesis will briefly investigate in which domain the expressions are used and how they are used.

A search on Web of Science (WoS) has been made based on the terms seen in the first cell of Table 1. The terms from the first cell were integrated with the additional term policy OR decision-support OR evidence. An exception was made for the 'integrated risk-, resilience-, and sustainability based' search since no results could be found with these search terms. The results from the search of integrated risk resilience and sustainability were obtained without any additional search terms. The search was conducted to highlight in what context the terms are used. The search has been analyzed using WoS's analytic tool to count how many times the search term was related to a WoS category. The analysis was limited to the top ten categories. The results can be found in the appendix (see heading 15.1). The results are further condensed to the top two relevant categories in Table 1.

In general, it can be said for all the terms that they are used to represent that a recognized methodology is used within the research and that the conclusions from the research are built upon other scientific studies, and by this indicating scientific objectivity and authority in the conclusions.

Table 1: The top two categories based on search terms in WoS

Term	Web of Science most relevant categories	
Science-based	Environmental science	Social science
Evidence-based	Public Environmental Occupational Health	Social science
Risk-based	Environmental science	Civil engineering
Risk-informed	Civil engineering	Social science
Resilience-based	Environmental science	Economics
Sustainability-based	Civil engineering	Economics
Integrated risk-, resilience-, and sustainability based	Environmental science	Civil engineering

From Table 1, five main categories exist where these terms apply. The term science-based is commonly used to qualify targets, i.e., 'science-based targets'. These targets are used, e.g., by countries and businesses, to reduce their climate impact based on what science projects will happen with the climate in the future (UK Parliament, 2021). The term has roots in trials and

experiments and tries to utilize the data acquired by trials and experiments and apply it to decision-making. By this, science-based means, decision-making based on conclusions found in science that predict future events and states of nature. The broad use and thus many interpretations of the term make it vague towards its purpose; some people think of social science, others natural science, etc.

Evidence-based refers to different categories of evidence from, e.g., the legal domain. There are four general types of evidence (i) tangible things, (ii) a model representation of what happens/happen in a specific situation, (iii) letters, blog post, or other documents, and (iv) testimonies. Evidence-based can also refer to the pyramid of evidence as described earlier in this chapter.

The term risk-based is used by the (Council of Europe, n.d.) when identifying, assessing, and understanding risks before using them for decision-making. As with the evidence-based and science-based terms, there is an intersection where these three terms meet since the risk-based term necessitates the consideration of both science and evidence when identifying, assessing, and understanding risks. A bibliometric study by (Nielsen & Faber, 2021) states that a risk-based approach aims to minimize or eliminate risks in relation to a given activity (Nielsen & Faber, 2021) further argues that stakeholders and indirect consequences are not considered in this approach in regards to a systems way that involves stakeholders where indirect consequences are concerned. (Nielsen & Faber, 2021) argues that risk-based and science-based terms are sometimes used interchangeably.

The term risk-informed intersects largely with the term risk-based. The (United Nations Development Programme, 2019), in fact, defines risk-informed as a risk-based decision process. (Nielsen & Faber, 2021) argues that there is a significant difference between risk-based and risk-informed approaches. According to them, the risk-informed approach is more holistic because it includes all stakeholders, direct and indirect consequences, risk perception, risk communication, and risk acceptance criteria.

Resilience-based is defined by (Mcleod, et al., 2019) as the use of knowledge of current and future drivers affecting ecological systems to prioritize, implement, and adapt management actions that sustain ecological systems and human well-being. However, as highlighted by (Nielsen & Faber, 2021), there is no commonly agreed definition of the term resilience, and the term is used differently across the various domains. This is further recognized in a conference paper by (Faber,

Qin, & Nielsen, Objectives and Metrics in Decision Support for Urban Resilience, 2019), where resilience at urban scales is used jointly to discuss sustainability.
The term sustainability-based adheres to actions/developments of the society as described in the (Brundtland Commission, 1987) as "(…) the needs of the present without compromising the ability of future generations to meet their own needs". Thus, when using the term sustainability-based, the term refers to the conclusions the research is built upon and the premises that the suggested conclusions (solutions) in the research does not exploit the currently available resources so the future generations cannot meet their own needs (Brundtland Commission, 1987). (Nielsen & Faber, 2021) argues that the term sustainability-based often is used in an ideological context or as a political instrument to promote research.

Integrated risk-, resilience- and sustainability, as proposed by Nielsen (2020), integrates these three knowledge domains from a systems perspective. The term covers the identification, assessment, management, and governance of systemic risks. The integration is a proposition of a new discipline with a standard set of concepts and methodological basis for reasoning. Although the term overlap with the other terms described above, it stands out in the way the term is well defined.

Even though efforts have been made to define some of the terms, there seems to be a range of different applications for the terms and no commonly agreed definitions of these. The terms overlap across different domains, and they are sometimes used interjectionally. The product of this section is thus a premise stating: a set of terms are used and understood differently in different knowledge domains. Sometimes the same terms carry a different meaning. Other times, the same meaning (conceptual content) is denoted by different terms. When applying these terms without defining them explicitly, the usage of the terms becomes bland, thus creating a risk of not having a common premise when talking about these terms, which can cause information asymmetry, as will be discussed later in the thesis.

From this section, it can be concluded that the terms are being applied without the backing of a common definition. When decision-makers make up their knowledge base for their decision action, they claim it rational in the sense that these terms are being used.

Words are what add differences to the way humans think. Optimally words are distinct entities with distinct individuality and clearly defined boundaries (Durkheim, 2006). For words, concepts, and

ideas to be understood the way the communicator intended, it is important to have a common reference foundation when communicating in writing or speech.

6 General approach

Figure 2 is a schematic representation of the approach that has been followed in the paper.

Introduction: The introduction outlines our motivation for investigating the current topic and points at current deficiencies. This section will state the primary research question with related sub-questions along with an introduction to core concepts.

Scope and methodology: A literature review of the present state of knowledge will provide input to scoping the problem context as well as to possible methods for analysis. Decision-rationales and contexts will be included based on the two principal approaches: structured and non-structured approaches. The methodology has been written with the basis in (Saunders, Lewis, & Thornhill, 2019) research onion and provides an overview of the research methodology used in the present thesis.

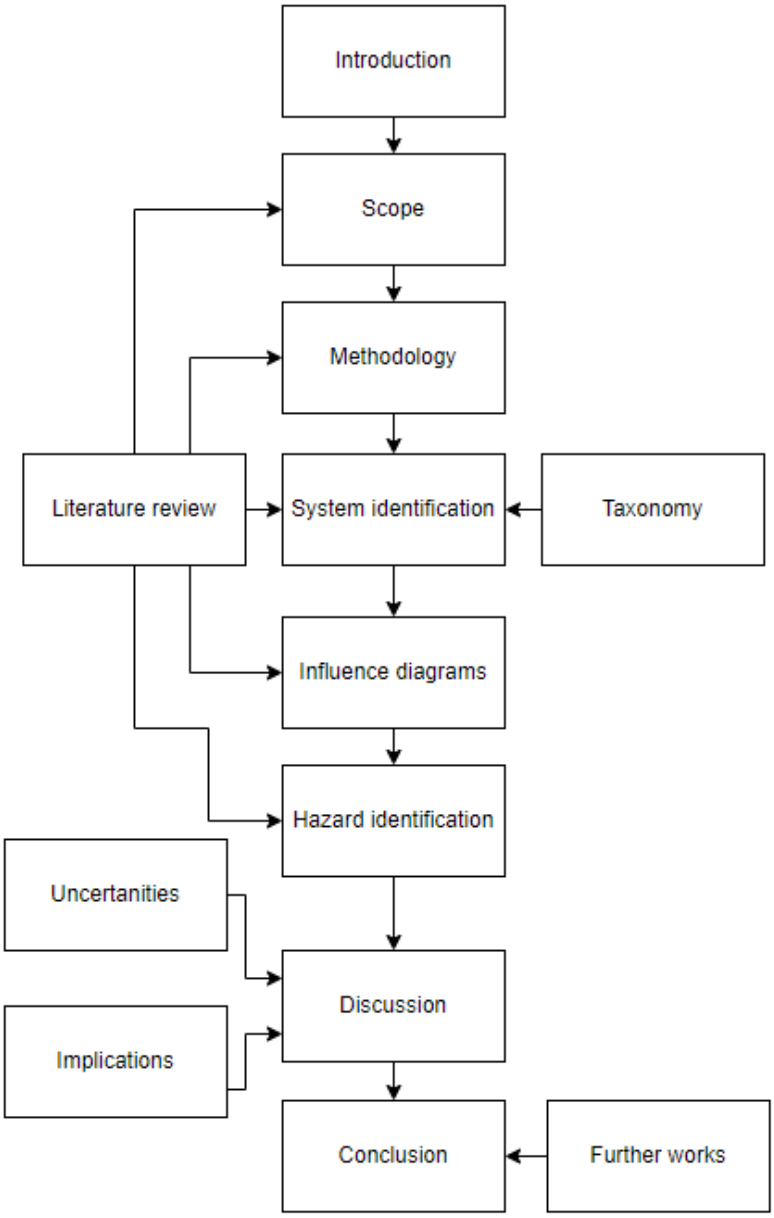

Figure 2: Proposition of method (authors' model).

System identification (literature review): A literature review of the present state of knowledge will be presented in the system identification. Based on the system identification, a taxonomy of decision-making rationales is derived and creates the basis for the later-described influence diagrams related to the taxonomy. The literature review also serves to provide input to scoping the problem context as well as to possible methods for analysis. The system identification is a part of the foundation for the hazard identification.

Influence diagrams: The influence diagrams are a schematic representation of the elements within the taxonomy. The influence diagrams give a general idea as to where hazards related to decision-making rationales may arise. The influence diagram is also a more detailed description of the taxonomy. Along with the system identification, the influence diagram creates the foundation for the hazard identification.

Hazard identification: Following the delimitation of the system boundaries in space and time, a hazard identification will be conducted, taking basis in the system identification, taxonomy, and the influence diagrams to arrive at a list of possible hazards associated with the process of decision-making. Although such identification cannot, in principle, account for all possible hazards related to decision-making, it is believed that it is nevertheless useful in building awareness of the range of such hazards with respect to both decision-makers and stakeholders.

Discussion: In this section, a summary and an interpretation of the results obtained in the thesis will be presented. Furthermore, the implications of the results will be discussed in terms of applicability. Lastly, the limitations and the uncertainties of the thesis will be discussed on a general level.

Conclusion: The conclusion serves to wrap up the thesis and reinforce the answers to the research questions. The conclusion section is finalized with a perspective on what further work would be interesting to pursue beyond this thesis.

7 Scope

The scope of the thesis is delimited by four approaches, ad-hoc and anarchy (non-structured) and cost/benefit, and the precautionary principle (structured). The main focus is on the structured approaches. From the literature review, it was indicated that most research was done in the area of individual judgment and behavior and societal decision-making concerning group interactions.

Category 1, 2, and 3 decision rationales are included (see Figure 3), i.e., group-on-group, group-on-individual, and individual-on-group, thus excluding decision-rationales exclusively intended for category 4, i.e., individual-on-individual as these cases are not, by the knowledge of the authors, very well documented. The figure and the table below will give a graphical representation of the extent of the scope.

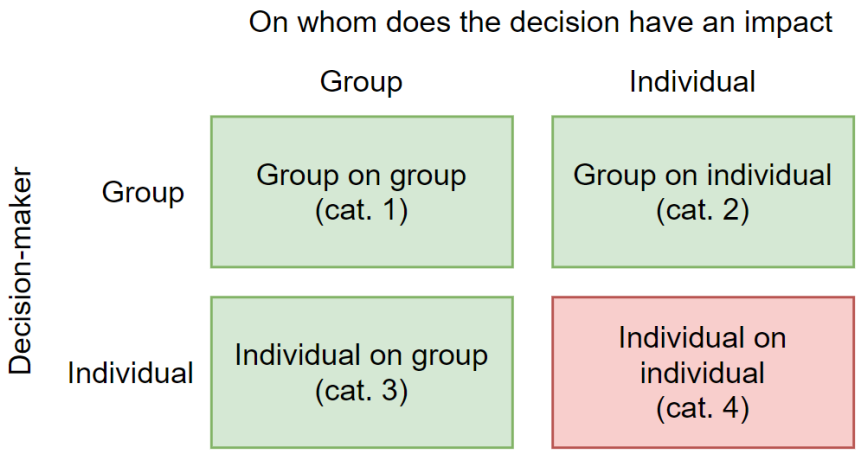

Figure 3: Scope delimitation group/individual (Green=included, Red=excluded), (authors' model)

8 Method

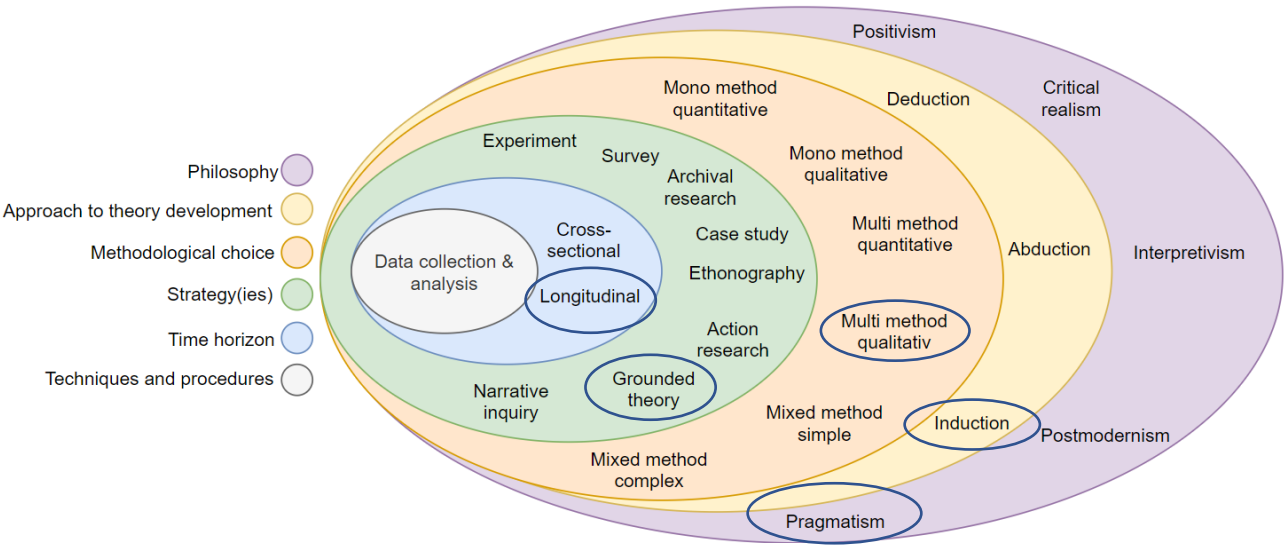

Figure 4: The research onion, own model inspired by (Saunders, Lewis, & Thornhill, 2019)

8.1 Research philosophy

The assumptions that influence the researcher's perspective of the nature of the topic under investigation are referred to as research philosophy. Ontology, epistemology, and axiology are the three broad perspectives further subdivided into four philosophical positions: positivism, critical realism, postmodernism, and pragmatism (Saunders, Lewis, & Thornhill, 2019).

The research philosophy of this master's thesis follows the pragmatist philosophy since the research questions of the thesis focus on the system identification of the constituents of a decision-making rationale and the related hazards. The practical application of the answers to the research questions is a unified definition of the constituents of a decision-making rationale and what hazards are relevant herein. The definition of a decision-making rationale serves as an understanding of the concepts or factors that constitute a decision-making rationale for the term to be more precisely used in future research.

8.2 Approach to theory development

The choice of logical argumentation: deduction, induction, and abduction, is referred to as the research approach (Saunders, Lewis, & Thornhill, 2019).

The approach in this master's thesis focuses on the inductive approach. The inductive approaches focus on going from the specific to the general. This approach is adopted in this thesis, where information is collected specifically and organized generally in a taxonomy

8.3 Methodological choice

The choice to perform quantitative or qualitative research or combine the two is the methodological choice (Saunders, Lewis, & Thornhill, 2019).
The primary method applied in this master's thesis is the qualitative approach. Information has been collected from an expert elicitation, and a literature review was made from the product of this elicitation to answer the research question. The literature has been identified partly by expert elicitation, and from the information provided by the expert elicitation, more literature was derived based on the sources of the provided literature.

8.4 Strategy

The research strategy outlines how the researcher intends to complete the project. Experiment, survey, archival research, case study, ethnography, action research, grounded theory, and narrative inquiry are examples of these methodologies (Saunders, Lewis, & Thornhill, 2019).
Grounded Theory is the study of concepts and a strategy for developing theories that involve an exploratory and inductive data-driven approach that may include deduction (Saunders, Lewis, & Thornhill, 2019).
This master's thesis study the concept of a decision-making rationale and proposes a system identification and related taxonomy for these components with the purpose of providing decision-makers with a pragmatic tool that encompasses the relevant aspects of decision-making rationales and highlight their related hazards.

8.5 Time horizon

Based on time, research may be divided into two categories: longitudinal or cross-sectional. The study of a phenomenon or a population through time is referred to as longitudinal research. The cross-sectional is a 'snap-shot' research and one in which a phenomenon or a cross-section of the population is investigated over a specified timeframe (Saunders, Lewis, & Thornhill, 2019).
The master thesis investigates the constitutions of decision-making rationales over time and thus provides a longitudinal perspective.

8.6 Data collection and analysis

The inner circle of the research onion refers to data collecting and analysis components that are more specific than mentioned in the sections above.

The primary data collection in this thesis aims to identify the constituents of decision-making rationales by collecting theories, approaches, and methods on decision-making rationales throughout sciences, disciplines, and application areas. Moreover, the data collection identifies hazards associated with decision-making.

The primary data analysis aims to describe how hazards are related to the different approaches and rationales and how the identified elements influence each other.

9 System identification

In the present section, we present a literature review of studies related to decision-making rationale. The literature serves to develop and sustain an argument and to give a critical evaluation of competing hypotheses. A review of books, research papers, and conference proceedings has been conducted to attain a deeper understanding of the current state of knowledge and the limitations thereof. The selection of relevant literature was based on an expert elicitation whereby foundational contributions to descriptive and normative decision analysis were identified. The expert elicitation furthermore provided information about recent contributions related to the topic. Bibliographic references in these sources further expanded the volume of reviewed publications. The literature review was conducted to identify the constituents of decision-making rationales and the most relevant research publications that highlight how decision-makers and stakeholders make decisions as well as the hazards related to decision-making.
A summary of the most significant literature can be found in the appendix (see heading 15.2).

First, some principal approaches for decision-making are presented, and related theories and models are described. Next the principal approaches are discussed with relation to four dialectic criteria: (i) individual/collective, (ii) participatory/non-participatory, (iii) outcome/intension-based and (iv) descriptive/normative. After this, preferences categories of the decision-maker and stakeholder are presented and discussed. Figure 5 is a visual representation of the system we associate with the problem context of identifying the constitutive elements of a decision rationale, see appendix for a larger representation (heading 15.3). There is no specific reading direction of the figure. From the system identification, a set of hazards are derived which are associated with each of the elements in the figure.

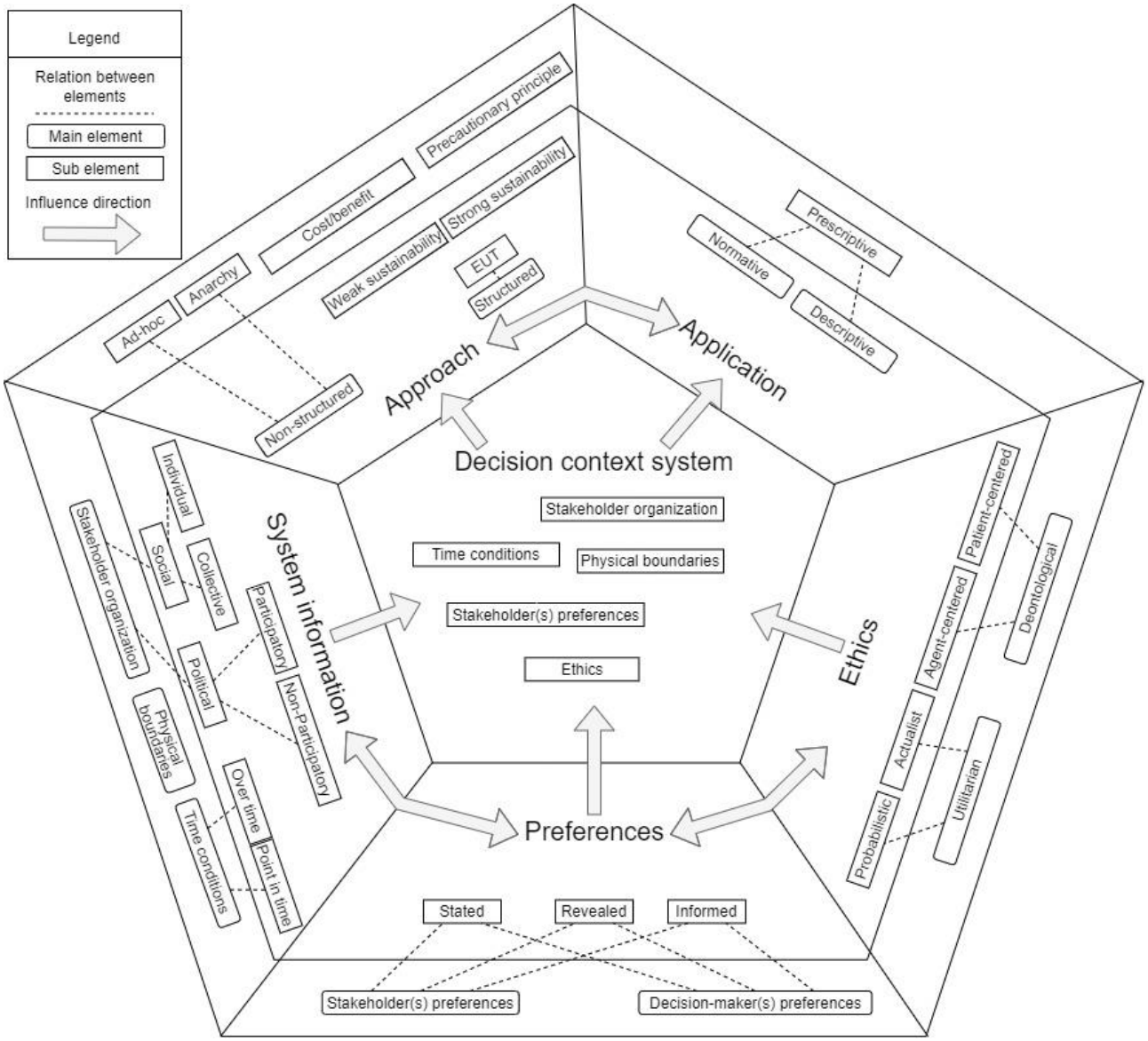

Figure 5: Decision Rationale Taxonomy (authors' model)

9.1 Principal approaches in decision-making

In the following principal approaches are divided between structured and non-structured approaches. The main focus of this thesis is on the structured approaches.
To understand the most important utilized approaches towards decision-making, the two main principal approaches are described along with sub-approaches that fit into these.

9.1.1 Structured

Structured decision-making approaches are based on a combination of formal models, normative frameworks, prescriptive, and procedural frameworks.

9.1.2 Non-structured

A non-structured decision-making approach is to be understood as the umbrella term for approaches, in which the method or selection of the method used in the decision-making process is not defined or made explicit but is often based on emotions and intuitions.

9.2 Structured principal approaches

The dominant structured principal approach to decision-making is the Expected Utility Theorem (EUT). Under this approach, the two sub-approaches, cost/benefit and precautionary principle, can be found.

9.2.1 Utility theory in general

In the late eighteenth century, utilitarianism became a distinct philosophical discipline, led primarily by William Paley, William Godwin, and Jeremy Bentham, who all published substantial work in the field. Bentham has become the most well-known classical utilitarian, while Paley and Godwin were more endorsed at the time. Bentham described utilitarianism as ‘the greatest happiness principle’. He argued that the job of a decision-maker is to maximize the happiness of the stakeholders. His definition of utility is the promotion of benefit, advantage, pleasure, or happiness and the prevention of pain, mischief, unhappiness, or evil. He advocated hedonism, which argues that pleasure is the basis of morality. Bentham further argued that all pleasures should be treated equally by the decision-maker (Mulgan, 2007).
The moral theory of utilitarianism states that decisions are morally acceptable if the outcome of the decision promotes happiness or pleasure and not morally acceptable if the decision outcome promotes the opposite of happiness or pleasure. Furthermore, it is only morally acceptable if the

decision outcome produces at least as much net pleasure or happiness as any other available decision. Utilitarianism focuses on the total amount of happiness or pleasure the decision outcome brings, not how this outcome is distributed among different people (Mill, 1863), (Mulgan, 2007). If it is unclear how to maximize human happiness due to factors that cannot possibly be known in advance, then utilitarianism becomes problematic. There are two subdivisions of utilitarianism: actualist utilitarianism and probabilistic utilitarianism (Mulgan, 2007). The actualist school judges a decision to be correct if it renders the outcome with the highest value despite the probability assignment of that outcome. On the contrary, the probabilistic school of thought argues that a decision is correct by combining value and probability when ranking decision alternatives. Thus, the actualist uses the values of outcomes to compare decision-alternatives, while the probabilists use the value of outcomes and their related probability. A further subdivision on the probabilistic school of thought can be done depending on risk appetite: (i) Maximin, which generally will prefer decision-alternatives that promote risk aversion. (ii) Maximax, which will prefer the decision-alternative with the highest possible benefit. (iii) Laplace which considers all outcomes as equally likely and determines the average for each alternative. Laplace prefers the outcome with the best average. (iv) Expected value which uses the product of probability and value in the ranking of decision-alternatives (Mulgan, 2007). Furthermore, Minimax regret will prefer decision alternatives that minimize the maximum losses. The probabilistic school of thought has been embraced by Von-Neumann and Morgenstern in the Expected Utility Theorem (EUT) (see heading 9.2.2.1).

9.2.2 Expected Utility Theory in general

The EUT is a normative theory based on utilitarianism that can be applied when facing uncertain decisions. The EUT concerns itself with decisions made under uncertainty with respect to preferences, system states, and outcomes.

While the decision alternatives provide a set of options for a specific decision, the states of the system are fixed and cannot be altered. Therefore, probability assignments would be applied to the system states based on the best knowledge available. In general, each of the outcomes would have a different value for the decision-maker. Not value in the sense of monetary gain necessarily, but in the sense of whatever is preferred by the decision-maker; this is what is called utility. The term utility involves all the desires, moral values, ethics, feelings, values, etc., that are seen as preferable for the decision-maker. The expected utility is the product of the utility of each outcome and the probability assignment of the related system states. The EUT describes that a rational decision-maker will make the decision that maximizes the expected utility (Baron, 2004).

Table 2: Outcomes based on system states and decision alternatives

	State A	**State B**
Decision-alternative 1	Outcome (1a)	Outcome (1b)
Decision-alternative 2	Outcome (2a)	Outcome (2b)

To give an example, it could be imagined that a hiker faced with a two decision alternatives; to go east or west around a mountain, see Table 2. Under good weather conditions, the road to the west is what the hiker prefers; even though it is a little longer, the hiker finds the trail more comfortable to walk on. The road to the east is bumpy, and the view is not as good as on the west side of the mountain. However, in the face of stormy and rainy weather, the hiker prefers the road to the east because it takes him less time to reach his destination, and therefore the hiker will not be as wet upon arrival. In this example, the decision alternatives are to go west or east around the mountain, and the states of the system are good or bad weather conditions. The different states of the system alter the utility of the hiker, and thus his decision to go west or east. The hiker cannot know the weather conditions in advance; however, his experience tells him something about the probabilities of each weather condition that certain day, and as such, his decision will be determined by the probability of each state and the utilities of each outcome.

Applications of this approach can be found, e.g., in bridge maintenance within the field of engineering (Honfi, Björnsson, Ivanov, & Leander, 2020), policies concerning insurance (Bernard, He, Yan, & Zhou, 2015), health, the public, and the economy. Due to the method of assigning

weights to everything relevant for a decision it can be seen as a universal method for decision-making.

9.2.2.1 Von Neumann-Morgenstern Expected Utility Theorem

(Von Neumann & Morgenstern, 1953) explain the expected utility model as a mathematical model for examining the behavior of individuals making decisions under uncertainty. Von Neumann and Morgenstern argue that when facing uncertainty, people make decisions based on the expected value of utility rather than the expected value. Thus, people do not prefer a specific outcome because it generates a higher expected payoff. Instead, they prefer it because it generates a higher expected value of utility. The expected utility theory is a compact way to summarize preferences by assigning numerical utility to, e.g., different outcomes. For the expected utility model to apply, four axioms must be followed, (i) completeness, (ii) transitivity, (iii) independence (iv) continuity (Spaniel, 2016).

9.2.2.1.1 Completeness

A preference ordering (ranking) is complete if and only if, for any two outcomes X and Y, an individual prefers X to Y, prefers Y to X, or is indifferent between the two. This axiom assumes that a decision-maker has well-established preferences and can always decide or be indifferent between two decision alternatives. As such, if a decision-maker has two decision alternatives and gets more expected utility when choosing decision alternative X rather than Y then alternative X would be preferred. If X and Y have the same outcome, the decision-maker would be indifferent between X and Y.

9.2.2.1.2 Transitivity

For any three outcomes X, Y, and Z, if X is preferred to Y, and Y is preferred to Z, then X must be preferred to Z. Transitivity rules out a preference cycle as seen in the game "rock, paper scissors" where scissor beats paper and paper beats rock, but rock beats scissor (see Figure 6) (Kerr, Riley, Feldman, & Bohannan, 2002).

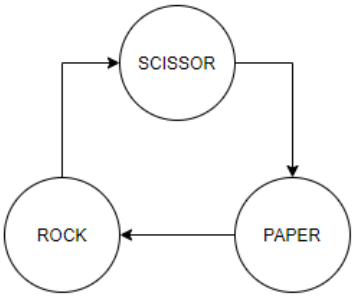

Figure 6: Preference cycle in" rock, paper, scissor" (Kerr, Riley, Feldman, & Bohannan, 2002).

9.2.2.1.3 Independence

If P is a probability between 0 – 1 and X, Y, and Z is outcomes or probability distributions over outcomes. Then independence would prefer X to Y if and only if pX + (1-p)Z is preferred to pY+(1-p)Z. If two decision alternatives have a common consequence, this consequence should not be considered, only what is unique for each decision alternative is relevant.

9.2.2.1.4 Continuity

If the decision-maker prefer X to Y to Z, then there exists a unique probability between 0-1 which makes the decision-maker indifferent between the two decision alternatives pX + (1-p)Z and Y. Consider the following example where X is a huge monetary gain which is preferred over Y.
Y is no gain, which is preferred over Z. Z is getting injured or dying. Every day people are commuting to various places and by this facing the risk of getting injured or dying (Z) while doing so. This is an accepted risk for the commuter. The risk is accepted because the commuter must go somewhere and not because there is any gain from the commute (Y). The continuity axiom states that if you are willing to commute and face the risk of injury and death (Z) without making a huge gain (Y) you are also willing to take some chance of getting injured or dying (Z) to make a huge gain (X).

9.2.2.2 Sustainability

The (Brundtland Commission, 1987) argues that for developments to be sustainable, the developments should satisfy current demands for decision-makers and stakeholders without jeopardizing future generations' capacity to fulfill their own requirements. What the Brundtland Commission claims about sustainability in the argument mentioned above can also be transferred

to decision-making, i.e., for decisions to be sustainable, the decisions should comply with current needs for decision-makers and stakeholders without putting future generations' capacity to fulfill their own requirements in jeopardy.

Sustainability can be divided into two categories, weak sustainability, and strong sustainability. The difference in the categories concerns the fundamental view on natural capital.

9.2.2.2.1 Weak sustainability

The weak sustainability approach allows changes and means that manufactured capital may replace natural depletable capital, i.e., things are exchangeable, and resources, even scarce resources, can be substituted by technology or other resources. Weak sustainability is necessary for allocating a monetary value for something that does not have a market value (Perman, Ma, Common, Maddison, & McGilvray, 2011).

9.2.2.2.2 Strong sustainability

If a strong sustainability viewpoint is adopted, the decisions can only be sustained in an endless time horizon by indefinitely exploiting natural capital, which might be impossible, with an exception for non-renewable resources. Strong sustainability makes it impossible to assign a monetary value to something that does not have a market value (Perman, Ma, Common, Maddison, & McGilvray, 2011).

9.2.2.3 Precautionary Principle

When strong sustainability is present, the precautionary principle is often invoked. The term precaution is commonly applied in contexts where specific preventative measures are used to avoid or reduce the impact of a hazard before it presents itself.
One of the main challenges in decision-making is the uncertainty associated with the consequence and probability modeling of a given event. This uncertainty can influence the estimated utility of decision alternatives and thus the associated preference rankings. In such uncertain situations, where stakes are perceived to be high, the precautionary principle is often adopted. (Macpherson, 2016) argues that the precautionary principle is commonly used in situations where environment or human health can be at stake, and there is no adequate scientific knowledge about the probability- and consequences of such situations. In general, (Macpherson, 2016) argues that the precautionary principle is the approach of "better safe than sorry" or "if you are in doubt, do not".

The (Commission of the European Communities, 2000) describes the precautionary principle as a structured approach to the analysis of risk and highlights that the precautionary principle is particularly relevant to risk management. Further, it is described that implementations based on the principle should have a background in scientific evaluation based on the best knowledge available. If the scientific knowledge is uncertain, an identification of the degree of scientific uncertainty should be made. The method of defining acceptable scientific uncertainty and the knowledge threshold that determines the required scientific understanding of an identified threat at which precautionary response is justifiable is said to be a political responsibility (Ahteensuu, 2008).
When applying the principle, the (Commission of the European Communities, 2000) states that the measures invoked should:

- Be proportional to the level of protection.
- Non-discriminatory in their application.
- Consistent with similar measures.
- Based on an examination of the potential benefits and costs of action or lack of action
- Subject to review.
- Capable of assigning responsibility for producing the scientific evidence necessary for a more comprehensive risk assessment.

Examples of the precautionary principal application can be found in various domains, e.g., the food industry, environmental impact assessment. A more current example is regarding public health and the decisions being made on the COVID-19 vaccine program. At the time of writing, France has invoked the precautionary principle on one of the major vaccines. The principle applies to people under the age of 30 (Berrod, 2021). An example from the domain of applied chemistry can be found in the European Commission, where the principle is given a central role in chemical policies (Commission of the European Communities, 2000).
The precautionary principle is generally used in decisions where specific knowledge about the consequences and probabilities is low or unknown.

9.2.2.4 Cost/benefit

The cost/benefit approach is often invoked when weak sustainability is present. The cost/benefit approach fits under the utility branch since it considers (i) the monetary value of the decision alternative and (ii) the utility of the benefits. The cost/benefit approach works by assigning a monetary value to all costs and benefits regarding a decision alternative. The allocation of a

monetary value to the cost (how much monetary value the decision alternative could cost to implement) and a monetary value to the benefit (how much monetary value the decision alternative could gain with implementation) and then comparing these two to see what combination give the best overall benefit. In more detail, the monetary cost of a decision can be split into explicit cost and implicit cost. The explicit cost is the monetary cost for implementing the decision alternative. The implicit cost considers the opportunity cost; instead of implementing a specific decision alternative, the decision-maker could have done something else that could have gained a higher monetary value. The opportunity cost considers what benefit and cost would have been obtained from a decision alternative not selected (Pearce, 1983).

9.2.2.4.1 Bayesian decision analysis

One of the normative standards within cost/benefit analysis in decision-making is Bayesian decision analysis. Bayesian decision analysis is a method based on an extension of conditional probability theory, namely Bayes rule. It was formulated by (Raiffa & Schlaifer, 1961) and later optimized for engineering decision problems by (Benjamin, Cornell, & Shaw, 1963). It is suggested that the reader looks into these sources for an exhaustive read on the methods associated with Bayesian decision theory. Bayesian decision analysis provides a framework for consistent management of information in decision contexts. Bayesian decision analysis can be divided into three categories, namely prior, posterior and pre-posterior decision analysis:

Prior decision analysis facilitates decision analysis with information already acquired prior to any decisions, with the aim of maximizing the expected value of utility.
Posterior decision analysis facilitates decision analysis when facing additional information to update the probabilistic descriptions with the use of Bayesian updating.
Pre-posterior decision analysis focuses on unknown information and the value of acquiring additional information on the market or through experiments (Faber M. H., 2007).
With these tools in mind, it is possible to consistently document and rank decision alternatives when facing uncertain information in decision-making contexts.

9.3 Non-structured principal approaches

The two dominant principal approaches to non-structured decision-making are (i) the anarchy principle and (ii) the ad-hoc principle.

9.3.1 Anarchy principle

The common theme of the philosophy of anarchism is to resist power. (Taylor, 2009) defines power as the ability to alter the range of someone's available actions. In the context of decision-making, the anarchy principle thus relates to alterations in the decision-maker's available actions.
The anarchy principle can be divided into two sub-categories: intentional and unintentional.
Following the unintentional sub-category of the anarchy principle, no approach is the preferred option. Decisions are made based on doing things in the decision situation without regulating anything. However, this is not done to necessarily achieve a specific order of preferences. This application can be found in decisions where the decision-maker does not adhere to any specific decision-making approach.
The intentional use also follows that no approach is the preferred option. However, in this application, the decision-maker is aware of not following an approach. Thus, when faced with a decision problem, the decision-maker would not act at all. The intentional use would mean to let things happen without interfering.

(Johnson-Laird, 1983) defines mental models as an inner mental replica that has the same ‘relation-structure’ as the phenomenon that it represents. (Kahneman, Lovallo, & Sibony, 2019) argues that when people form mental models, they are often based on limited evidence, and the models are slowly adjusted as more knowledge is comprehended. Because the models are based on limited evidence, they are often a simple and more coherent (i.e., the mental models make it fit where the person thinks it belongs) representation of the state of the system than how the actual state of the system is. The authors further argue that mental models do not assign decision weights correctly. This approach may seem irrational, but as (Lakoff & Johnson, 1999) argues, what (Kahneman, Lovallo, & Sibony, 2019) has shown is how humans have biologically evolved to make decisions based on reason by using these mental models (Lakoff & Johnson, 1999).

9.3.2 Ad-hoc principle

The ad-hoc principle is an adaptive and iterative principle where decision-makers use whatever approach seems necessary or needed based on their judgments when dealing with a decision problem (Lundgrén-Laine, et al., 2011). Applying the ad-hoc principle to a decision problem means approaches from both the structured and non-structured can be applied. The key aspect of the ad-hoc principle is to be agile and switch approaches when necessary, which is why the authors categorize it as a non-structured approach.

9.4 Considerations in principal approaches

In the present section, we consider four additional criteria that can contribute to the development of a taxonomy for decision-making rationale. Each criterion consists of a dialectical pair that facilitates the further classification of principal approaches. The first criterion concerns socio-cultural organization and is instantiated by the pair individual – collective. The second criterion concerns limitations imposed by the political organization to which the decision-makers are subject to, namely participatory – non-participatory systems of governance. The third criterion relates to the ethical positions that a given social or political organization may impose as boundary conditions, namely the axiological pair deontological – utilitarian. Finally, the fourth criterion is associated with the application of information in society, whereby we distinguish between descriptive and normative purposes for acquiring and using information.

9.4.1 Individual/collective (relation to a social and cultural organization)

Two models are presented to understand the social and cultural interactions within groups and organizations. The first model presented is made by the authors to systematically distinguish between decision interactions with respect to stakeholders and decision-makers. The second model introduced is the grid/group model (Douglas, 1970) that is introduced to understand biases across cultures. After introducing these models, two examples of risk acceptance criteria applied within collective and individual decision-making are presented, namely the Life Quality Index (LQI) and FN diagrams.

9.4.1.1 A proposed framework for categorizing decision contexts

A generic model for distinguishing between different decision-making interactions (see Figure 7) and categories (see Table 3) is proposed/outlined with respect to all the possible relations between stakeholder(s) and decision-maker(s). This distinction is based on whether decision-maker(s) and

stakeholder(s) are considered as a group or as an individual and the applied context of the decision-making, i.e., business, societal, personal, or medical.

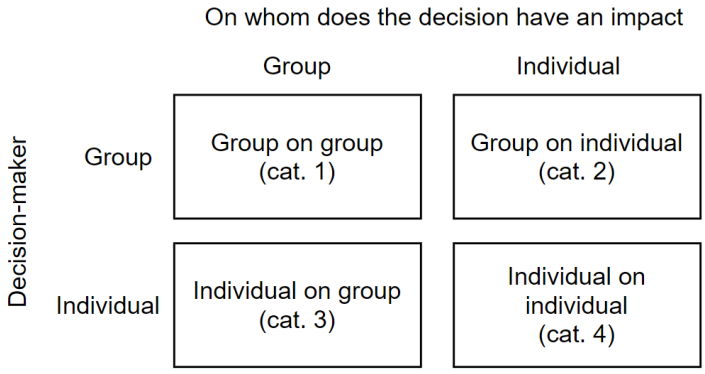

Figure 7: Decision interactions (authors' model)

The decisions are categorized by the contexts of the (life) activities to which they apply; see Table 3 below. Though further sub-categorization of these activities is possible, it is not considered essential for the generic, illustrative purposes of the framework. However, it should be noted that the "group on group" and "individual on individual" examples can go both ways.

In the context of business, the board could decide to decrease the wages paid to the working staff. In turn, the working staff could decide not to work or decrease the quality of the work, which indirectly affects the board by, e.g., decreasing the monetary value of the produced product.

In a societal context, the population elects who gets to be in the parliament. In turn, the parliament can introduce new legislation to which the population must adhere.

In the context of the personal domain, the parents and grandparents can decide how to raise the children. In turn, the children can decide to put their parents and grandparents into a nursing home when they reach a certain age and mental condition.

In the context of medicine, the medical board can recommend a specific drug for a specific disease. In turn, the patient group could refuse or accept to ingest the medical medicaments the medical board recommends.

Table 3: Decision categories

EXAMPLES	Business	Societal	Personal	Medical
Group on group (cat.1)	Board on working staff	Population on parliament	Parents and grandparents on children	Medical board on patient-group
Group on individual (cat. 2)	Board on CEO	Parliament on minister	Family on child	Medical board on patient
Individual on group (cat. 3)	CEO on staff	Minister on society	Parent on children	Consultant on medical staff
Individual on individual (cat. 4)	CEO on manager	Minister on civil servant	Parent on child	Doctor on patient

9.4.1.2 Grid/group

The grid/group model can be used to identify cultural biases and to explain ways of perceiving, justifying, reasoning, and feeling across different cultures and individuals. The grid/group model is relevant to include in the taxonomy because it provides important considerations as to how people understand different phenomena and objects. This understanding can provide relevant insights in decision-making when assigning weights to probabilities, and consequences and ultimately make better informed decisions (Favre & Sornette, 2016).

As seen in Figure 9, the model consists of two independent variables impacting the structuring of personal relationships, defined as ‘grid’ and ‘group’. The grid variable describes the difference between people in a group (stratification, regulation). The scale in the grid variable goes from being a group with many and varied interpersonal differences to a group where there is significant similarity between people (Spickard, 1989).

The group variable refers to how strongly people are bonded (collectivity, integration). The scale in the group variable goes from groups with weak bonds between people to a group with strong bonds between them.

The model is categorized into four different groups, (i) fatalism, (ii) hierarchy, (iii) individualism, and (iv) egalitarianism (Douglas, 1970):

(i) Groups consisting of people with weak bonds and varied interpersonal differences are defined as a fatalistic group. The people in this group perceive the world as deterministic, i.e., everything that happens, will happen, or has happened in the world has already been determined.

(ii) Groups consisting of people with strong bonds and varied interpersonal differences are defined as a hierarchic group. The people in this group perceive the world as a collective system where the individuals are less important than the group.

(iii) Groups consisting of people with weak bonds and significant similarity between them are defined as an individualistic group. The people in the group perceive the world as full of humans who act as rational beings, i.e., they are able to use reason to make decision and determine personal choices.

(iv) Groups consisting of people with strong bonds and significant similarities between them are defined as an egalitarian group. The people in the group perceive the world as a place where individuals should have equal quantities of well-being or morally relevant factors that affect their lives.

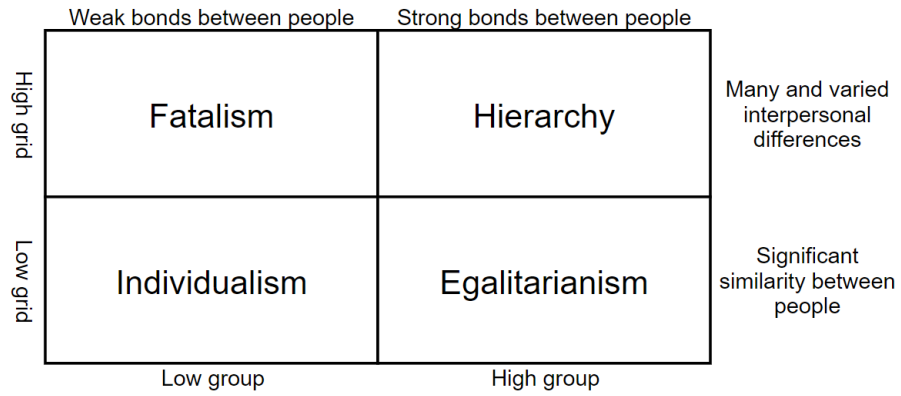

Figure 8: Forms of social relationships in distinct cultural settings based on (Favre & Sornette, 2016).

For decision-making, the model can be utilized, e.g., on a higher political level, like the European Union (EU), which is an entity that imposes regulations upon its member states. The EU could utilize the model to better understand how a specific regulation would be received in each of the member states and create regulations that fit better into the reality of the people living in the states. Another example could be in the tourist industry. If a company wants people from a certain culture to visit more frequently, they could utilize the model to better understand how to optimize their business model to reflect the values and perceptions of the culture.

9.4.2 Risk acceptance criteria

9.4.2.1 Individual

As an example of an individual risk acceptance criterion in life safety management, F-N diagrams, often called farmer diagrams, are used to present risk acceptance in a schematic manner for specific activities. On the x-axis of the F-N diagram, the consequence of the given event related to the activity is shown, often by the number of fatalities, injuries, or what consequence is relevant for the specific activity. The y-axis shows the probability of occurrence of events corresponding to the consequences shown on the x-axis (Faber M. H., 2007). The areas on the top right of the F-N diagram are high probability, high consequence events in the ‘not acceptable’ zone, and the lower-left corner of the F-N diagram are the low probability, low consequence ‘acceptable’ events. See Figure 9.

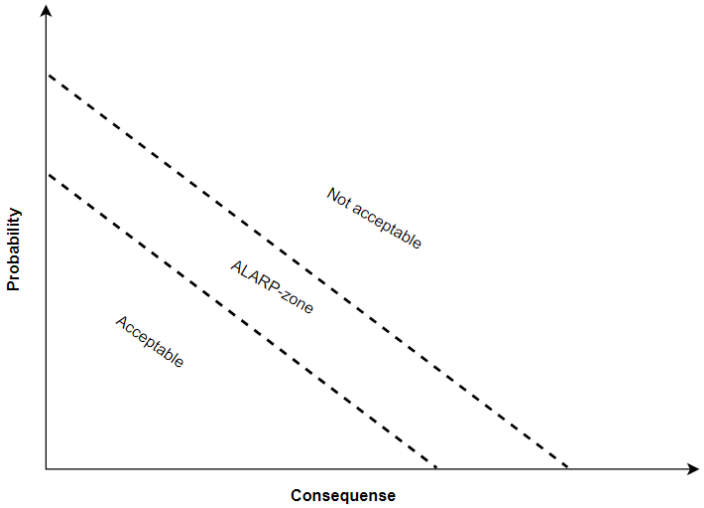

Figure 9: ALARP-zone (authors' model)

The zone between acceptable and non-acceptable risks is where risk reduction measures are generally applied. In managing the risks between the acceptable and not acceptable zone, a principle known as 'As Low as Reasonably Practically' (ALARP) is often used. This principle is used to cost-efficiently manage risks for individuals. ALARP implies that risk-reduction costs should be proportional to its return in risk reduction (Faber M. H., 2007). Because of how intuitively laymen can understand F-N diagrams, they are used in a broad spectrum of industries to communicate risk. The use of F-N diagrams and ALARP as a decision-criterion would fall in the category 2 and 4 (group/individual on individual) in the model of decision-interactions depending on the decision-maker constellation, see Figure 7.

9.4.2.2 Collective

(Nathwani, Lind, & Pandey, 1997), introduced the Life Quality Index (LQI). The Life quality index is based on the idea that the only resource available for humans is time and that time can be traded for money. The LQI is a metric used to model the preferences of a society based on life expectancy as a measure of safety and the GDP per capita as a measure of the quality of life (Nathwani, Lind, & Pandey, 1997).

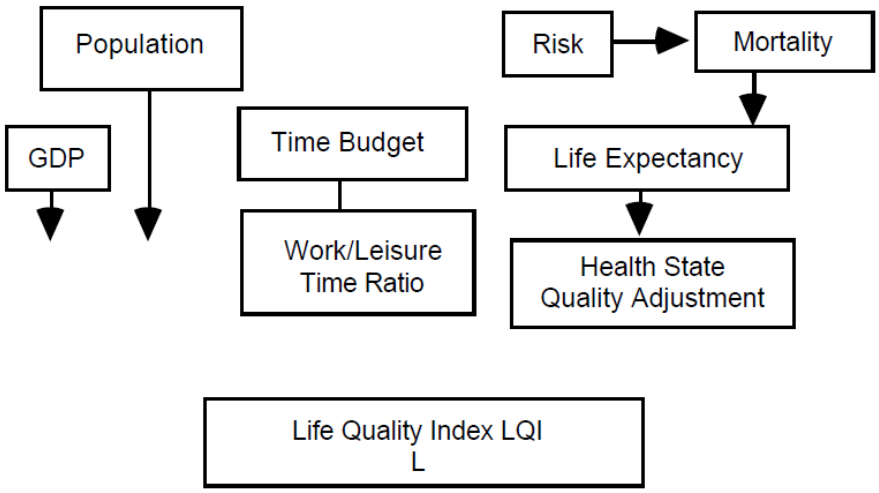

Figure 10: LQI (Nathwani, Lind, & Pandey, 1997)

As seen in the figure above, the three components that relate to LQI are the GDP per capita used for risk reduction, the work/leisure time ratio, and the Life expectancy at birth adjusted for life in good health.

Every risk reduction measure should lead to an increase in the LQI (Rackwitz, 2002), and thus the LQI can be used to derive risk acceptance criteria such as 'societal willingness to pay' (SWTP). SWTP is a measure of how much resources society is willing to put into lifesaving purposes. SWTP will delimit the feasible decision alternatives in risk reduction on a societal level. Furthermore, a metric that can be derived from the LQI is the 'societal value of a statistical life' (SVSL). SVSL is a metric used to describe the societal willingness to pay for the prevention of fatality, which can be used to extract compensation costs in cases of fatal accidents. In general, LQI is used on a collective level based on a statistical individual of the society, and the resources being used to invest in life safety via LQI come at a collective level normally via taxes.

9.4.3 Participatory/non-participatory in relation to political organizations

When considering decision-making in a political organization as one of the elements that constitute a decision rationale, a distinction between participatory processes and non-participatory processes can be made. This is done to further categorize the possible effects between stakeholders and decision-makers in political contexts for the taxonomy presented in Figure 5.

9.4.3.1 Participatory

Participatory decision-making is, in this thesis, understood as (i) decision-making, where the stakeholders impacted by decisions are also the decision-makers, and (ii) decision-making where

the decision-makers are directly influenced by the stakeholders impacted by the decisions. An example of (i) is direct democracies where the stakeholder/decision-maker (population) vote upon the regulations that have an impact on themselves. An example of (ii) is representative democracies where the stakeholders (population) are electing decision-makers (politicians) that represent their political viewpoints. In the model of decision interaction, see Figure 7, both (i) and (ii) would be category 1.

A current approach to participatory decision-making is associated with the programmatic position known as ‘post-normal science’, as introduced in the field of ecology by (Funtowicz & Ravetz, 1991). Post-normal science is about increasing stakeholder involvement in decision processes when consequences and uncertainties are high. One of the arguments in post-normal science is that the interaction between systems in nature and society is complex and hard to understand. It further argues that science has limitations and cannot provide the answers needed when managing the natural world to society's advantage. Some system interactions might be so inherently complex that further scientific studies might not be able to decrease uncertainties in decision-making. In those cases, further studies can unforeseeably increase the perceived complexity of the systems with, e.g., the discovery of factors impacting the system interactions that are not yet understood. Decision-makers, using the approach of post-normal science, must account for the consequences impacting stakeholders as well as the preferences of the stakeholders in their decision-making. This is especially true when conclusions cannot be derived solely from scientific facts or policy but rather values held by stakeholders. Stakeholders involved in the post-normal decision-making approach form ‘extended peer communities’, which involve the stakeholders interested in participating in the decision-making process about the decision context. These extended peer communities are not a result of an increased democratic process but serve as a tool used in matters where traditional quality assurance of decision-making is not adequate (Ravetz, 1999). Use-cases of post-normal science could be complex systems such as managing the health of society, the climate debate, ecology in general, or the management of natural resources. In such cases, uncertainties in scientific knowledge could have large consequences for decision outcomes, thus putting preferences in dispute.

9.4.3.2 Non-participatory

Non-participatory decision-making is, in this thesis, understood as decision-making where stakeholders impacted by decisions have no direct influence on the decision-making. Non-participatory political systems could be autocratic types of leadership such as dictatorships where decision-makers have an impact over the entirety of the population. In these cases, the population

has no direct political influence on the decisions made upon them. It could be argued that even in cases of autocratic leadership, the population will have some sort of influence on the decision-maker through, e.g., the implicit threat of rebellion. Autocratic leadership would be a category 3 decision interaction shown in Figure 7.

In contrast to post-normal science, expert-driven normative approaches to decision-making have limited stakeholder involvement. This approach is often seen in businesses where the utility function that is being maximized is the business-owner's and not necessarily the stakeholders.

In general, the use of the participatory/non-participatory approach is influenced by the ethics the political organization has a boundary condition. These main ethical boundary conditions will be explained in the following section of the thesis.

9.4.4 Ethics

The third criterion relates to the ethical positions that a given social or political organization may impose as boundary conditions, namely the axiological pair deontological – utilitarian, or intention vs. outcome based.

Ethics are relevant to consider in a decision-making context since ethics contains a system of principles that might influence the decision-maker and the stakeholders to move in a specific direction depending on how the ethical principles in the decision context system are defined. Ethics in general is a boundary condition defined by the social or political organization (stakeholders) and is part of the decision context system the decision-maker faces. Ethics can influence how the decision-maker defines his/her preferences, objectives, and his/her morale.

9.4.4.1 Outcome based

Outcome based decision-making is focused on the net consequence of the results rather than the method by which the results are achieved. This approach involves a decision-making process where the decision-maker is choosing among decision alternatives to maximize the benefit of the decision outcome. Outcome based approaches are rooted in the theoretical position of utilitarianism (see heading 9.2.1).

9.4.4.2 Intention based

Intention-based decision-making is focused on the ethics applied in decision-making as a boundary condition for the available decision-alternatives. This approach involves a decision-making process where the decision-maker is choosing among decision alternatives that are within the boundaries of a predetermined set of ethical criteria. Intention-based approaches are rooted in the axiological tradition of deontological ethics.

Immanuel Kant is considered to be the founder of deontology. Kant argued that people must act from duty and obligations to be morally right and that it is the motives of an action rather than the consequences of an action that makes it right or wrong. An action must be intrinsically good, and the only intrinsic good value that exists is good will. Moral actions must therefore be based on goodwill (Larry & Moore, 2021). Thus, it is more important for decision-makers that the method to acquire a specific goal is right than actually achieving that goal. The right has priority over the good (Larry & Moore, 2021).

Deontological ethics can be subdivided into two branches, agent-based deontology, which focuses on the individual, and patient-based deontology, which focuses on groups and rights. These branches can be further subdivided, see Figure 11:

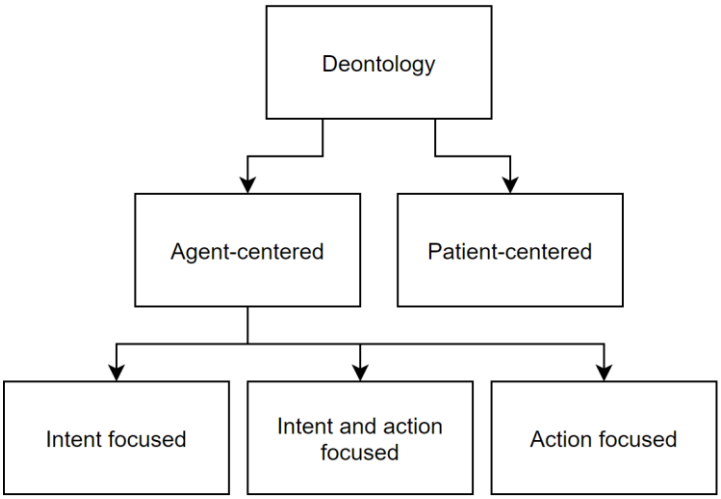

Figure 11: Deontology (authors' model)

There are several types of agent-based deontology. However, agent-based deontology is, in general, the philosophy that moral values are determined by the duties and obligations of an individual. Duties and obligations are agent-relative. Thus, different individuals have different duties and obligations. Those obligations and duties are subjective and could be towards a specific social circle, family, work, etc., and do not have to be supported or be meaningful for anyone else. Consequently, the agent-centered branch is based on the idea that moral values are personal.
In general agent-based deontology can be subdivided into intent-focused branches and action-focused branches or a combination of the two.
The intent-focused branch refers to an agent's intent, thoughts, and mental states as the main determinant of the agent's duties and obligations. If there are good intentions to an end or to the means to reach that end, then the act is considered morally good. If there are bad intentions behind a fruitful outcome, then that act would be considered morally bad. An example of intent-focused deontology ethics could be a traffic accident where a driver non-intentionally hits a pedestrian with a fatal outcome. Because the accident was not intended, it is still considered a morally acceptable action.
The action-focused branch deals with the actions of an agent as the basis of the duties and obligations of that agent. In this view, the agent is obligated to do or not do certain acts. The morality of an action is based on the will to cause good or bad.
The will is different from the intent in that will implies that there is causality between action and outcome, while intent does not. In the action-focused branch, using the same example as previously, the driver will still be morally responsible for the action of killing the pedestrian, even though that action was unintended.

The third branch uses both action and intent as the main determinant of duties and obligations. In this branch, the two other types of agent-focused deontology are combined in that the duties and obligations of an agent are determined by intended actions and not intent and action separately. Here the driver would only be morally responsible for the killing of the pedestrian if it was an intended act, i.e., an intended murder of the pedestrian.

Patient-based deontology, in contrast, judges a decision to be morally good if it, rather than personal belief about morals, takes people's rights into account. In that sense, patient-based deontology is agent-neutral; you have certain rights that have to be respected regardless of who you are. It also implies that an individual must not be used to generate good outcomes without that individual's consent (Alexander & Moore, 2021). In that way, patient-based deontology is the moral value for many libertarians because it would imply that, for example, the collection of taxes without the consent of the individual is morally unacceptable.

9.4.5 Application

Figure 12 is a schematic representation of the elements that constitute ‘application’ in Figure 5. The element “information” is the entirety of available information that can be derived from “state of nature”, which can represent itself in different “system states”. The information available to humans is the perceived information (i.e., sensory stimuli from the environment and the cognitive processing of these stimuli into image schemas, also referred to as conception). The perceived information about the state of nature is the basis for the “natural sciences” that have their basis in physics, chemistry, and biology. The perceived information about the state of nature is also the source for “human behavior”, which includes all human behavioral characteristics (including cognition). Human behavior is studied in the “cognitive and social sciences”, which in this thesis encompasses all sciences related to human behavior such as sociology, anthropology, political science, economics, and cognitive sciences. Both natural sciences and cognitive and social sciences are the basis of “descriptive models/theories” (see heading 9.4.5.3). These “descriptive models/theories” can be put into direct “application” by a decision-maker, but they can also be used to form “normative standards”. Normative standards are specific standards applied in specific circumstances (see heading 9.4.5.2). These circumstances are defined by the “decision-context system” and “decision-maker objectives” described later in heading 10.1 about influence of approach.

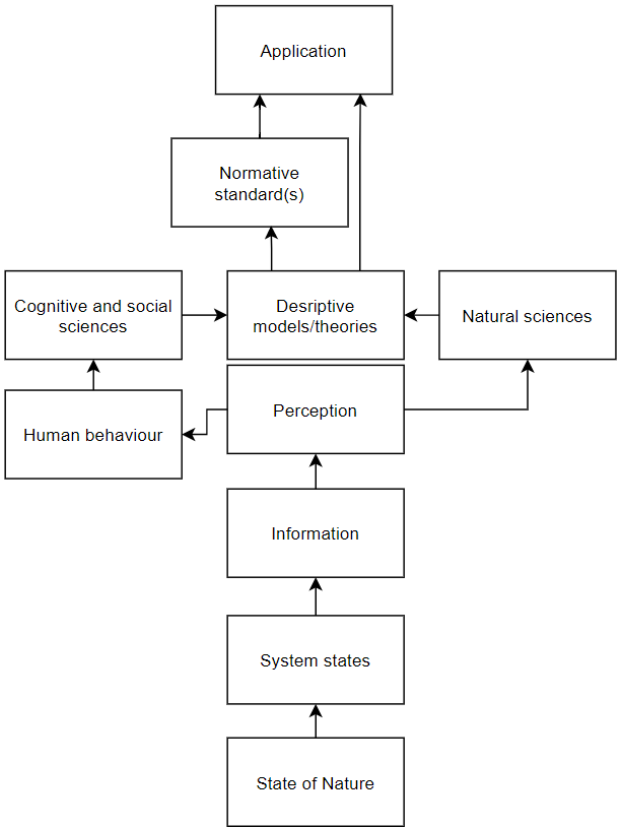

Figure 12: Application (authors’ model)

9.4.5.1 Descriptive / normative

Finally, the fourth criterion is associated with the application of knowledge in society, whereby we distinguish between descriptive and normative purposes for acquiring and using information.

9.4.5.2 Normative

The term normative is used in a variety of scientific fields. (Baron, 2004) argues that 'normative' denotes the norms, e.g., standards that allow us to evaluate if decisions are good or bad. The term normative is used differently in anthropology and sociology, where the term refers to cultural standards. The difference between the anthropological and sociological use of the term and how (Baron, 2004) uses the term is that deviations or adherence of cultural standards are not, per definition, good or bad. The major normative standards have a basis in utility theory, probability theory, and statistics. (Baron, 2004) argues that normative models, in general, should not include behavioral characteristics. Biases are argued to be systematic deviations from the norm, and thus the normative models can be used to extract biases found in decision-making by comparing the decisions with the normative model.

Based on the decision context system, normative approaches can be applied by a decision-maker as the standard which should be followed. These standards include the best available knowledge about how to make decisions when the specific criterion for the application of the normative standard is met. The normative standards can be used to derive how to use knowledge or how to collect information in a specific context to make better decisions.

9.4.5.3 Descriptive

Descriptive models and theories account for both behavior and reflective judgment – the latter being the ability to process information (e.g., from behavior) to draw possible conclusions. (Baron, 2004) argues that to understand biases (systematic variation from normative models), descriptive models and/or theories are made. Descriptive information is often used as input to normative models, as a priori knowledge subject to updating.

The descriptive acquisition of knowledge by the decision-maker is acquired from collecting information about the decision context system. The collected information includes the state of nature, which defines the boundaries of the decision context system in relation to space and time. The descriptive acquisition of knowledge by the decision-maker also includes the acquisition of knowledge related to the preferences of stakeholders. The grid/group, discussed in heading 9.4.1.2, is an example of a descriptive model.

9.4.5.4 Prescriptive

With both normative and descriptive models, the biases can be corrected with the use of prescriptive models to better align with norms. Prescriptive models are used in applied fields, such

as medicine, that seek to correct the biases (diseases) that occur in the implementation of normative models (the healthy body).

9.4.6 Preferences

Stakeholder preferences, in general, are considered descriptive information used by the decision-maker to use in his/her evaluation of the decision context system. The decision-maker can implement the preferences of stakeholders in several ways. In participatory systems, e.g., post-normal science, as described earlier in 9.4.3.1, the descriptive information about stakeholder preferences is used normatively on how to make decisions. In contrast, in non-participatory systems, such as autocratic systems, the preferences of certain stakeholders, e.g., the population, is of less relevance to the decision-maker. The decision-maker will also have preferences that will be influenced by the decision-context system. There are, in general, three ways of categorizing preferences, i.e., stated preferences, revealed preferences, and informed preferences, as described below.

9.4.6.1 Stated preferences

When confronted with a choice with at least two mutually exclusive options (the transitivity axiom), decision-makers or stakeholders will have to choose one decision alternative over the other. When decision-makers or stakeholders are asked to give their opinion on what decision-alternative they would prefer from a range of decision-alternatives; the answer is the stated preference. Examples of stated preferences are the answers given in surveys or questionaries, where individuals have to state which decision-alternative they would prefer in a given situation.

9.4.6.2 Revealed preferences

When decision-makers or stakeholders transit from saying what they intend to choose to actually choose a specific decision-alternative the revealed preference is shown. Examples of revealed preferences are shown in markets where people reveal their preferences of what they want to acquire by using their resources on those items. The revealed preferences are, therefore, a product of behavioral outcomes and do not necessarily align with the stated preferences.

9.4.6.3 Informed preferences

The informed preference is a different category: it is the basis for modeling preferences and is defined as a preference based on a full understanding of the possible outcomes of decision

alternatives (Faber M. H., 2007). Given how much information is available to the decision-maker or stakeholder, the preferences will be more or less informed. The preferences of stakeholders and decision-makers are based on their state of knowledge and perception about the system encompassing the decision-alternatives, i.e., the decision context system, and not the actual state of that system. Full information about probabilities and consequences of decision-alternatives, and thus informed preferences are something that should be strived for in rational decision-making. Nevertheless, in the interaction between complex social, cultural, and natural systems, decision-making is rarely based on fully informed preferences. Aleatory and epistemic uncertainty can make the task of obtaining full information impossible in such system interactions. Domains in which informed preferences are more likely to be obtained are in closed systems, e.g., in games or thought experiments. Since individuals or groups rarely are fully informed about their decisions, the decision they make can partly be explained by the individuals and groups risk appetite.

9.4.6.4 Risk appetite utility functions

As mentioned in heading 9.2.1 there are different types of risk appetite. In this section, the following three types of risk appetite will be described: (i) risk averse (related to maximin), (ii) risk neutral (related to expected value), and (iii) risk seeking (related to maximax), see Figure 13.

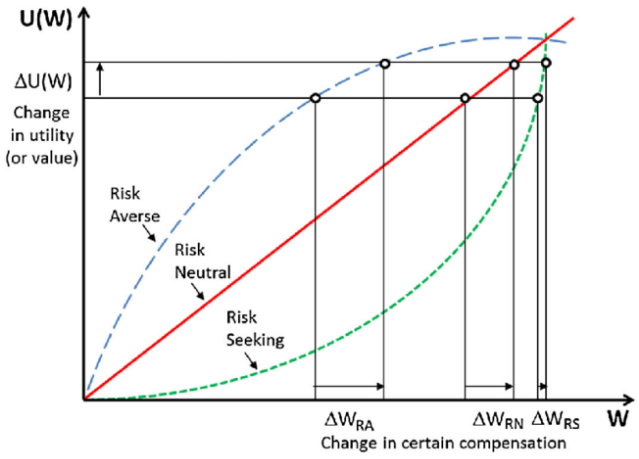

Figure 13: Utility function shapes for risk averse-, risk neutral-, and risk seeking individuals (Harris & Wu, 2014)

A risk neutral decision-maker (see the red line in Figure 13) is going to exhibit constant marginal utility of wealth and thus have a linear utility function.

A risk averse decision-maker (see the blue line in Figure 13) will exhibit diminishing marginal utility of wealth, thus having a concave utility function.

A risk seeking decision-maker (see the green line in Figure 13) is going to exhibit increasing marginal utility of wealth and thus have a convex utility function.

9.4.6.5 Prospect theory

Prospect theory examines the same concepts as described in heading 9.2.1. However, prospect theory takes into account the individual's references point, see Figure 14. The normative model of expected utility does not consider the descriptive model described as the psychological aspect of utility by Kahneman and Tversky in the prospect theory (Kahneman & Tversky, 1979). While (Bernoulli, (1738) 1954) argued that the utility of wealth is what makes people more or less happy, Kahneman and Tversky argued that what makes people happy is the change in wealth relative to a reference point (e.g., what one would expect to happen). Kahneman and Tversky argue that people perceive gains and losses differently relative to the reference point. What Kahneman and Tversky showed is that if individuals consider a decision alternative where the individual can gain something, relative to the current amount this individual has, the individual is more likely to choose a certain gain, i.e., individuals dislike losses more than individuals like gains; hence people, in general, are risk averse. The exceptions are when individuals are faced with bad outcomes; here, individuals, in general, turn to the risk seeking behavior to reach a better outcome.

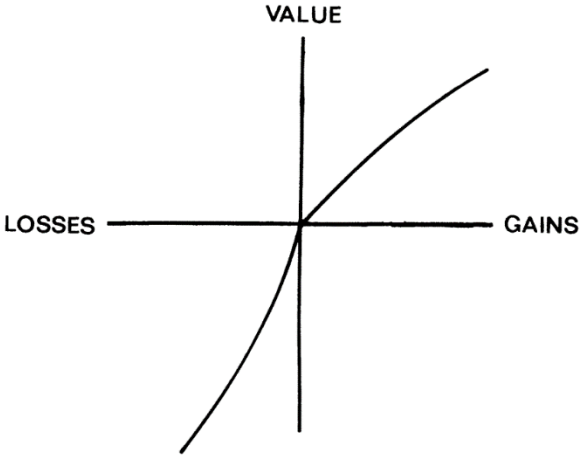

Figure 14: Shape of a utility function (Kahneman & Tversky, 1979)

9.4.7 Additional considerations

9.4.7.1 Time considerations

Time considerations are divided into two categories: point in time and over time. Point in time refers to a specified time frame, whereas over time refers to an unspecified time frame.

The preferences of the decision-maker define how the time considerations within the system are defined, e.g., if a decision-maker prefer to do something about a decision problem at a specified point in time or over time, and what the decision-maker wants to do at that point in time, and over time. Management options and preferences would differ if something had to be optimized for now versus over a longer period of time. An example could be a kayak taking in water at the open sea due to a crack. At the specific point in time tactical, a repair is needed, and a simple solution, e.g., a piece of waterproof clothing, could be used to seal the hole. However, the solution would only be temporary as the clothing might not be the best option for continued use of the kayak. In that case, a more substantial repair or a new kayak could be a preferred option over time for the decision-maker.

9.4.7.1.1 Modes of operations and time considerations

In this thesis, two modes of operation are defined as strategic mode and tactical mode.

Over time	Point in time
Strategic	Tactical
Defining strategy/direction	The reaction to an exposure event
Holistic	"Disaster mode"
Allocation of ressources	First principles applies and are being developed

Figure 15: Over time and point in time (authors' model)

The strategic mode is where an exposure event is considered before it happens, see Figure 15.
In the strategic mode, decision-makers define objectives and define the path he/she needs to follow to reach the objectives, this mode happens over time, and the approaches utilized are normally the structured approaches such as cost/benefit under EUT (see heading 9.2).

When the exposure event happens, at a point in time, the tactical mode becomes the dominant mode where the decision-makers react to the exposure event, see Figure 15. Different rationales can be applied depending on how informed the decision-makers are about the exposure event. If the decision-makers are well informed, the selection of decision-making approach might be easier to choose, whereas, if the decision-makers are lesser informed, first principles could be developed and applied ad-hoc. A structured approach that is also often used in these situations is the

precautionary principle. The tactical mode is not an optimal mode to operate since decisions taken are under the influence of great uncertainty. When in the tactical mode, decision-makers could try to turn the situation from a tactical situation to a strategic situation by collecting enough relevant and precise information about the exposure event to specify the optimal strategy. An example of a strategic situation becoming tactical is the covid-19 situation, as mentioned in header 5. Before the covid-19 virus came to Denmark, the decision-makers were in a strategic mode, defining the strategy to combat the virus, if it should ever cross the borders to Denmark. When it hit, the decision-makers were forced into the tactical mode by responding/reacting to the exposure event and how it affected Denmark's population.

9.4.7.2 Physical boundaries

The physical boundaries are the physical delimitation defining the boundaries of the decision context system, e.g., buildings, country borders, roads, etc. The physical boundaries exist as the state of nature and can be influenced by different system states, see Figure 16.

9.5 Decision context system

The decision context system is the system boundaries of a decision problem; it contains a set of information categories that describe the spatial and physical boundaries, time boundaries, ethics, and stakeholder preferences (and thus, stakeholder objectives). The decision context system includes the decision-makers cumulative knowledge and life experience; this is referred to as the element memory (see Figure 16). Furthermore, the decision context system encompasses the degree of information that the stakeholder has about the decision context; thus, it is equivalent to how informed the stakeholder is about the decision context. The decision context system is the perceived state of nature by the decision-maker and is the foundation of the decision context. It is within this system's boundaries that a decision must be made. The decision context system will be explained in more detail in the influence diagrams in heading 10.1.1 and 10.2.1.

10 Influences in the taxonomy

This section describes the influence between three of the elements within the taxonomy, namely the approach, the preferences, and the application. The last two elements (ethics and system information) were not directly described since the dependencies of these are indirectly illustrated in the influence diagrams of the three elements. The overview of influences between the elements serves to give a general idea as to where hazards may arise. The influence diagrams also serve as a more detailed description of the dependencies within the taxonomy.

10.1 Influence: Approach

This part of the thesis focuses on the influence and interactions of the different elements in Figure 5. More specifically, this section analyses how the different elements influence a decision-maker to conclude which approach to use. When considering a decision problem, a decision-maker has to make a decision, even if this decision is to do nothing. The process of acquiring knowledge to know what to decide includes considering the decision context system (see Figure 16) and whether the consideration of the decision context system is made consciously or unconsciously. The conscious consideration of the decision context system means analyzing, weighting, and ordering the different information of the decision context system (structured approach). The unconscious consideration of the decision context system can mean acting based on intuition and gut feelings as defined in the psychology and cognitive science literature. However, it can also be a conscious choice to act on intuition and gut feelings, as described in header 9.3.1 (non-structured approach).

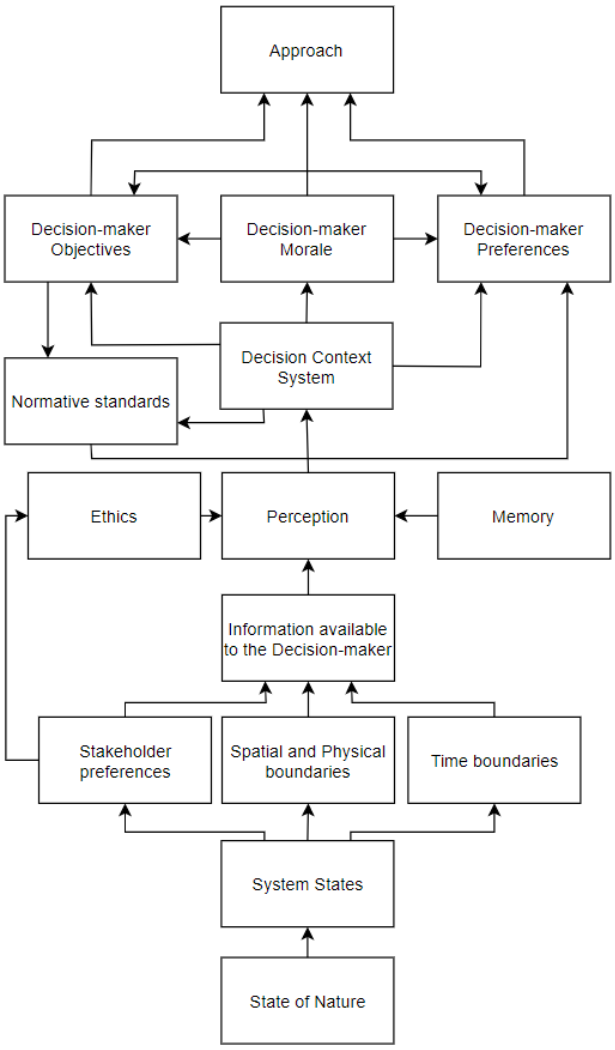

Figure 16: Schematic representation of what leads to selecting upon the principal approach (authors' model).

To arrive at a set of decision alternatives and make a decision, the decision-maker must choose an approach for decision-making. How this approach is selected is based on the following elements of information: the decision context system (descriptive information), normative standards (normative application), the objective, the decision-maker's moral values, and the preferences of the decision-maker. This set of elements is based upon the decision maker's decision context system, as seen in Figure 16.

The influences between the elements that constitute the decision context system have an important role when settling for a decision-making approach since this is the foundation of what can be known by the decision-maker, and thus the foundation for what available options the decision-maker has for selecting an approach.

The decision maker's objectives are based on what the decision-maker wants to do and what the system allows. The objectives are the definition of the end goal for applying an approach.

The decision-maker's morale is the decision-maker's moral principles of right and wrong to obtain well-being for him/herself and stakeholders; these principles are subjective (Lakoff & Johnson, 1999).

The decision maker's preferences refer to preferences influencing the selection of an approach. This element in the schematic representation shows how influences among the decision context system, decision-maker morale, decision-maker objectives, and the normative standards interact in informing the preferences of the decision-maker. Whether information is applied descriptively or normatively the application is dependent on the decision-makers preferences. The normative application are the standards, models, methods, etc., which define what is known as “best practice” for the decision problem. The application of information can indirectly influence which approach is perceived most beneficial for the decision-maker. The normative standards suggest what should be done with the information derived from the decision context system, which can influence the decision-maker to apply approaches that belong to the category of structured approaches (EUT).

The decision context system is described in heading 9.5.

The normative standards are the standard models, methods, etc., which define what is known as “best practice” for the decision problem.

The conception of these elements is based on how the decision-maker perceives the information. The element named decision-maker preference is based on the decision-maker's preference towards the approach and the objectives taking ethics, morals, and the decision context system into consideration.

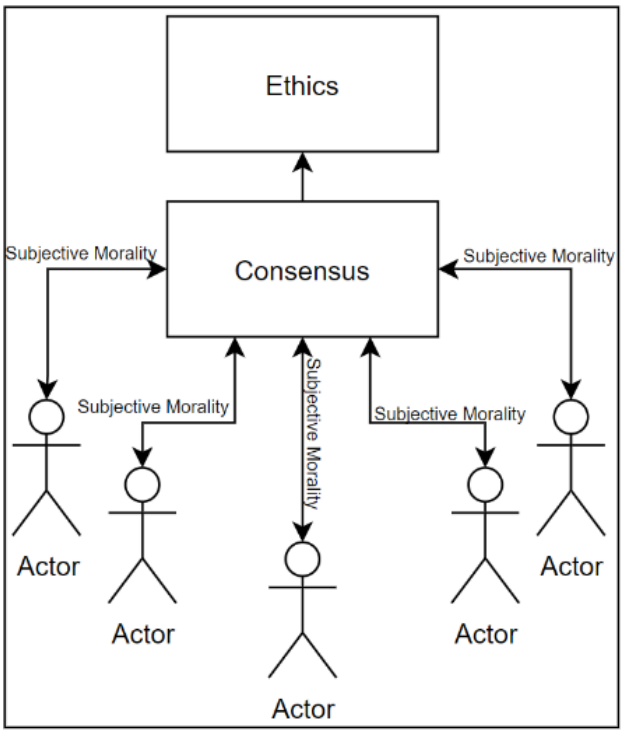

Figure 17: Ethics (authors’ model)

As represented in Figure 17, the ethical boundaries create the boundaries of what is perceived as right or wrong on a societal level. The ethical boundaries are the aggregation of subjective moralities in the social context of the system (Lakoff & Johnson, 1999). The relation between ethics and subjective morality is mutually dependent. Ethics also defines what goes into subjective morality via group dynamics. The ethical boundaries define the rules the system provides and adheres to, e.g., a code of conduct or political manifestos.

10.1.1 Decision context system

Figure 18 shows the input and outputs of the element decision context system. The element labeled perception influences the decision context system in that all the information aggregated from the spatial and physical boundaries, time boundaries, ethics, system states, memory, and stakeholder preferences are perceived by the decision-maker by sensory stimuli from these elements and the stimulus from this cognitive process is formed into a

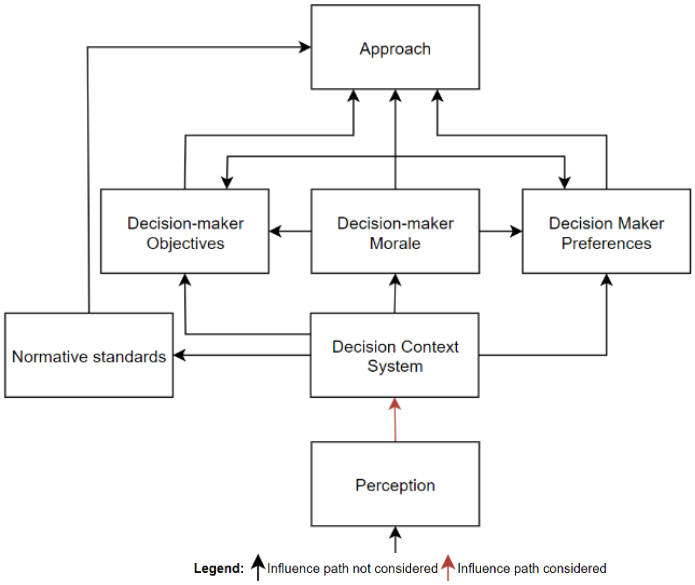

Figure 18: Inputs and outputs of Decision Context System (authors’ model).

perception of what is known about the decision context system by the decision-maker.

10.1.2 Decision-maker objectives

Figure 19 shows the input and outputs of the element decision-maker objectives. The decision-maker objectives are influenced by the decision context system in the way that the perception of the stakeholder preferences and information about the system is present, i.e., the stakeholder preferences influence the objectives of the decision-maker, and the information about the system creates the foundation of what can be done, e.g., how many resources are available (physical boundaries).

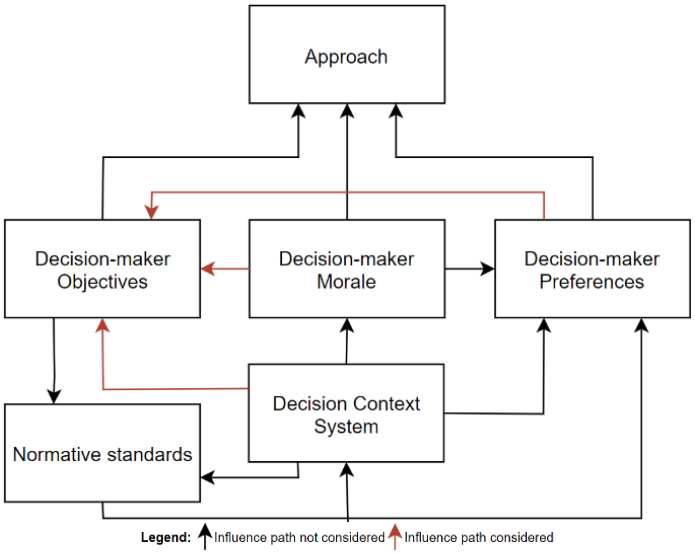

Figure 19: Inputs and outputs of Decision-maker objectives (authors' model).

The decision-maker preference influences the decision-maker objectives in that the decision-maker has his/her preferences towards the objective, which is not necessarily the same objective as the stakeholders.
The decision-maker morale influences how the decision-maker can define the decision-maker objectives. The decision-maker's moral principles of what is right or wrong can influence how the objectives are defined and thus, leave an opening of a deviation from the ethical boundaries where the system's ethical boundaries are violated. In this case, the decision-makers moral principle could override a given approach that would be rational in the circumstances or based on collective consensus and opt instead for an idiosyncratic action favored

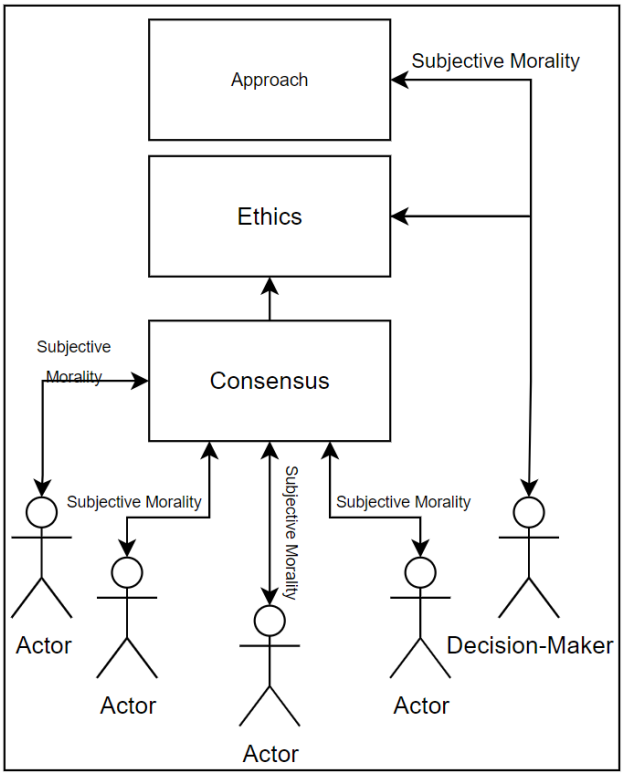

Figure 20: Morality could override ethics in a decision context (authors' model)

by his/her subjective morality. An example of such action is what is popularly referred to as making ‘an executive decision’, as seen in Figure 20.

10.1.3 Decision-maker morale

Figure 21 shows inputs and outputs of the element decision-maker morale.

The decision-maker morale is influenced by the decision context system in that the moral principle of the decision-maker is subjective, and thus the moral values are not necessarily aligned with the system's ethical boundaries. However, the moral values of the decision-maker can be influenced by the decision context system in the way that the decision-maker interacts with it and might not be able to ignore the ethical boundaries of the system and, thus, change or adapt his/her moral principles.

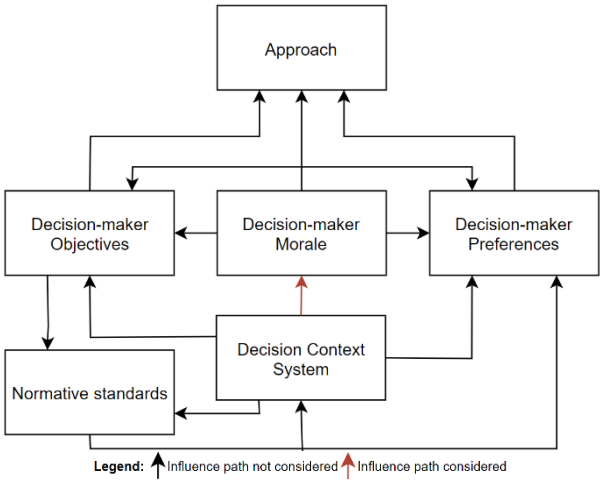

Figure 21: Inputs and outputs of Decision-maker morale (authors’ model).

10.1.4 Decision-maker preferences

Figure 22 shows inputs and outputs of the element decision-maker preferences.

The decision-maker preferences are influenced by the decision context system in that the decision context system defines time boundaries and the spatial and physical boundaries (e.g., resources available) and, thus, what is possible to accomplish. If the decision context system changes, what the decision-maker thinks is possible to accomplish changes; thus, the preferences might change. The decision-maker preferences are also influenced by the decision context system in that the decision-maker interacts with the system and thus, cannot ignore the system's ethics. Based on the stakeholder’s preferences, the decision context system can also influence the decision maker's preferences, as described earlier in this section.

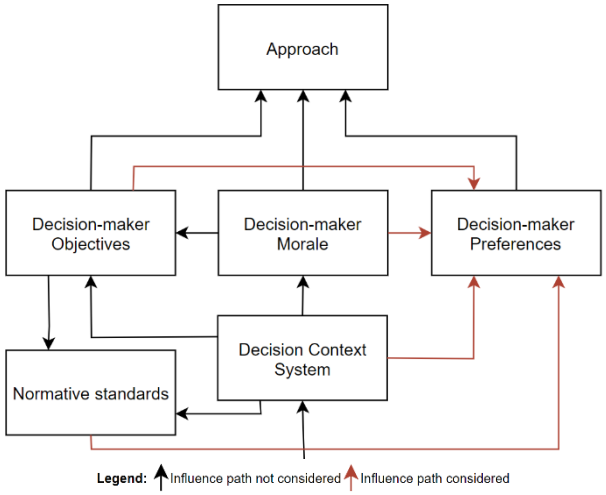

Figure 22: Inputs and outputs of Decision-maker preferences (authors’ model).

The decision-maker preference is influenced by the decision-maker objectives in that the decision-maker preferences might change if the decision context system changes (e.g., a change in stakeholder preference/objectives). The decision-maker could realize other preferences based on the new objectives in terms of risk and opportunity.

The decision-maker's morale directly links to decision-maker's preferences, i.e., decision-maker morale is one of the elements that directly affect what goes into defining a preference. The decision-maker's principles of right and wrong create the foundation of how the decision makers' preferences are defined.

The normative standards influence the decision-maker preference because the normative standards may provide a standardized model or method to apply to the decision problem. The normative standards can potentially provide a knowledge base to inform the decision-maker better.

10.1.5 Normative standards

Figure 23 shows the inputs and outputs of the element normative standards.

The normative standards are influenced by the decision context system in that the decision context system sets the context for the decision problem, e.g., the stakeholder preference defines the objective of the stakeholders and, the time, spatial and physical boundaries define the resources available.

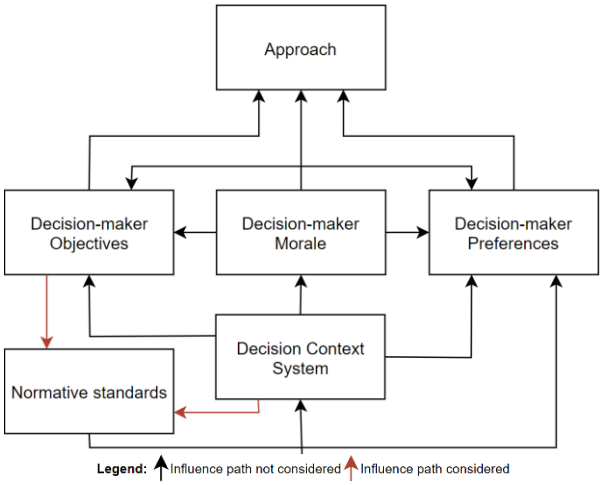

Figure 23: Inputs and outputs of Normative standards (authors' model).

The decision-maker objectives influence the normative standards in that the decision-maker has an objective he/she wants to reach. Thus, selecting the standard that optimizes the chances of reaching that objective would be preferable.

10.1.6 Principal approach

Figure 24 shows the inputs of the element approach.

Depending on the decision maker's objectives, it might be advantageous to select an approach in line with what best represents the decision maker's objectives.

The decision-maker moral is as described above.

The decision-maker preferences influence the approach in that the decision-maker might have a more informed preference towards an approach and thus is likely to apply a specific approach with which he/she is most comfortable.

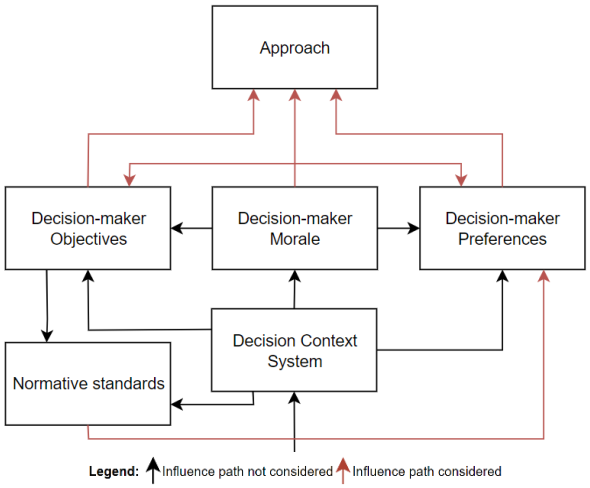

Figure 24: Inputs of Approach (authors' model).

Lastly, the normative standards influence the approach indirectly through the decision-maker preference. This indirectly influence can happen since normative standards (e.g., best practices) vary depending on the domain in which it is applied. Furthermore, if the objective is to prove a point in a specific domain, the decision-maker objectives could influence the decision-maker preferences towards a specific approaches that may be more recognized in some domains than others.

10.2 Influence: Preferences

This section will describe the influences and interactions of the different elements in Figure 5. More specifically, this section analyses how the different elements influence the preferences of stakeholders. Later the decision-maker preferences are outlined, and the relation between stakeholder and decision-maker preferences is analyzed. A more detailed part about the preference of the decision-maker can be found in heading 9.4.6.

As mentioned earlier (in heading 9.4.6), the three categories of preferences are stated, revealed, and informed (see Figure 25). The informed preference can be two things, (i) where the decision-maker has full information, which primarily is applicable in a closed mathematical system, and (ii) informed preferences utilized as a scale for how informed the decision-maker is about something This section uses informed preferences in the context of an open system, where it is more of a scale for how much the stakeholders know about the decision problem, wherein the closed system, there is potentially full information.

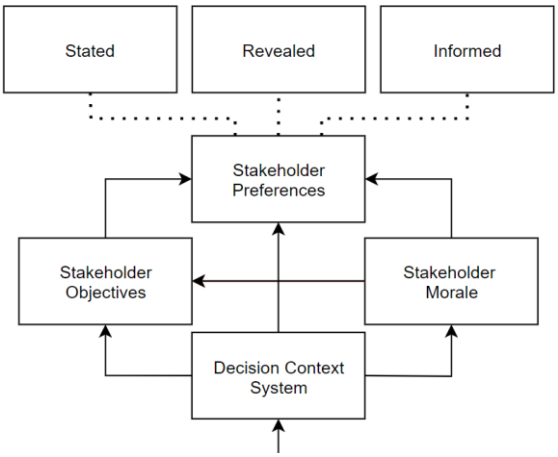

Figure 25: Stakeholder preferences (authors' model).

For the stakeholder to know whether to state or reveal a preference can be a tactical decision. The tactical aspect can be used by stating a preference towards a decision-maker which could influence the decision-maker to move in a certain direction. The same is true with the revealed preference; if the decision-maker observes the stakeholder behave a certain way, the decision-maker might move in a different direction than first anticipated by the decision-maker.

10.2.1 Decision context system

The decision context system has been described in heading 9.5. However, it is relevant to emphasize that the decision context system encompasses the degree of information that the stakeholder has about the decision context; thus, it is equivalent to how informed the stakeholder is about the decision context.

The decision context system (as described in heading 10.1.1) influences the stakeholders moral. Note that the decision context system is the same as described earlier, and the stakeholder will be influenced by the stakeholders linked to the related social/political group/organization, i.e., part of the stakeholder's decision context system. The stakeholder moral and the decision context system will form the stakeholder objectives. The stakeholder objectives, together with the stakeholder morale, will define the stakeholder preferences, as seen in Figure 26. These preferences can either be stated, revealed or informed see heading 9.4.6.

10.2.2 Stakeholder objectives

Figure 26 shows the input and outputs of the element stakeholder objective.

The stakeholder objectives are influenced by the decision context system and the stakeholder morale. The decision context system influences the stakeholder objectives in that it is the basis for the decision problem, i.e., the boundary conditions and how informed the stakeholder is about this.

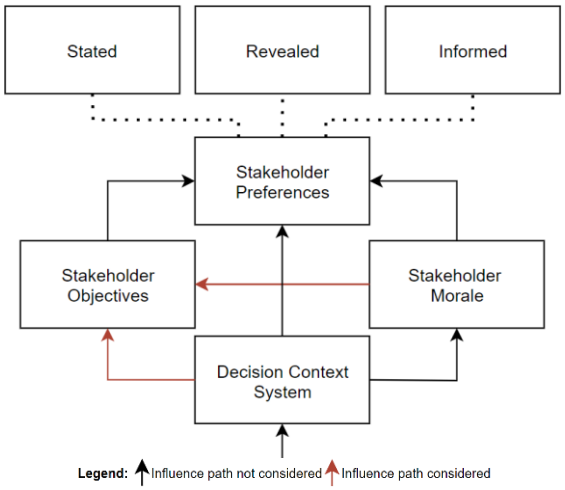

Figure 26: Inputs and outputs of Stakeholder objectives (authors' model).

The stakeholder objectives are influenced by the stakeholder morale in that this is the basis for what the stakeholder thinks of as right and wrong. The stakeholder forms the objectives based on the subjective moral principles of right and wrong.

10.2.3 Stakeholder morale

Figure 27 shows the input and outputs of the element stakeholder morale.

The stakeholder morale is influenced by the decision context system as described in heading 10.2.1. Through the decision context system, the stakeholder morale is also influenced by the ethics of stakeholders.

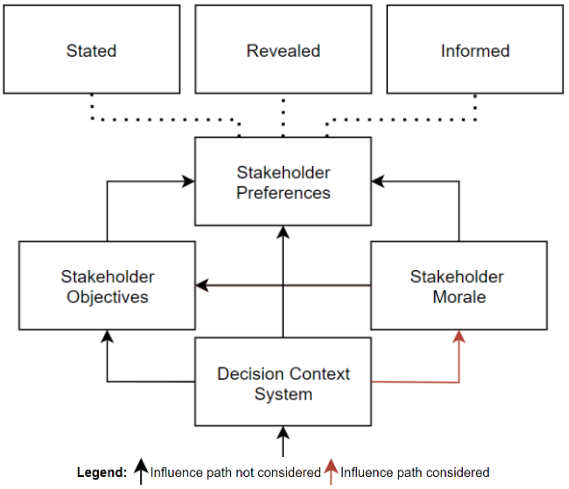

Figure 27: Inputs and outputs of Stakeholder morale (authors' model).

10.2.4 Stakeholder preferences

Figure 28 shows the input and outputs of the element stakeholder preferences.

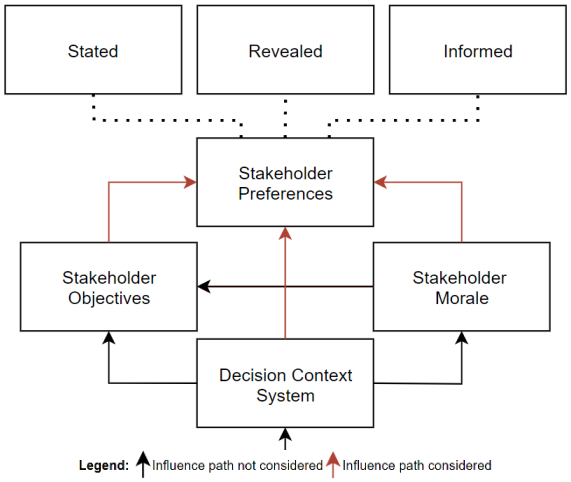

Figure 28: Inputs and outputs of Stakeholder preferences (authors' model).

The stakeholder preferences are influenced by the stakeholder objectives, the stakeholder morale, and the decision context system.

The stakeholder preferences are influenced by stakeholder objectives in that the chosen preference can influence how the stakeholder can reach his/her objectives.

The stakeholder preferences are influenced by the decision context system since the more the stakeholder knows about the decision problem and boundary conditions, the more informed preferences the stakeholder can have.

10.2.5 Decision-maker preferences

The decision-maker preferences are in part described in the chapter about approach, see heading 10.1.

The decision-maker preferences are influenced by the sub-elements of the figure in the same way as stakeholder preferences. However, the decision-maker preferences might also be influenced by the normative standards. The normative standards are influenced by the decision-maker objectives and the decision context system. A schematic representation of the constituents of the decision-maker preferences can be seen in Figure 29. This schematic representation should be seen in the context of Figure 16 as a description of the arrow that goes from decision-maker preferences to approach.

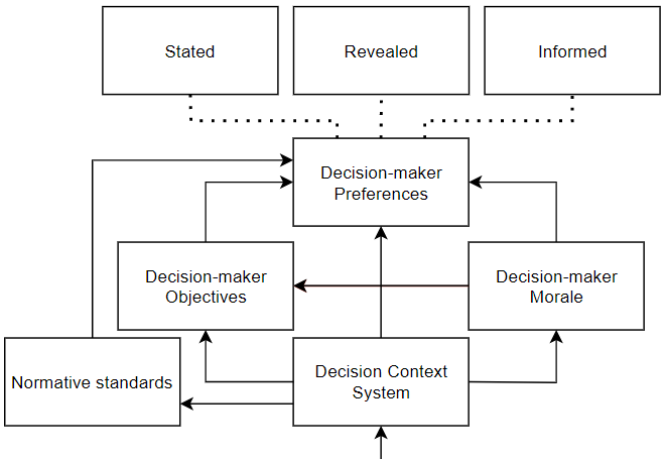

Figure 29: Stated, revealed, and informed preferences (authors' model).

10.2.6 Relation of stakeholder and decision-maker preferences

The following section will focus on how the decision-maker and stakeholder preferences are related.

The decision-makers “stated/revealed” preferences can influence the state of nature. This influence could come from a decision-maker stating a preference toward a specific decision-alternative. The influence could also come from a revealed preference in the form of a specific behavior from the decision-maker. Whether stated or revealed, the preferences of the decision-maker can influence the state of nature. As seen in Figure 30, the state of nature influences the entirety of the “decision context system” directly and indirectly. The stakeholder preferences are part of the “decision-context system” thus creating an influence loop. To which degree this loop will influence the preferences of stakeholders or decision-makers depends on how much weight the stakeholders and decision-makers put in each other’s preferences and to which extent these preferences influence the state of nature.

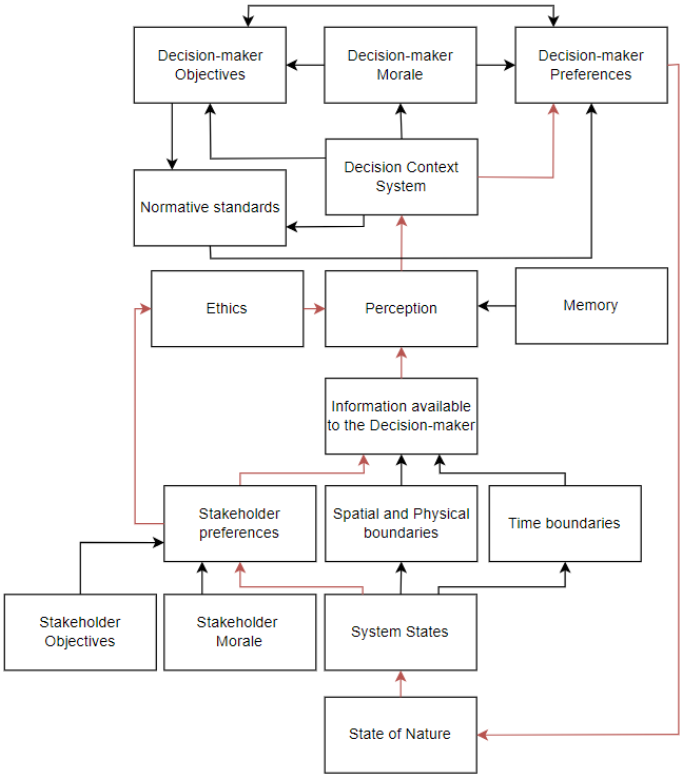

Figure 30: Stakeholder and decision-maker preference relation (authors’ model).

10.3 Influence: Application

This part of the thesis will describe the influences and interactions of the different elements in Figure 5. More specifically, this section analyses how the different elements influence the application of the information in normative and descriptive ways, see Figure 31.

How the decision-making approach is applied has been described in three categories, normative, descriptive, and prescriptive.

Descriptive information is derived from the decision context system. Whether the information is applied normatively or descriptively is influenced by the decision context system and the decision-maker preferences. The decision-maker has the option to apply the descriptive information normatively, if he/she prefers to utilize a normative standard, if not the decision-maker can choose to apply the descriptive information directly.

The stakeholder perceptions toward the decision problem may form the stakeholders' objectives and their moral principles of right and wrong. The stakeholders can arrive at a set of written or unwritten rules (ethics) which define their collective perception of right and wrong related to the decision context.

The information available for the decision-maker is perceived by the decision-maker, and thus the decision context system is formed.

By this, the "decision context system" includes the descriptive information that forms the stakeholder's perception and their opinion on the decision problem. Depending on the context of the decision problem, the decision-maker's objectives towards the decision problem can vary.

In a societal decision problem context, it can be assumed that a part of a societal decision-makers (elected politician) objective is to be re-elected. Thus, the stakeholder's opinion about the decision problem becomes an important part of the decision maker's objectives.

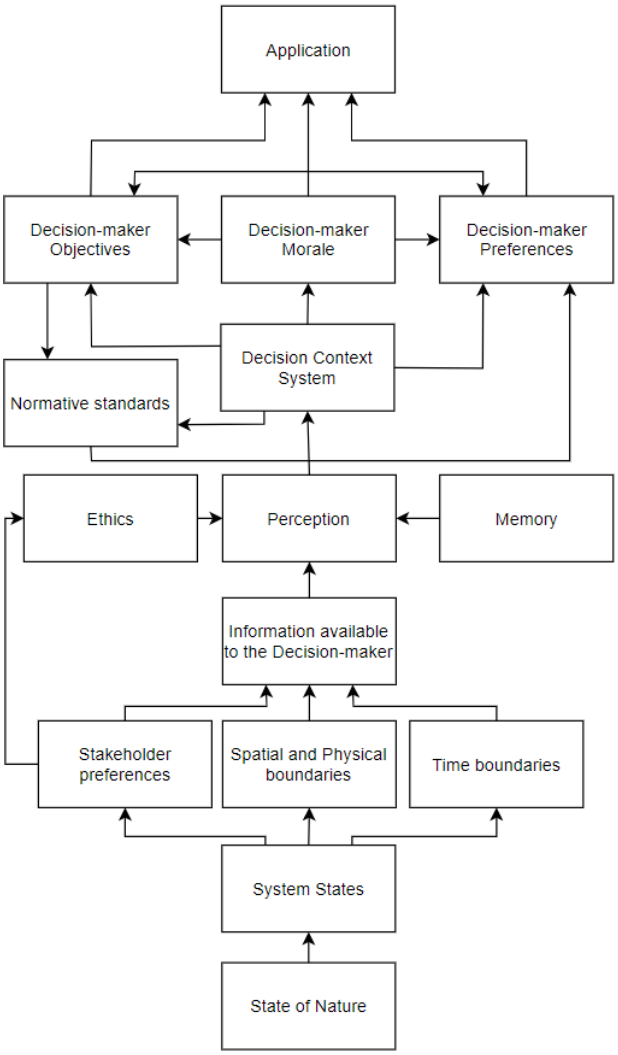

Figure 31: Schematic representation of what leads to selecting the application (authors' model).

The decision-maker has the option to utilize normative standards to the decision problem, which could be beneficial for a decision problem where there are standards and verified knowledge, e.g., in the field of civil engineering. However, suppose there is a competing objective, which is more important to the decision-maker than the actual decision problem. In that case, the normative standards might be put away, and a descriptive application to the decision problem might be applied, i.e., the stakeholder's opinion and view on the decision problem weighs more in the decision-making process than using the normative standards used in similar decision problems with success.

11 Hazard identification

The purpose of this section is to provide decision-makers with information on the hazards related to the identified decision-making rationales.
To do this end, the hazards involved in decision-making on a general level, as well as hazards related to each of the elements in the taxonomy, are outlined. Lastly a summary of the identified hazards is presented.

The hazard identification consists of two parts:

1. Identification of general hazards involved in decision-making.
2. Identification of hazards related to the identified elements in the taxonomy.

11.1 General hazard categories in decision-making

In general, hazards related to the use of information (information conditions 2-5, see heading 5.3.2) are relevant for both structured and non-structured approaches. In this section of the thesis, the general hazards that can influence any of the elements in the taxonomy are described.

The availability and obtainability of information pose a general informational hazard. Moreover, the ability and willingness to correctly use the principal approaches pose a hazard. The consequences

of these hazards can be selecting the wrong decision alternative and thus, depending on the decision context, can lead to direct and indirect consequences.

A schematic model of the processes causing consequences is proposed by the (JCSS, 2008), see Figure 32. Given that the analysis of consequences is not a part of the scope of the thesis this schematic model was not adopted. However, inspiration was found in the model, thus some of the terms used in the model has been applied in the hazard identification.

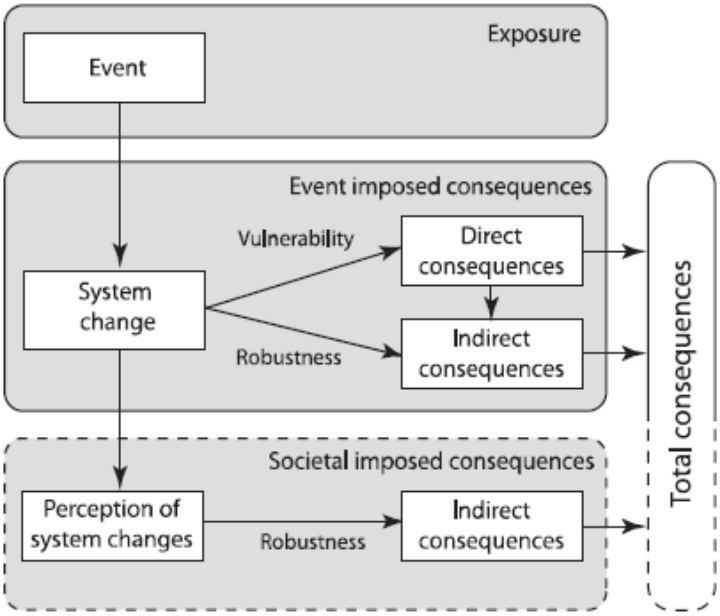

Figure 32: A schematic model of the processes causing consequences (JCSS, 2008)

11.1.1 Cognitive biases

In this section of the thesis, a brief introduction to cognitive biases is made and some proposed effects on decision-making are outlined. It is important to note, that different cognitive biases can have a different impact on decision-making based on the context of the decision problem and the decision-maker's mental attributes. A selected number of cognitive biases is explained on a general level, and in the further sections of the thesis, some examples are given of how they can be hazardous in specific decision-making contexts related to the elements of the proposed taxonomy.

Biases are generally understood as systematic deviations from the norm. Cognitive biases can be understood as a systematic deviation from normative or rational thinking patterns used in judgment (Tversky & Kahneman, 1974). To understand the dependencies and influences of cognitive biases, as well as the terms used on the subject of this topic, a simplistic schematic model is created, see Figure 33 below.

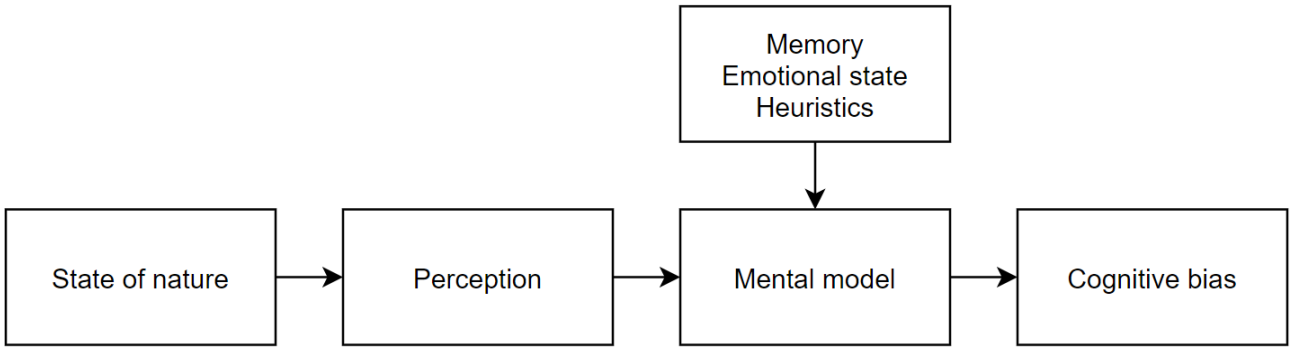

Figure 33: The constitutions of a cognitive bias (authors' model)

"State of nature" provides information that can be perceived by humans. This "perception" is to be understood as sensory stimuli provided by "state of nature" and the cognitive processing of these stimuli into "mental models", which can be understood as the subjective impression of the state of nature (Kahneman, Lovallo, & Sibony, 2019). The subjective impression of the state of nature can be influenced by the memory (including experience), feelings (emotional state), and heuristics (mental shortcuts) applied by the individual. Mental models are based on prior and current subjective exposure to the state of nature, i.e., individuals can only perceive the parts of the state of nature that has been brought to his/her attention. Because attention is a limited resource, what is being perceived by individuals comprises only snips of the full information contained within the state of nature. Not having full information compounded with the impact of flaws in memory, emotions, and the application of heuristics on judgment is a combination that unconsciously can create "cognitive biases". (Kahneman, Lovallo, & Sibony, 2019) argues that mental models are oversimplified and excessively coherent versions of the state of nature based on a limited amount of evidence (lack of information). Furthermore, the information applied in mental models is often biased to being weighted inaccurately, i.e., some information gets more attention than it should while other information is being excessively overlooked.

11.1.1.1 Confirmation Bias

(Bacon, 1620) describes the confirmation bias as a phenomenon where individuals tend to seek confirmation of preexisting mental models, thus giving more weight to information that is coherent with the mental model than non-coherent and equally relevant information. In that way, the confirmation bias can impact decision-makers to be biased towards preexisting beliefs about the state of nature even when relevant information suggests otherwise.

11.1.1.2 Representativeness bias

Individuals can be prone to use the representativeness heuristic when assessing the probabilities that an event or object belongs to a class or category. This is done by evaluating to which degree that event/object resembles a mental model of that class/category, rather than paying attention to base rate, i.e., prior probabilities of outcome (Tversky & Kahneman, 1974). In that way representativeness heuristic bias makes use of stereotyping in the assessment of a certain class/category. Imagine a tall person that looks like a stereotypical baseball player. Base rate would tell that the probability that the person is, at the same time, tall and a baseball player is less likely than that person just being tall even if resemblance might intuitively suggest otherwise.

11.1.1.3 Availability bias

The availability bias suggested by (Tversky & Kahneman, 1974) says that in some situations people tend to assess probabilities or frequencies of specific instances by the ease of which those instances come to mind. This ease of which something is brought to mind can originate from, e.g., recent experiences or headline stories in the news. To exemplify if an individual just fell over a rock, the availability bias would suggest that he will give relatively higher estimates of frequency and probability of fall accidents compared to the base rate of fall accidents.

11.1.1.4 Anchoring bias

(Tversky & Kahneman, 1974) introduces the anchoring bias. This bias suggests that people are influenced by reference points when estimating a value. The reference point can influence estimations, i.e., a reference point of 100 will give larger quantitative estimates than a reference point of 30, even if what is being estimated is constant. The anchoring bias suggests that the formulation of a problem with the use of reference points can introduce biased estimates of values such as probability assignments in decision-making.

11.1.1.5 Egocentric bias (illusion of control)

The egocentric bias suggests that in circumstances heavily influenced by chance, individuals tend to overestimate their degree of control over the outcome. (Langer, 1975) suggested that this is true if factors such as familiarity with the context, personal involvement and having a predefined desired outcome are present. (Alloy & Abramson, 1979) also suggest that emotional state affects to which degree people tend to think they have control in situations determined by chance, e.g., people who are depressed are less likely to overestimate their ability to control situations they have little to no impact on. In decision-making this illusion of control could lead to sub optimal use of resources in

trying to manage contexts where those investments will make a lesser difference than anticipated by the decision-maker.

11.1.1.6 Hindsight bias

The hindsight bias is the tendency of individuals to exaggerate in hindsight what was known in foresight. When confronted with new information that leads to new beliefs about state of nature individuals tend to have a hard time memorizing preexisting beliefs, thus being inclined to think in hindsight the new belief was in fact not new but preexisting in foresight (Pohl & Erdfekder, 2016). This flaw in memory, depending on context, can be a hazard in decision-making as it could lead to, e.g., trust issues between stakeholders and decision-makers.

11.1.1.7 Risk aversion and framing

Framing is the way a problem is presented to, e.g., a stakeholder or a decision-maker.
People in general are risk averse, i.e., they are willing to put more resources into mitigating risk than expected value would suggest. Risk aversion is well-known within behavioral economy and cognitive sciences, first suggested by Bernoulli in the 1700's and later refined by (Kahneman & Tversky, 1979) in prospect theory. Because the phenomena of risk aversion seem to be an inclination generally applicable to individuals, risk averse utility modeling has become the norm (Maes & Faber, 2004). In decision-making risk aversion could mean that if a problem is framed based on losses, e.g., if a doctor suggests that a patient should stop smoking by saying "if you do not stop smoking you could risk getting lung cancer" rather than on gains "you will feel much healthier if you stop smoking" it is more likely that the patient will appreciate the advice from the doctor if the problem is framed based on losses rather than due to the gains associated with the advice. One exception to risk aversion has been shown in gambling, where people tend to be willing to spend more money on a gamble than expected value would suggest. This could be argued to be due to loss of opportunity associated with not gambling, thus still being risk averse. In decision-making, problem framing combined with the aversion of risk could be a hazard as it can bias the preferences of both decision-makers and stakeholders.

11.1.1.8 Status Quo bias

A consequence of loss aversion is the status quo bias. This bias suggests that individuals are inclined to choose the status quo, i.e., to stay in their current situation, even if equally good or slightly better options are available. It is the disadvantage associated with moving from option A to option B that is the source of the status quo bias (Kahneman, Knetsch, & Thaler, 1991). The

consequence of the status quo bias is that individuals tend to prefer small over large changes from the status quo, which might not be optimal in decision-making.

11.1.1.9 Endowment effect

Another consequence of loss aversion is the endowment effect described by (Kahneman, Knetsch, & Thaler, Anomalies, 1991).The endowment effect is a cognitive bias individuals have towards valuing possessions more than the selling price would suggest. In that sense, individuals have two values for the same item, i.e., one value if they possess it, and another value if they want to buy it – this is in contrast to standard economic theory which implies that an item's buy and sell value should be the same. The consequences when under the endowment effect in decision-making could be inefficient management of resources or wasted opportunity.

The biases listed above are just a few of the biases that decision-makers and stakeholders can be prone to adopt in their judgements. The biases described above are chosen based on what is being described later in the thesis.

11.1.2 Logical fallacies

Logical fallacies can be understood as a misapplication of logical arguments.

11.1.2.1 The sunk cost effect

The sunk cost effect is the tendency to continue ventures, even if those ventures do not possess value once resources has been invested. (Baron, 2004) argues that the sunk cost effect could be explained overapplication of the normative rule not to be wasteful. The main findings of sunk cost effect are also described by prospect theory (Kahneman & Tversky, 1979), i.e., in decision-making the sunk cost effect could mean that decision-makers are wasting resources on behalf of themselves or the stakeholders.

11.1.2.2 Bandwagon fallacy

The bandwagon effect is the tendency of individuals to conform with the group, even if the individual’s belief should suggest otherwise. This conformity could be towards perception, opinions, or actions, and has been confirmed by (Asch, 1961). Asch suggests that the pressure of social influence, had several influences on individuals via different mechanisms:

1. Distortion of perception:
   In this category individuals was not aware that their perception had been distorted under the stress of group influence, thus judging group perception to be correct.
2. Distortion of judgment:
   Most individuals in the experiments done by Asch belonged to this group - individuals were convinced that group perception was superior to their own, this was primarily due to doubt and a lack of confidence.
3. Distortion of action:
   In this category individuals were confident in their own perception and judgment, however, due to a need to not be indifferent or to be perceived as being wrong in the eyes of the group they behaved in conformity with the group, thus violating their own belief and judgment.

In decision-making the bandwagon effect can cause decision-makers or stakeholders' preferences to be influenced by group pressure.

11.1.3 Information hazards

11.1.3.1 Hazard: Incomplete information

The hazard of incomplete information expands on a general level as to everything a person knows is based on a representation of the world produced by the cognitive mechanism known as mental models. The mental models are subjective and unique for each person; thus, each person perceives, remembers, and interprets everything in his/her own way according to these models. That is to say, knowledge generated by people is never totally accurate and free of biases; aleatory and epistemic uncertainties will always exist.

11.1.3.2 Hazard: Failure in identifying the origin of information

As seen in Figure 34 (Nielsen, Glavind, Qin, & Faber, 2019), two different systems, system 'X' and system 'X^', provide similar information to 'I' caused by different actions. To manage the systems 'X' and 'X^', there is a need for a clear distinction between the origin of information related to the systems. Actions impacting system 'X' will be different from actions impacting system 'X^'; consequently, the states and the management options will be different for each system. This makes the causal relationships of information an important, if not critical, venture to pursue in decision-making.

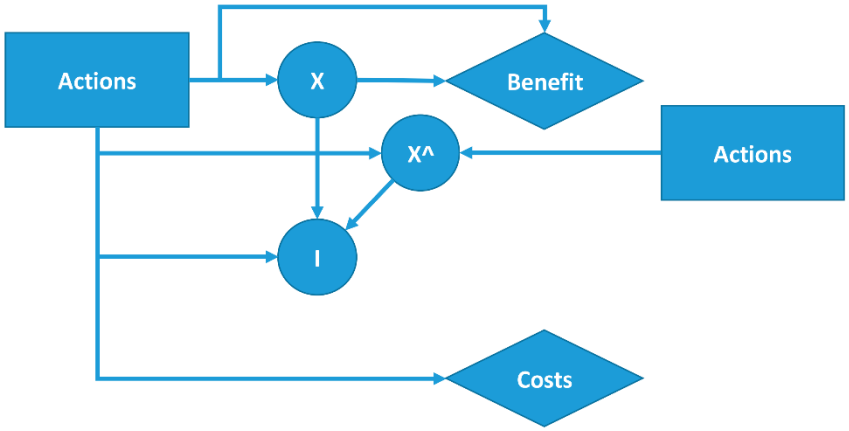

Figure 34: Illustration from (Nielsen, Glavind, Qin, & Faber, 2019).

The identification of causal relationships in the system is important, as correlation is easily mistaken for causality in many cases. Using information that originates from a different system than the decision context system in decision-making could result in hazards related to the third category of information, i.e., information that is irrelevant for the decision context system.

11.1.3.3 Hazard: Information asymmetry

Information symmetry is a state where all entities involved in a given situation know the exact same information. An information asymmetry in decision-making is formed when a different amount or different conditions of information are available to stakeholders and/or decision-makers involved in a decision.

Information asymmetry can be a problem when stakeholders have to state their preferences to a decision-maker as their preferences will be less informed than the preference could be. There may be experts with access to parts of the available information and a limited number of decision-makers who have access to the full information about a decision problem. The rest of the stakeholders could be presented only with fragments of the full information from, e.g., a press release, executive summary, etc. By this, the decision-makers may control what information should be presented to the stakeholders; thus, the stakeholder(s) preferences might be based on limited information and not the full available information the decision-makers possess.

Furthermore, information asymmetry can be a hazard where transparency in decision-making is of importance. By presenting only parts of the full information, the decision-maker can manipulate what information is available to stakeholders. This manipulation might serve to the decision maker's advantage. By this, the information asymmetry could cause a lack of transparency in how the decision-makers act and, furthermore, could cause issues related to the power dynamics in the system of governance in the three categories, respect, trust, and cooperation among the stakeholders (Nielsen & Faber, 2021).

On the other hand, the decision-maker might not be able to acquire complete information due to knowledge gaps or time limitations when deciding upon a decision alternative. Reports can be created by experts on the assumption of what is perceived as valid information for the decision-maker (as described in heading 5.4). These reports can be specialized and may not be accessible for the decision-makers in terms of understanding the totality of information herein. Lack of comprehension could be evident in cases where decision-makers have to make decisions within domains in which they are not experts. Thus, the reports are often simplified and condensed to the essentials of what experts perceive as necessary information for the decision-maker, with details or parts left out. The hazard here is that the expert's assumption of what is sufficient knowledge might not be sufficient from the perspective of the decision-maker. Such hazards could occur in situations where experts provide information and decision-makers receiving information perceive the decision context system differently.

In summary, information asymmetry can go both directions; the decision-maker's considerations towards the stakeholders' preferences depend on how informed the decision-maker is about the stakeholders' preferences. In turn, the stakeholders' judgment of a decision might be warranted or unwarranted depending on how informed the stakeholders are about the decision process or outcome. Depending on the decision context, decision-makers could have more information than the stakeholders and vice versa. The potential consequence of information asymmetry could be decisions or judgments of decisions made with incomplete information.

11.1.3.4 Hazard: Not acquiring relevant and precise information

People's perception of information varies based on how each individual brain's cognitive processes work (including memory), and because different information is available to different people, biases are introduced. Biases like the availability and confirmation bias (see heading 11.1.1) introduce a bias towards the decision-makers perception of the decision context system (Maes & Faber, 2004) which makes it difficult for the decision-maker to represent the views of stakeholders (Maes & Faber, 2007). The decision context system can, therefore, be perceived differently from stakeholder to stakeholder and from stakeholder to decision-maker. The process of defining the decision context system depends on acquiring as much relevant information as possible. However, this information is not always available for the decision-maker. Some information could be bought by, e.g., hiring an expert, researcher, or buying a specific dataset. Other information could come from conducting experiments. Either way, the information could come at a monetary cost, and if the monetary cost is perceived to be too high compared to the perceived benefit from acquiring it, the information might not be included in the decision-making process (see headings 9.2.2.4 and 9.2.2.4.1). There is also the possibility that some relevant information is not possible to acquire by any means, or that uncertainties make the information too imprecise to depend on.

By including some, but not all available information, the decision-making process would be influenced by information that is relevant but imprecise (category 2), as described in header 5.3.2 (Maes & Faber, 2004), (Nielsen, Glavind, Qin, & Faber, 2019). Even if the decision-maker decides to purchase information, there might be a reliance that the information is applicable and can be utilized for the decision-making context. The availability and confirmation bias could have a role in the hazard of requesting irrelevant information (category 3), simply because the decision-maker thinks he/she knows what kind of information is best suited for the decision problem.

The influence of the before-mentioned biases could potentially leave the decision-maker with irrelevant information at a high monetary cost. The hazards described above can be condensed to applying relevant but imprecise or irrelevant information in the decision-making process.

11.1.3.5 Weighting of information

(Tversky & Kahneman, 1974) found a tendency for people to assign higher weights towards the information that they have heard about recently. This tendency is related to the availability bias, as described in header 11.1.1. People assess probabilities or frequencies of specific instances by the ease with which the information comes to mind.

When trying to manage a decision problem, the system that is being managed is modeled in some way. Either by normative standards or simply by mental models. The modeled system is updated consciously or unconsciously whenever new information about the decision context system is being provided.

Because of the tendency to assign higher weights to recently available information, a consistent framework for dealing with information is required. Bayesian decision theory (see heading 9.2.2.4) provides such a framework. By the influence of the availability bias in combination with not adhering to Bayesian decision analysis, the hazard could be that some information is given too much weight in the system modeling. (Tversky & Kahneman, 1974) suggests that new information is often given too much weight in judgment.

11.1.4 Hazards related to memory

When identifying hazards about memory, it is relevant to investigate why and what people remember to get an idea of what is stored in the mind as long-term memory and what is disregarded as short-term memory since this potentially can reveal hazards. Through the evolution of humanity, it has been important for the human race to remember what kind of animals were dangerous, what plants could be eaten and not eaten, where drinking water and food were located, etc., in order to sustain life. Because of this (Kroneisen & Erdfelder, 2016) argues that humans are exceptionally good at remembering information that has been used to survive over generations. However, in this thesis, the sustention of life in the context of human evolution is not necessarily relevant.

11.1.4.1 Hazard: Distortion of memory

(Nairne, Thompson, & Pandeirada, 2007) and (Elizabeth, 2007) argues that one explanation to why this information is stored in long-term memory is due to emotion, i.e., if people experience something in a context where emotion is present, it is more likely that this is stored in long-term memory. However, the long-term stored memory is vulnerable; when memory is stored, and people recall it in a context outside of where it was acquired, the memory can be distorted; an example of this is when people mix memories of events that happened before or after the memory was stored with the 'actual' memory. By this, memory is vulnerable to interferences from other experiences; information bits are added or reduced from the memory when experiencing new things or recalling old memories (Roediger & Gallo, 2016).

11.1.4.2 Hazard: Misinformation

As demonstrated by (Loftus & Palmer, 1974), and (Loftus, 1975) misinformation can be planted into long-term memories by asking misleading questions. Misinformation planted in long-term memories can result in people thinking something that happened which did not or what happened was of a more or less serious nature. Misinformation is easier to plant into long-term memory depending on how long time has passed since the memory was conceived; the original recollection becomes less accessible as time passes (Pickrel, McDonald, Bernstein, & Loftus, 2016). Moreover, if people have a hard time recalling specific information from memory, it is easier to plant different information (misinformation) into the memory of the person who cannot recall it (McCloskey & Zaragoza, 1985).

11.1.4.3 Collective memory hazards

Collective memory is subject to incomplete information, i.e., we only have the information from the past which has passed the test of time. By this, there is a selection bias in the constituents of the current collective memory. There have been several historical instances where information from the past has been purposely destroyed or manipulated by cultures that did not want that information to pass down to future generations. Furthermore, information from the past could be lost due to a host of reasons. For decision-makers, conclusions made based on the available information from the past could be subject to errors in interpretation due to incomplete information or logical fallacies and biases, such as information framing, availability bias, and the bandwagon fallacy (explained in section 11.1.1 and 11.1.2). The information which has survived and is available could be subject to category 2-5 of information, i.e., it could be relevant but imprecise (2), irrelevant (3), relevant but incorrect (4), or disrupted/delayed (5). In general, it is a hazard not to recognize the limitations on conclusions based on collective memory, especially the further back in time the information that constitutes the collective memory has its origins.

11.1.5 Preferences hazards

When a decision-maker collects information about preferences from a group of stakeholders, he/she gain insights towards what decision alternative is most preferred by that specific stakeholder group. However, if the decision is applied in a context where a different stakeholder group is present, the collected preferences (information) might be relevant but imprecise (see heading 5.3.2) towards the decision. This condition of the preference (information) can be because the preferences collected were only from a snippet of the overall stakeholder group or because the stakeholders have acquired new information that alters the preference.

11.1.5.1 Hazards in stated preference

When individuals state a preference, it is based on their current knowledge. After stating a preference, the individual could gain further insights into the decision context, and thus the stated preference could change. If decision-makers apply stated preferences into the decision-making process, it might be hazardous due to the uncertainties of a stated preference (a stated preference does not necessarily, predict what a stakeholder will do). The decision-maker might utilize stated preferences that have changed, rendering the information derived from the stated preferences irrelevant or incomplete (see heading 5.3.2).

Stated preferences can also be used in the context of malevolence, e.g., if a decision-maker has a specific objective, he/she could state a preference towards something other than what he/she actually prefer because he/she would know the influence the stated preference could have on the state of the system. This ‘false’ stated preference could steer the stakeholders in a certain direction. An example of this has been given in heading 10.2.6, where it is shown how decision-makers stated preference could influence the state of nature.

11.1.5.2 Hazards in revealed preference

When individuals reveal a preference, it is, like the stated preference, based on their current knowledge. After revealing a preference, the individual could gain further insights into the decision context, but the specific already revealed preference cannot change. Decision-makers applying revealed preference into the decision-making process collect their data on descriptive data of what individuals or groups have already done. Depending on the application of this information, the hazard can, e.g., be that the individual, who already revealed a preference, might gain new insights that could influence the individual to reveal a different preference next time.

There is a possibility that revealed behavior might not be a good representation of preferences. A certain behavior could be due to other factors such as, e.g., a necessity rather than preference. In those situations, revealed preference could be misleading, and labeling behavior as a proxy for preferences without knowing the reason behind that behavior could be hazardous. To give an example, a person might choose to use the bicycle rather than the car, not because the person prefers the bicycle, but simply because the car is broken. In that case, revealed preference might suggest that the person would prefer to use a bicycle rather than a car. Thus, identifying the system encompassing the behavior and mapping the incitements behind the specific behavior might be of value in preference analysis.

11.1.5.3 Hazards in informed preference

As mentioned earlier (heading 9.4.6.3), informed preference is defined as a scale of how informed the decision-maker is about the decision context. The hazards related to the informed preferences are as described in heading 11.1.3.

11.1.5.4 Preference reversal hazard

The process in which an individual is presented with decision alternatives affects the preference ranking made by the individual. The preference might change (reverse) based on how the decision alternative is presented (Lichtenstein & Slovic, 1973). This preference change/reversal is related to the framing effect as described in heading 11.1.1.3. Furthermore, the less-is-better effect shows preference reversal when decision-makers view decision alternatives jointly rather than separately. The less-is-better effect has shown that when decision alternatives are examined individually by decision-makers, rather than in the relation with other decision alternatives, the decision-makers pay less attention to important features and are more affected by what is easy to evaluate, resulting in different rankings when decision alternatives are considered jointly and separate (Hsee, 1998).

11.1.5.5 Preference hazards in relation to ethics

11.1.5.5.1 Utilitarian preference hazards

When making a decision that affects many stakeholders, the individuals' opinions are aggregated into a pool, and a conclusion is derived from what seems to benefit most. This aggregation is the utilitarian approach, and by this, the decision-maker introduces a hazard towards misrepresenting the individuals' views for the better of the group. The hazard occurs when a decision-maker has the objective to do what benefits the most consequently not taking individual preferences into account. Furthermore, statistical challenges might occur when only taking the mean value of the group's preferences into account rather than the mode value of the preferences, as the mean might not be the preferences of any individual of the group.

By basing a decision on information derived from preferences, aggregating it into a pool, and concluding on something specific can introduce the hazard of overstepping the decision-makers or the stakeholder's own moral principles or the ethical principles of the group. The utilitarian principle focuses on the end (thus, not the means to the end); the approach accepts all consequences as long as what happens, in the end, brings the most utility.

11.1.5.5.2 Deontological preference hazards

The different branches of deontology are described in heading 9.4.4.2. All branches of the deontological preference to decision-making consider the means to get to the objective higher than the objective itself. The means considered in the deontological views are the individuals' own perception of duties, obligations, and rights as described in heading 9.4.4.2. The hazard occurs

when a decision-maker has the objective to consider all stakeholder's subjective perceptions of duties, obligations, and rights and make sure the stakeholder's consent to the decision alternative selected. The task of considering all stakeholders perceptions can be a burdensome affair in terms of the resource that would need to be allocated for the collection of this information, and even impossible in some cases since some individuals might not be able to state their consent due to e.g., mental illness or physical conditions. Moreover, the consideration of stakeholder consent and the resulting decision-making constraints can decrease the management options severely for decision-makers.

11.1.5.5.3 Time-related preferences and deontological ethics

Decision-making that has consequences for future generations is based on assumed preferences for future generations. The hazard is that the preferences in the current time of decision-making might not be identical to the preferences over time due to the changing world. For a decision-maker who follows deontological ethics (especially the patient-centered), decision-making for the future generation would not be possible since the future generations (who are not born yet) cannot be asked to consent to the decisions.

11.1.5.5.4 Time related preferences and reputation

If a decision-maker or stakeholder is asked about their opinion towards a solution of a decision problem, and the decision problem was to be managed now, their stated- or revealed preferences towards a solution might be different, than if the decision problem were to be managed in, e.g., several years from now. In societal decision-making a decision-maker is often elected for a specific period whereas, the decision-maker has an incentive to optimize their election period by stating and revealing socially accepted preferences with high popularity that can be measured within the election period. The hazard about the time related preference is that preferences can be stated or revealed at non-optimal times for the society, but in optimal times for the decision-maker to gain popularity and therefore, a good reputation among stakeholders. The decision-makers objective towards popularity and good reputation could have a negative outcome for the stakeholders.

11.1.6 Hazards related to semantic problems with knowledge framing

Important decisions are often based on the knowledge acquired through research. However, there is a hazard that this research can lead to false and/or biased results resulting in a false knowledge/information base for decision making. As mentioned in header 5.4, a range of different terms is being used across various industries in various ways, and there seems to be no common definition to utilize these terms.

11.1.6.1 Hazard: Interpretation of undefined terms

The terms that constitute ‘valid knowledge’ (as described under heading 5.4) are often applied to represent that a recognized methodology is utilized within the research. However, the missing definition causes a direct consequence as to using the knowledge based on a potentially false premise. The hazard is that the stakeholder will interpret the terms based on how the stakeholder perceives the term. This is referred to as confirmation bias, where the stakeholder interprets, focuses on, and remembers information in a way that confirms the stakeholder’s prior experiences with the term (Kahneman, Lovallo, & Sibony, 2019). The indirect consequences caused by the direct consequences may be the effects of a wrong decision being made. To exemplify this, assume a manufacturer whose main goal is to earn as much money as possible. The manufacturer is producing a lotion and claims the product has the ability to remove wrinkles. The manufacturer knows that if he/she could prove that the product works, he/she would sell more. Thus, the manufacturer needs evidence that the product is working. Learning that the term is not well defined, the manufacturer goes for the cheapest option for something to be evidence-based. The manufacturer hires an expert to give his/her opinion on the composition of ingredients and by this receiving a statement from the expert. The manufacturer can now utilize the information asymmetry between him/herself and potential customers, and say the product is evidence-based based on the lowest level of the hierarchy of evidence (see Figure 1).

11.1.6.2 Hazard: Misinterpretation of information

When policymakers make decisions about laws/regulations, they rely on what their advisors tell them. The policymakers have to do this since they are not experts in a specific field more often than not. This means that when the advisor presents evidence to support a decision alternative. The evidence's quality depends on the advisor's knowledge and perception about how the terms are used. This is also known as the halo effect, where an error is made based on how people perceive a phenomenon, i.e., their mental model of this phenomenon. The advisor may judge the

evidence to be valid because a specific term was used if his/her mental model of the term was modeled so that when these terms are used, it is valid scientific evidence based on valid points. On the other hand, if the advisor had a mental model that suggests these terms are used to manipulate the audience to believe something, the cognitive bias, known as the horn effect (or reverse halo effect), would come into play.
The horn effect would suggest that the advisor is aware of the issue with defining the term and therefore frown upon research using that term.

The halo and horn effect could cause a potential hazard to the system as the decision-maker might not be presented with the best available information.

As long researchers do not define what they mean when they use terms related to knowledge framing, and as long as there do not exist any formal definitions to rely on, the hazard of misinterpretation and potentially applying wrong or lower quality knowledge than expected to a decision problem will exist. Researchers could potentially imply different meanings on the same terms and, thus, be working in different directions. During the literature review, it was observed that the terms related to knowledge framing were rarely defined. The only option for stakeholders, to understand the meaning of the terms related to knowledge framing, is to interpret the sources individually to identify what is meant in each specific case.

11.2 Identification of hazards related to elements in the taxonomy

11.2.1 General hazards related to principal approaches

When having to make a decision, two different overall approaches have been described along with four sub-approaches. This short section focuses on the two general overall approaches, structured and non-structured. The hazards related to using a set of pre-defined principal approaches can be derived from the cognitive biases known as confirmation bias and status quo bias. These two cognitive biases may be present in that the decision-maker, who must utilize an approach, might be inclined to look at what is known already and thus, do not explore the possibility of a new approach that could reveal a potentially better decision process along with a potentially better outcome.

11.2.2 Hazards related to structured principal approaches

This section focuses on one of the two overall approaches, the structured approach in general. Hazards related to the structured approaches on an overall level could be the limitation in the options for a decision-maker, as described in the section above. Thus, there is a hazard that a different approach would have suited the situation better, and the decision-maker has a limited ability to maneuver freely. If a structured approach is followed, the person who uses this approach does not have the option to utilize the options from a different approach, even if it seems like a better idea. This lack of appreciation of different options is also described as a status quo bias, where the person using the approach is excessively dependent on a well-known technique or procedure, with alternative options being ignored or undervalued.

11.2.2.1 Hazards related to utility theory

The theory of expected utility (as described in heading 9.2.1.) In this section, the hazards related to the EUT are described.

11.2.2.1.1 Von Neumann & Morgenstern's axioms

If the Von Neumann & Morgenstern axioms are violated, there is no utility function to start with (Von Neumann & Morgenstern, 1953). The violation of an axiom, i.e., not satisfying the four axioms (as described in header 9.2.2.1), could mean using relevant but incorrect information. The hazards related to the violations of the axioms can therefore be found in the hazards related to the five conditions of information described in header 5.3.2.

11.2.2.1.2 Violation of the completeness axiom

The completeness axiom is described in header 9.2.2.1.1. If an individual says he/she prefers the outcome X to Y and at the same time says he/she prefer Y to X and is not indifferent between the two, the completeness axiom is violated.

11.2.2.1.3 Violation of the transitivity axiom

The transitivity axiom is described in header 9.2.2.1.2. If an individual says he/she prefer the outcomes X to Y and Y to Z, and at the same time says he/she prefers Z to X or Z to Y, the transitivity axiom is violated.

11.2.2.1.4 Violation of the independence axiom

The independence axiom is described in header 9.2.2.1.3. If a person considers several outcomes from several decision alternatives, these decision-alternatives have a common outcome. The common outcome should not play a role in ranking preferences; if it does, the independence axiom is violated.

11.2.2.1.5 Violation of the continuity axiom

The continuity axiom is described in the section Continuity. If an individual says he/she prefers the outcomes X to Y and Y to Z and can put a unique probability to when he/she has these preferences, the continuity axiom is not violated. The violation happens when the individual cannot state a probability or have the same probability for two outcomes.

11.2.2.1.6 Risk aversion towards professional and personal negative consequences

The decision-maker's risk aversion poses a hazard to the decision-making process and the outcome of a decision. When decision-makers make a decision on behalf of a larger group, the decision-maker has to consider the hazards related to reputation, as described in heading 11.2.7.2.1. Depending on the decision context, the decision-maker can receive more or less attention from the stakeholders towards what decision alternative is selected. If the amount of attention towards the decision-maker is high, the decision-maker could be motivated to devote more resources to initiatives that have a low likelihood but high consequences. This motivation

could be due to popularity; high consequence events with low likelihood could cause more popularity than events with high likelihood and low consequences. The amount of attention from the stakeholders can come from various factors. These factors could be how much knowledge and dread the stakeholders have towards a specific hazard, as described by (Slovic, 1992). The decision-maker's motivation towards the allocation of more resources to initiatives that have a low likelihood, but high consequences can result in a potential opportunity cost where the stakeholders' resources are not being utilized to their best potential. Instead, the resources could be used as insurance for the decision-maker to mitigate his/her professional and personal negative consequences (Faber, Schubert, & Baker, 2007).

11.2.2.1.7 Incompetence

A hazard when applying the utility theory on a decision problem is also incompetence, i.e., how knowledgeable and, thus, the person is at applying the different steps in the process.

11.2.2.1.8 Hazard: Difference in the assessment of monetary value (cost/benefit)

The perception leading to what the decision-maker thinks of as the decision context system (see heading 10.1) defines what could be gained in terms of monetary value and benefit from the different decision alternatives. In a cost/benefit analysis, in regard to monetary value and benefits assignment to decision elements are not easily calculable in terms of money, e.g., the value of life, inconvenience, discomfort, impact upon the quality of life or upon the environment (Maes & Faber, 2007). There is a hazard that the decision-makers and stakeholders might have a different perception of how much the abovementioned, not easily calculable elements are worth. This difference in perception could be due to differences in objectives, perception, or information asymmetry between stakeholders and decision-makers. The process of defining the decision context system is an aggregation of the perception of the presented information available to the decision-maker, the memory of the decision-maker (see header 5.3.3), and the ethics defined by stakeholders, as seen in Figure 16.

11.2.2.1.9 Not utilizing prospect theory

As described in heading 9.4.6.5, Kahneman and Tversky argue that people perceive gains and losses differently relative to a reference point. Given the nature of the prospect theory, it tries to describe how people, in general, make decisions based on loss and gains, whereas the normative model of expected value (Bernoulli, (1738) 1954) tries to explain how individuals should,

theoretically, value gains and losses. If the prospect theory is not utilized in decision contexts where people's perception towards loss and gain is considered, the decision process could be built upon relevant but imprecise information (see heading 5.3.2).

11.2.2.2 Hazards related to the precautionary principle

This section focuses on the precautionary principle, which fits under the sub-category of structured approaches. As described in heading 9.2.2.3, the precautionary principle is the principle of "being careful in advance". The principle is frequently used in situations when particular preventative steps are taken to avoid or mitigate the effects of a threat before it occurs.

An exposure event can cause a system change. The system change can be observable, but the decision-makers might not know or have limited information about the direct and indirect consequences and how these are formed. Thus, the precautionary principle can be invoked.

11.2.2.2.1 Doing more harm than good (opportunity cost)

By invoking the precautionary principle, the decision-maker might have concluded that the knowledge base for other approaches is insufficient. The lack of information in the knowledge base can be the reason for invoking the principle but also poses a hazard in itself. Implementing a precautionary measure to mitigate the consequences of the exposure event. However, the aleatory and epistemic uncertainties associated with the information about consequence and probabilities of the exposure event could be high. Potentially, by not implementing a precautionary measure, the total negative consequences would have been smaller than by invoking it. It might be indicated as new information about how the exposure event influence the system is verified and recognized as "valid knowledge" (see under heading 5.4). Consequently, it could turn out that a different approach would have been more optimal.

In risk management, the precautionary principle might be costly and could lead to an overall decrease in risk reduction of the system that is being managed. This could happen when evoking precaution towards an income-generating endeavor, where risks are relatively small. The total risks within the system would, in that case, be increased due to the opportunity cost by not having the income available for risk reduction elsewhere in the system, where they could potentially make more of a difference. Consequently, the decision-maker would not be using resources in contexts where the most amount risk reduction per unit of resource is achieved.

When implemented on the strictest level by, i.e., not accepting even the smallest risks, the precautionary principle can lead to an inability to act and, in a sense, become paralyzing to societies wanting to innovate by solving problems in a new way. This inability to act could

potentially reduce the advancement of societies in general and decrease the overall incitement towards innovation.

11.2.2.2.2 Reputation and judgment

In continuation of the section above, the decision-maker could be judged by stakeholders on the knowledge that is available at present but was unavailable during the decision-making process. This judgment could originate from the cognitive bias known as the hindsight bias (described in heading 11.1.1.6).

11.2.2.2.3 Disregard of information

When decision-makers and stakeholders have formed an opinion about the decision context system e.g., potential harm to the system caused by an exposure event, they could be inclined to stick to that opinion even when new information suggest otherwise; this could originate from the cognitive biases known as confirmation bias (described in heading 11.1.1.2), the status quo bias (described in heading 11.1.1.8), and the endowment effect (described in heading 11.1.1.9). However, Decision-makers and stakeholders could also unconsciously focus more on the new information than the old information through the availability bias (described in 11.1.1.3), and by this, making it more difficult to remove e.g., the precautionary regulation and introduce new regulation based on new information. In summary, decision-makers and stakeholders can be biased towards old and new information through different mechanisms.

11.2.3 Hazards related to non-structured principal approaches

This section focuses on one of the two overall approaches, i.e., the non-structured approach. Hazards related to the non-structured approaches on an overall level could be the inconsistency in methods and a lack of transparency to stakeholders.
When utilizing a non-structured approach, it can be difficult for other people to reproduce the evidence.

11.2.3.1 Hazards related to the anarchy principle

This section focuses on the anarchy principle, which fits under the sub-category of non-structured approaches. The anarchy principle is, as described in heading 9.3.1, the principle of resisting power and in decision-making relates to alterations in the decision-maker's available actions.

11.2.3.1.1 Idleness

The principle was, in heading 9.3.1, divided into two different sub-categories, intentional use and unintentional use. The intentional use of the principle is characterized as being idle, i.e., letting an exposure event happen without interfering. By being idle, the exposure event will have an undisrupted ability to change the system in according to either (i) nature (related to natural phenomenon) or (ii) objectives (related to human objectives). From the perspective of an anarchist, this is not a hazard, as their preference is not to act. However, if the decision maker's preference is to mitigate the consequences of the exposure event, idleness would be a hazard.

11.2.3.1.2 Human cognition

The unintentional sub-category is based on human cognition using mental models, as described in heading 9.3.1. The hazards related to human cognition can be found in the cognitive biases described in heading 11.1.1.

11.2.3.2 Hazards related to the ad-hoc principle

This section focuses on the ad-hoc principle, which fits under the sub-category of non-structured approaches. The ad-hoc principle is, as described in heading 9.3.2, an adaptive and iterative principle where decision-makers use whatever approach seems necessary or needed based on their judgments when dealing with a decision problem.

11.2.3.2.1 Unpredictability hazards

Not sticking to a specific approach of making decisions can make decision-makers seem unpredictable in their approach. The unpredictability in the ad-hoc principle could make it difficult for stakeholders to scrutinize the decision-making process. Depending on the context, this could be related to one or more of the information categories, e.g., number 5, i.e., the information is disrupted or delayed. From the decision-maker's point of view, this lack of predictability can be both a positive and a negative depending on whether predictability is a criterion for success or not. It can be imagined that decision-making processes are not suitable, from the point of view of the decision-maker, for stakeholders to scrutinize. This could be the case in affairs in the intelligence communities or in military operations where predictability could be taken advantage of in a malevolent way, especially when there is a conflict of interests between stakeholders and the decision-makers. In these cases, predictability can lead to undesirable consequences.

On the other hand, unpredictability might be a hazard in some ventures, e.g., where shared resources between stakeholders and decision-makers are at stake and risks of malevolent activity based on predictability are low. The unpredictability of the ad-hoc principle might not be suited in cases where decision-makers are expected lawfully or by stakeholders to follow normative standards in the decision-making process. This could be the case where trust is a factor of concern, such as in the banking industry, where resources are stored on behalf of customers.

11.2.3.2.2 Judgmental hazards

When using the ad-hoc principle, the decision-maker can shift from one method to another based on judgment. The judgment of which method to apply in a specific context will largely depend on the attributes of the decision-maker. The attributes impacting the judgment of a decision-maker shifting approaches could be influenced by:

1. Experience with the ad-hoc principle
2. Knowledge about the system that is intended to manage
3. Perception about the system that is intended to manage

1a) If the decision-maker lack experience and therefore does not have the competence required in using the ad-hoc principle, he/she might not choose the appropriate method for the decision context that he/she intends to manage.

2a) When using the ad-hoc principle, the knowledge of the system the decision-maker intends to

manage could be subject to incomplete information. A lack of information about the system that is intended for management will result in less informed preferences for the selection of approach. This is especially a hazard when the decision-maker is not using the appropriate normative standards in the collection of relevant information for the given decision context.

3a) Even if knowledge about the system that is being managed is acquired is perceived to be sufficient, that information could be subject to information hazards as described in header 11.1.3.1. The relevant information hazards will depend on the decision context and could result in an inaccurate system identification by the decision-maker. An inaccurate system identification could lead to a less informed preference on which method to apply for the given decision context. As described earlier (see header 11.1.1), cognitive biases could also interfere with the perception of the system and thus the judgment of which method to apply for the given decision context. Cognitive biases such as the availability bias, confirmation bias, and the endowment effect could be hazards in the preference ranking of methods. Moreover, logical fallacies could impact how the decision-maker reaches conclusions when dealing with information and thus impact which method to apply to in a given context.

11.2.3.2.3 Evaluation hazards

When switching methods using the ad-hoc principle, there might not be a sufficient foundation for the decision-maker to evaluate his decisions or to juxtapose his decision-making with other cases within the same domain. Reaching meaningful conclusions when evaluating decision processes and their related outcome can be problematic even without shifting methods, as it can be subject to logical fallacies and cognitive biases. The shifting of methods could further complicate this matter and could increase the probability that logical fallacies and cognitive biases will be present. This can result in a low quality evaluation of whatever methods the decision-maker has used, as it might be challenging to comprehend the relationship between the methods applied ad-hoc and how each method influences the decision-making outcome.

11.2.3.2.4 Hazards in tactical/strategic mode

In tactical situations, there is a risk that problem framing, and information asymmetry combined with a sense of urgency could create fear among stakeholders, leading to excessive risk aversion. This risk aversion could change the preferences of stakeholders, especially if a problem is framed on losses (see heading 11.1.1.7) and the stakeholders do not have the same amount of information as the decision-maker. These factors could create room for decision-makers to use

more agile, unstructured approaches such as the ad-hoc principle to increase agility in decision-making. The shift in approach and risk appetite could be justified in the eyes of the stakeholder if the problem is framed as being sufficiently severe. So could the shift from being participatory being to being non-participatory. Because the ad-hoc approach is generally not as transparent as structured approaches, there is a hazard that decision-makers could push personal or strategic agendas rather than maximizing the utility of the stakeholders. The outcome of these decisions would likely not follow the expected value of utility and would have a large impact on stakeholders. The direct consequence would, in retrospect and from the point of view of the stakeholders, be unacceptable decisions from the decision-maker. Indirect consequences would be trust issues between stakeholders and decision-makers.

11.2.4 Hazards related to consequence modeling

This section will not describe general hazards but specifically focus on what is relevant for consequence modeling.

11.2.4.1 Stated preferences

As (Maes & Faber, 2007) describe, decision-makers can have diverse preferences regarding consequences. This divergence in preferences can lead to the consequence of a wrong or biased process when defining the consequence model and, as an indirect consequence, the wrong outcome of a consequence model. The reasons for these diverse preferences are described elsewhere within this thesis and thus are referred to. The reasons which are not already described will be outlined here:

- Decision-makers fail to act “rationally”, see sections under heading 9.2.2.1.
- Decision-makers do not act in good faith and show personal and professional bias, see heading 11.1.1.
- Decision-makers do not respect the rules of preference ranking; see heading 9.2.2.1.1.
- Decision-makers appraise specific consequences in different ways; see heading 11.2.4.2.
- Decision-makers find it hard to represent the views of a large organization or (part of) society; see sections under heading 11.1.1.
- Decision-makers are affected by how preferences are solicited; see heading 11.1.5.4.
- Decision-makers use different, or “home-made” priors in a Bayesian analysis see heading 11.1.3.5.

11.2.4.2 Combination of different consequences

When different decision-makers (or stakeholders) investigate the same exposure event and its related hazards, the decision-makers and stakeholders can have different perceptions regarding the exposure event and thus different perceptions about the consequence of the exposure event. This difference in perception can be due to the mental models and cognitive biases (see heading 12.1.4.1) that form the decision-maker's and stakeholders' opinions about how the exposure event could influence a system and thus the related consequences.
The difference in perception about the consequences can also happen when several decision-makers or stakeholders combine several exposure events and their related consequences. The decision-makers and stakeholders could have different opinions about how the consequences should be ranked.

11.2.4.3 Neglecting long-term and follow-up consequences

The long-term and follow-up consequences can be neglected by decision-makers as described in (Maes & Faber, 2007). However, they are relevant consequences to consider, and failing to do so introduces the hazard of utilizing incomplete information in decision-making. Regarding long-term and follow-up consequences this could pose a host of risks e.g., non-sustainable decisions in society or neglecting stakeholder communication.

11.2.5 Hazards in ethics

This section will describe hazards involved with applying either deontological or utilitarian ethics on a general level. Some hazards, e.g., ethical hazards related to preferences, have already been described earlier in their respective sections.

Generally, ethics will serve as a boundary condition for the available management options. Thus, the hazard will mostly be related to the implications of those. In pragmatic situations, a combination of deontology and utilitarianism ethics is mostly present as boundary conditions.

11.2.5.1 General deontological hazards

11.2.5.1.1 Decreased management options

One of the main hazards involved with deontological ethics for a decision-maker managing a system is that deontological constraints must be respected. These constraints include the rights of stakeholders as well as their consent on any decision that has a direct impact on them. These constraints embedded in the deontological branch of ethics could reduce the available

management options for a decision-maker, thus making it difficult to maximize the utility for most people. For high group populations (see 9.4.1.2), the deontological constraints could be viewed as unnecessary considerations that have a negative impact on the group as a whole.

11.2.5.2 General utilitarian hazards

11.2.5.2.1 Consent and rights

A general hazard for stakeholders in decision-making based on utilitarianism is that decision-makers using utilitarianism does not necessarily take stakeholders' rights and consent into account. For stakeholders, this could introduce a situation where they have no control over the decision that has an impact on them. Not taking stakeholders' rights and consents into account could lead to a decreased utility for individuals depending on the context. Furthermore, the decisions stakeholders must adhere to (e.g., regulation), could potentially be morally unacceptable for the stakeholders. This could potentially be a hazard in high 'low group' populations (see 9.4.1.2). Following the grid/group model, individualist and fatalist groups will tend to prefer instances where decisions are not imposed upon them but would rather engage in society on a voluntary basis.

In pragmatic decision-making in the western world, there will almost always be national and international regulation that will secure the basic rights of humans; however, from a deontological point of view, these rights have to be defined by each individual within society and not by an external regulator.

11.2.5.2.2 Information hazards

When making decisions based on utilitarianism, it is important for a decision-maker to strive for full information about the system that is being managed, as lacking information could lead to decisions that do not maximize the utility.

Other hazards based on information are also relevant; for these, see section 11.1.

11.2.6 Hazards in application

In this section, hazards associated with implementing normative and descriptive approaches in decision-making are discussed.

11.2.6.1 Hazards associated with normative applications of information

11.2.6.1.1 Hazard: Misapplication

A hazard associated with using any information is misapplication. Misapplication could be the result of not understanding how to implement information or applying information for the decision context that is irrelevant, incorrect, imprecise, or disrupted/delayed (information category 2-5). These conditions of information could also be present in the available information on how to apply the normative standard. Furthermore, misapplication of information could be caused by cognitive biases and logical fallacies (see heading 11.1.1).

In unique decision contexts where no normative standard has yet been developed, it can be hazardous to choose related normative standards that are in proximity but do not fit exactly to the decision context. In doing so, there might be a hazard that the chosen normative standard cannot be applied directly with the decision context at hand. The attempt to adjust the standard to the context could be tempting for decision-makers but hazardous if those adjustments have not been scrutinized and accepted by competent evaluators. Self-made adjustments to normative standards could furthermore be subject to cognitive biases and logical fallacies (see heading 11.1.1).

11.2.6.1.2 Hazard: Theory-induced blindness

An overreliance on normative standards could be hazardous as one might not see the limitations of the standard; this phenomenon is often referred to as theory-induced blindness. If a person finds fundamental mistakes in the normative theory/method, they tend to think that there must be a good reason for it and will keep using the theory/method rather than criticizing the theory. This could be due to excessive trust in authorities, which could undermine their own opinion. This is closely related to the bandwagon effect described in heading 11.1.2.2, which shows that people can be convinced to follow the majority opinion, even if their own perception tells them otherwise. This could especially be true in the high group domain in the grid/group model (see heading 9.4.1.2), i.e., hierarchical groups and egalitarian groups where individuals tend to conform with the group opinion and might be opposed to revealing their own perspective.

11.2.6.2 Hazards associated with descriptive approaches

In general, the information used in descriptive approaches can be subject to the categories of information and the general hazards associated with information described in heading 5.3.1 and 11.1.4.

11.2.6.2.1 Acquisition of information

There is a hazard that the selection of relevant information that forms the descriptive model/theory could be influenced by a mental model of the problem context, which can be subject to cognitive biases and logical fallacies. The mental model of what is relevant and what is not relevant could determine what information goes into the descriptive model/theory and what information is excluded.

Another source for the hazardous conditions of information is how the information is obtained. There could be epistemic uncertainties involved in the quantitative measurement of information. These epistemic uncertainties could be due to lack of calibration of the measurement equipment, incompetence of using that equipment, or the ability of the equipment to provide sufficient accuracy and precision in measurements. Another reason could be the misidentification of the sample space, i.e., not including all relevant information, see heading 5.3.2. Depending on the context, there could also be aleatory uncertainties associated with the acquisition of information that must be accounted for in the representation of data. The aleatory uncertainties could be due to variance in phenomena, such as changing weather conditions, daily fluctuations in blood pressure, etc.

11.2.6.2.2 Interpretation of information

When using collected information to form descriptive theories/models, there is a hazard of misinterpreting the results. One of the misinterpretations could be what is often referred to as the illusion of validity, in which individuals tend to overestimate their ability to derive meaningful conclusions from data. This is closely related to the representativeness heuristic (see heading 11.1.1.2).

One of the hazards associated with the interpretation of information is the mixing of correlation and causation. An example could be the interpretation of retrospective cohort studies, as these can only show a correlation between, e.g., exposure and outcome. Interpreting results from such studies as causal could be hazardous as there might be factors other than the exposure event influencing the outcomes of the study. These factors are often referred to as confounding factors. In principle retrospective studies cannot identify in which direction a potential causality flows, i.e., retrospective study designs cannot separate what is the cause and what is the effect. When neglecting the weaknesses of study designs, there might be a hazard that decisions are made on false premises. Furthermore, as these concepts can be hard for laymen to grasp, there is a hazard that weaknesses of study designs can be exploited by decision-makers that want to justify

decisions that otherwise would not be justifiable in the given context. Decision-makers might label these findings as “evidence-based” (see heading 5.4.4) and, e.g., invoke the precautionary principle (see heading 9.2.2.3).

11.2.6.2.3 Misapplication

There is a hazard that the descriptive methods might be misapplied in contexts that do not represent the findings of that method when using a descriptive model about, e.g., human behavior, the data collected might be specific for a certain demographical group; thus, the results might not apply in contexts outside of that group. This could be due to informational hazards such as incomplete, imprecise, or irrelevant information in the descriptive model or due to cognitive fallacies/biases in the application process.

11.2.7 Hazards related to system information

11.2.7.1 Hazards in participatory approaches

11.2.7.1.1 Communication hazards

When decision-makers manage the decision-context system, how those changes are perceived by stakeholders could lead to indirect consequences, e.g., in the form of an outcry if those changes lead to a decrease in utility for stakeholders. Those consequences can be either potentiated or mitigated by the way the decision-makers communicate to stakeholders. Therefore, lack of or inappropriate communication could be a hazard that could increase the indirect consequences of the decision.

11.2.7.1.2 Hazard in tactical situations

A hazard involved in participatory approaches is the speed at which these approaches operate. Compared to non-participatory approaches, decision-making that involves the participation of stakeholders is, in many cases, a slower and more deliberate process. Depending on the decision context, participatory decision-making can be rigid, as the acquisition of preferences can be a lengthy process, and the settlement of potential conflicts in stakeholder preferences must be considered before the decision can be finalized. This hazard is related to the information category number 5, i.e., the information about stakeholder preferences is delayed before any decision can be made. In tactical situations, this could be a problem as the ability for decision-makers to be agile in their decision-making is compromised.

11.2.7.1.3 Hazard: Mix of agendas

In participatory decision processes, such as democracies, the decision-maker should try to maximize the utility for the stakeholders involved. A hazard in participatory decision-making can be that there is a mix of agendas; the decision-maker could be attempting to maximize his/her own utility rather than the utility of stakeholders. When in the process of deciding which approach to apply in decision-making, the different elements influence each other (see heading 10.1). The decision-maker's objectives and preferences could influence the decision-making process to tweak the preference ranking to match the decision-makers objectives better. This can happen due to a conscious decision to behave in a way to achieve personal or professional advancement. Moreover, the decision-maker could be unwilling to update the decision-making models if they fit into his/her narrative of obtaining his/her objectives. These observations could lead to the hazard of not selecting the decision-alternative that provides the highest benefit for most, but rather selecting one that benefits the decision-maker the most.

11.2.7.1.4 Hazards in post-normal science

To extract the biases that could be present in the application of post-normal science, a schematic figure has been made; see Figure 35.

11.2.7.1.4.1 Misapplication of post-normal science

Following the red arrows in Figure 35, it is seen that post-normal science, in contrary to traditional normative approaches, does not lean on traditional views of science, i.e., the “natural sciences” or the “cognitive and social sciences”, but rather preferences stated by stakeholders formed in the before mentioned extended peer communities (see header 9.4.3.1). It could be argued that adopters of post-normal science are using descriptive information about stakeholder preferences as a normative standard. Therefore, it is important that post-normal science is used in contexts where science or political contexts cannot provide the conclusions needed. Following this, a hazard in the use of post-normal

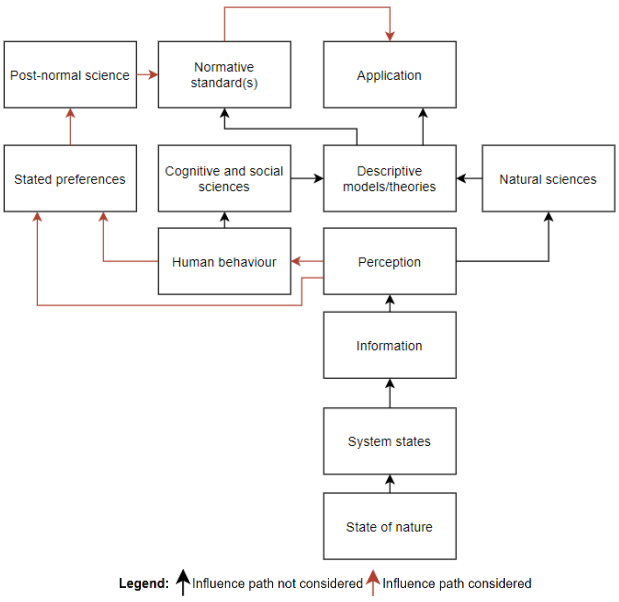

Figure 35: Application of post-normal science (authors’ model).

science is misapplication. This misapplication could, depending on circumstances, be due to informational hazards about the use of post-normal science, i.e., that the information is incorrect or imprecise. Another reason could be logical fallacies or biases in the cognitive process of applying the method.

It is a hazard if post-normal science is applied in a decision context where execution, knowledge, and experience are of importance for a successful outcome. By using post-normal science in such instances, there is a risk that the hierarchy of competence is being neglected, i.e., that laymen's opinion has just as much weight in the ranking of decision-alternatives as expert opinion. Such fields could be structural engineering, medicine, or any field where safety is provided by traditional normative approaches, based on accumulated knowledge and experience, and where dialog with stakeholders makes little to no difference.

11.2.7.1.4.2 Preference hazards in post-normal science

The structure of the extended peer communities and how this structure influences the preferences that are extracted is important to recognize. It could be hypothesized that the normal effects of group dynamics are influencing the jointly agreed-upon preference extracted from the extended peer community. To exemplify this, the grid/group model is used:

In hierarchical groups (see Figure 8), the manner in which the preferences of the group are aggregated from individuals to a joined group preference is important to consider, as individuals could be influenced by the bandwagon fallacy (see header 11.1.2.2). If influenced by the bandwagon fallacy, the aggregated preferences would not accurately represent the preferences of the individuals within the group, thus making the post-normal science less participatory than the method would suggest. It could be imagined that leaders or spokespersons within the group are de facto governing the opinion of the group by way of the bandwagon fallacy. Consequently, decision-makers that use extended peer communities in their decision-making would rely on preferences that are, in fact, not representative of the group.

Egalitarian groups (see Figure 8) that form extended peer communities would be inclined to have the same preferences on the subject at matter. However, these groups could be more inclined to be risk averse, thus making problem framing a hazard. As stated in the header 11.1.1, the problem framing has a large impact on how preferences are formed. Because egalitarians are generally even more risk averse than average, the problem framing could be utilized by decision-makers or

other stakeholders to persuade the extended peer communities based on egalitarians to shift their opinion in circumstances where there are disputed values at stake.

A goal in post-normal science is to form extended peer communities that include the opinions of stakeholders affected by the policy implemented. Thus, another hazard is the selection bias that comes for people joining extended peer communities in the first place, as those people would be entitled to have their opinion represented, while people not inclined to take part in such groups would not. The people not inclined to join groups would typically be in the low group directions of the grid/group model, i.e., the individualists and the fatalists. While these individuals might have something at stake in the problem at hand, their preferences will likely not be taken into account by a decision-maker relying on the opinion of an extended peer community.

11.2.7.2 Hazards in non-participatory approaches

11.2.7.2.1 Hazard: Stakeholder neglect in non-participatory approaches

One of the hazards in the non-participatory approaches is that stakeholders are being neglected or misrepresented in the decision-making. Furthermore, when enforcing decisions upon stakeholders in a non-participatory way, there is a risk that the decision-maker's reputation will be diminished. This could be due to stakeholder neglect or the difference in moral viewpoints involved stakeholders have towards what decisions are acceptable to impose on other stakeholders. Depending on the context, this could have different meanings:

In autocratic or expert-driven systems on a national level, there is a hazard for the decision-maker that stakeholder neglect could cause decreased utility for the stakeholders. This decrease in utility for stakeholders could result in uproar/outcry by, e.g., the stakeholders within the decision-makers domain (e.g., the population) or stakeholders outside that domain (e.g., other nations). This uproar could make it necessary for the decision-maker to invest more resources into maintaining the position of power. These extra investments of resources into maintaining the position of power could lead to an opportunity cost for the decision-maker, i.e., spending resources that could have been used more productively elsewhere to obtain the decision-maker's overall objectives.

From a business point-of-view, stakeholder neglect by the decision-maker (i.e., CEO/ company owner) could, e.g., be expressed as the decision-maker not wanting to invest resources into optimizing working conditions for the employees. Not optimizing working conditions could lead to unsatisfied employees, which could decrease the reputation of the firm, making it harder to recruit

and maintain qualified employees when necessary. Stakeholder neglect could also be towards business partners by not valuing the relationship to a degree where the relationship is terminated.

In autocratic systems on a national level, this decrease in reputation could lead to termination of relationships with other nation-states or sanctions in the form of decreased options or unfavorable pricing when trading on various markets.

Stakeholder neglect might also result in less informed decision-making that would otherwise be possible. By not taking into account the opinion of stakeholders, relevant and precise (condition 1, see heading 5.3.2) information might not be included in the decision process resulting in less informed preferences.

11.2.7.3 Deontological hazards for participatory and non-participatory approaches

A hazard from a deontological perspective is that non-participatory approaches to decision-making violate the need for stakeholders to consent (see 9.4.4.2) with the decisions impacting them.

This is also true in participatory approaches such as democracies, where it is typically the utility of the majority that is being optimized, i.e., the outlying preferences among the population might not be considered when ranking decision alternatives.

11.2.8 Risk acceptance criteria

This section describes the hazards related to the risk acceptance criteria outlined in headings 9.4.2.1 and 9.4.2.2.

11.2.8.1 F-N diagram / farmer diagrams

A representation of a simplistic F-N diagram (farmer diagram) can be seen in Figure 9. The information used to for the estimation of consequences and probabilities in the x- and y-axis can be subject to the conditions of information described in heading 5.3.2. The source for the hazardous conditions, i.e., categories 2-5, could originate how the information is collected and perceived (see more in heading 11.2.6.1).

When an F-N diagram is presented, it is often done in a farmer diagram. Farmer diagrams exist in several variants, one of which is the risk matrix (Faber M. H., 2007). The following sections describe hazards related to the use of risk matrices.

11.2.8.1.1 Range compression hazard

A variant of farmer diagrams is known as risk matrices. The risk matrix is defined by a range of likelihood on one axis and ranges of consequences on the other axis. These ranges are put in an ordinal scale (i.e., a scale with named and ordered variables, but without proportionate intervals within the variables) by naming the ranges (giving it a rating) and ordering them based on the name. To exemplify: consider an exposure event that has a probability of >40% of happening. This range could have the rating ‘6’; if it is in the range of 20% to <=40%, it could have a rating of ‘5’, and so on. The same with the consequences. Consequences in the range of 20 million USD or over can be assigned the rating ‘6’, consequences between 5 million USD and 20 million USD could have the rating ‘5’, and so on.

The expected loss is then calculated by multiplying the ratings of likelihood and consequence, which in turn creates a range compression. A range compression is where consequences and likelihood are turned into a single rating. When turning the two ratings into one, the distance between the ratings in the risk matrix does not represent the actual difference between the expected loss, and by this, it is possible to assign identical ratings to quantitatively different expected losses (Cox, 2008). To exemplify: Consider two exposure events, ‘A’ and ‘B’.

Exposure event ‘A’ is assessed to have a likelihood of 60% of occurrence (likelihood rating ‘3’), and the consequence in monetary value is assessed to be 100.000 USD (consequence rating ‘1’).

Exposure event ‘B’ is assessed to have a likelihood of 15% of occurrence (likelihood rating ‘1’), and the consequence in monetary value is assessed to be 10 million USD (consequence score ‘3’).

The range compressions can be seen in Table 4.

Table 4: Range compression examples

Range compression	Rating 1	Rating 2	Rating 3
Consequences	100,000 USD to <1 million USD	1 million USD to <10 million USD	>10 million USD
Likelihood	>1% to 25%.	>25% to 50%.	>50% to 99%.

By this, exposure event ‘A’ and ‘B’ would have the same expected loss in the risk matrix, however doing the math, the actual expected loss is different:

$$\text{Exposure event ‘A’: } 60\% * 100.000 = 60.000$$

$$\text{Exposure event ‘B’: } 15\% * 10\ million = 1.5\ million$$

11.2.8.1.2 Miscommunication hazard

As described in heading 11.7.1.3, laypeople intuitively understand the F-N diagrams (farmer diagrams); thus, the farmer diagrams are used in a broad spectrum of industries to communicate risk. As described in the section above (heading 11.2.8.1.1), the farmer diagram’s rating method reduces the range of possible outcomes, which can miscommunicate the relative size of both consequences and likelihood. The farmer diagram’s failure to express this distinction could invalidate the claim that it is easy and intuitively understandable.

11.2.8.1.3 Missing standards hazard

Farmer diagrams with distinct hazards in itself pose hazards as described above. If two or more farmer diagrams are used to compare a specific hazard, e.g., the same hazard compared in two separate places, there is a hazard that the comparison of the farmer diagrams might be founded on the wrong grounds.

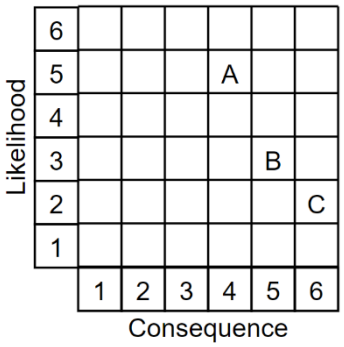

Figure 36: Risk matrix with an ordinal scale from 1-6 (authors’ model).

Since there is no normative standard as to how a farmer diagram should be made, one farmer diagram can have different intervals in the

range compression (see heading 11.2.8.1.1) than the other. Moreover, the ordinal scale in one diagram could be different, e.g., 1-6, and the other 6-1, leading to different calculations of the expected loss of the exposure event in the diagram.

To exemplify this consider the following example from (Thomas, Bratvold, & Bickel, 2013): An exposure event is plotted into a farmer diagram with an ordinary scale of 1-6, and three exposure events are ranked, 'A', 'B', and 'C', see Figure 36.

'A', ranked '5' in likelihood and '4' in consequence, giving a total rating of '20'.

'B' is rated '3' in likelihood and '5' for consequences, giving a total rating of '15'.

'C' is rated '2' in likelihood and '6' in consequence, giving a total score of '12'.

What can be deducted from this rating is that exposure event 'A' is the one whit the highest expected loss. Now consider a farmer diagram with the same range compression, but with an ordinary scale from 6-1 instead of 1-6, see Figure 37. The exposure events would be rated the following way:

'A' has a likelihood score of '2' and a consequence score of '3', resulting in a total rating of '6'.

'B' has a likelihood score of '4' and a consequence score of '2', resulting in a total rating of '8'.

'C' has a likelihood score of '5' and a consequence score of '1', resulting in the total rating of '5'.

In the first farmer diagram, the exposure event with the highest expected loss was event 'A'; in the second, it is event 'B'. The hazard here is the arbitrary decision as to how to design the ordinary scale, and thus the exposure events can be ranked arbitrarily.

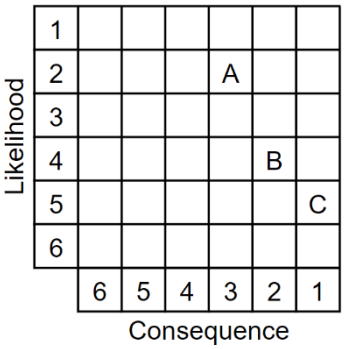

Figure 37: Risk matrix with an ordinal scale from 6-1 (authors' model).

11.2.8.2 Life Quality Index

11.2.8.2.1.1 Supra-national considerations

One of the applications where risk acceptance criteria derived from LQI such as SWTP might not be satisfactory is the mitigation of hazards associated with supranational events. These supra-national events could be catastrophes where nation-states would require help from outside systems and where consequences, if not mitigated, could spill over to outside systems. Examples

of such events could be local epidemics, which could turn into pandemics if not mitigated locally. Other relevant catastrophes might be the eruption of super volcanoes or asteroid impacts (Faber M. H., 2011). In such catastrophic events, it would be a hazard to mitigate the exposure event to the degree suggested by SWTP, as purchasing power for life safety would differ immensely between nation-states. Furthermore, the mitigation measures at such events would likely require international collaboration and joint investment of resources.
Other than international catastrophes, there are issues such as aviation, regulation of nuclear power, etc., that are relevant as supra-national safety considerations. In these cases, LQI derived risk acceptance criteria would not be appropriate metrics at their current state. As a solution, a supra-national metric Earth Societal Willingness To Pay (ESWTP) derived from LQI on an earth-scale has been suggested by (Faber M. H., 2011).

11.2.8.3 Deontological considerations

One of the ethical considerations from a deontological perspective regarding LQI is that it presumes the constituents of life quality. Western societies might find it appealing to use the LQI (derived from GDP per capita, work/leisure time, and lifespan in good health) as the ultimate proxy for life quality. There is also reason to believe that LQI could be the aggregated revealed preference of societies as (Faber & Virguez Rodriguez, 2011) shows that 70% of the earth's population develop in accordance with the LQI principle. By presuming that LQI can be used as a utility function that is universally applicable between cultures, it is inferred that there are no cultural differences in the constituents of life quality. From a deontological point of view, there is a need to consider the outliers among these nation-states and investigate why they are not following the LQI trend.

Consequently, if organizations try to help other cultures to maximize LQI without considering the value systems of that particular culture, they are imposing value systems that might not apply to those cultures. By doing so, there is a hazard that the organizations are doing more harm than good as well as wasting resources. The hazard of subjectivity in the constituents of life quality is also mentioned briefly by (Nathwani, Lind, & Pandey, 1997).

11.2.8.4 Sustainability

LQI derived risk acceptance criteria consider the tradeoff between the economy and the ability to save lives; it does not consider the tradeoff in sustainability. By not considering sustainability, there is a hazard that nation-states exhaust local resources in an attempt to improve life-saving

capabilities through LQI (Faber, Qin, & Nielsen, 2019). Consequently, LQI, at its current state, might not be adequate when considering sensible inter-generational development.

11.2.8.5 Lack of data

To determine the LQI of a nation-state, information regarding population number, lifespan, and work/leisure time must be collected. This information can be subject to the categories of information mentioned in heading 5.3.2, including category 2-5 and its related hazards. In nation-states where this information cannot be obtained to a sufficient degree, it can be hazardous to use the LQI as a decision-making basis as it might not accurately represent the nation-state's population. This non-accurate count of the population could be the case in underdeveloped countries where birth registration is not carried out sufficiently and where lifestyle suggests that work and leisure time cannot be separated completely. In these cases, there would be uncertainties associated with the constituents of the LQI and its related risk acceptance criteria.

11.3 Summary of identified hazards

The hazard identification has described hazards related to the decision-making taxonomy (see Figure 5). This section serves to summarize the hazard identification. The summary is represented in Table 5 table where the hazards described throughout the hazard identification have been condensed.

Table 5: Summary of the identified Hazards

General hazards	Hazard	Heading
Information hazards	Due to epistemic and aleatory uncertainties and incomplete information always exists (incomplete information)	11.1.3.1
	Individuals might mistake correlation for causation (failure in identifying the origin of information)	11.1.3.2
	The difference in knowledge levels among stakeholders and decision-makers (Information asymmetry)	11.1.3.3
	The information acquired can be wrong (not acquiring relevant and precise information)	11.1.3.4
Memory hazards	Individuals remember specific aspects better than other	11.1.4
	Memories can be distorted and mixed with other memories	11.1.4.1
	Memories can be planted into individuals' minds	11.1.4.2
	Collective memories (text, buildings, stories etc.) can have been misinterpreted and passed along	11.1.4.3
Preference hazards	The use of preference collected from a snippet of a stakeholder group might not work on a larger group	11.1.5
	Preference might change based on how information is presented	11.1.5.4
	Stakeholder neglect (EUT approach)	11.1.5.5.1
	Overstepping moral or ethical principles (deontological viewpoint)	11.1.5.5.1
	Decreased management options (deontological viewpoint)	11.1.5.5.2

	The popularity of a stated- or revealed preference might affect the decision process (over time)	11.1.5.5.4
	Misrepresentation (utilitarian preference hazard)	11.1.5.5.1
	Overstepping moral or ethical principles (utilitarian preference hazard)	11.1.5.5.1
Stated preferences	The iterative process of learning can change a stated preference	11.1.5.1
Revealed preferences	Confounding factors might be present when relying on revealed preferences	11.1.5.2
Informed preferences	See general hazards "Information hazards"	11.1.3
Cognitive biases	Systematic deviations from the normative or rational thinking patterns	11.1.1
Confirmation bias	Preexisting beliefs makes an individual focus more on what he/she already know, than what is new	11.1.1.1
Representativeness bias	Individuals tend to make connections that does not exist when seeing something of resembles	11.1.1.2
Availability bias	Individuals tend to assess probabilities by the ease of which those instances come to mind	11.1.1.3
Anchoring bias	Individuals tend to be influenced by reference points	11.1.1.4
Egocentric bias (illusion of control)	Familiarity with a decision-context make individuals overestimate their degree of control over an outcome	11.1.1.5
Hindsight bias	People tend to accept new knowledge as being preexisting knowledge (reputational hazard)	11.1.1.6
Risk aversion and framing	Preference might change based on how information is presented	11.1.1.7
Status quo bias	Individuals prefer small- over large changes	11.1.1.8
Endowment effect	Individuals might value some things more than they are worth (market price)	11.1.1.9
Logical fallacies	Misapplication of logical arguments	11.1.2
The sunk cost effect	Resources could be wasted because decision-makers hold onto something they invested in, even when not effectful	11.1.2.1

Bandwagon fallacy	Individuals could do like the rest, thus not considering other options (conformity)	11.1.2.2
Hazards related to semantic problems with knowledge framing	Appliance of the wrong knowledge base, by ministration of terms	11.1.6
Element from taxonomy	**Hazard**	**Heading**
Approach	Pre-defined principal approaches (when utilizing described principal approaches)	11.2.1
Non-structured	Inconsistency in methods (when the same method is not used)	11.2.6
	Lack of transparency to stakeholders (it can be difficult to reproduce a non-structured approach)	11.2.6
Ad-hoc	Unpredictability for stakeholders to anticipate what the decision-maker will do next	11.2.3.2.1
	Misapplication based on experience, knowledge- and perception about the system	11.2.3.2.2
	Evaluation/comparison of different approaches might be burdensome	11.2.3.2.3
Anarchy	Idleness (for non-anarchists)	11.2.3.1.1
	Human reasoning when using the anarchy principle unintentionally	11.2.3.1.2
Structured	Decreased management options (when having decided to use a structured approach)	11.2.2
EUT	Not utilizing all relevant available knowledge for decision-making	11.1.3.1
	Violation of rationality axioms (Von Neumann & Morgenstern)	11.2.2.1.1
	The decision-makers risk aversion towards professional/personal negative consequences	11.2.2.1.6
	Misapplication based on experience, knowledge- and perception about the system	11.2.2.1.7

	Relying on inferior models when better models are available	11.2.2.1.9
	Misapplication based on experience, knowledge- and perception about the system	11.2.4.1
Weak sustainability		
Cost/benefit	Ambiguity in assignment of monetary value	11.2.2.1.8
Strong sustainability		
Precautionary principle	Doing more harm than good due to incomplete information	11.2.2.2.1
	Reputation and judgment (being judged by knowledge in hindsight)	11.2.2.2.2
	Retainment in precautionary mode - it can be difficult to switch from this approach to another	11.2.2.2.3
Application		
Normative	Application of normative standards to unknown decision contexts	11.2.6.1.1
	Ignoring fundamental mistakes in normative standards	11.2.6.1.2
Descriptive	Acquiring and interpreting irrelevant or incomplete information based on the collector's mental models	11.2.6.2.1
Ethics		
Utilitarian	Not taking individual rights and consents into account (deontological viewpoint)	11.2.5.1
	Lack of information can lead to decisions that do not maximize utility	11.2.5.2.2
Deontological	Decreased management options (when having to ask everyone to consent, and this is impossible)	11.2.5.1.1
System information	Information hazards	11.1.3
Time conditions	Information hazards	11.1.3
Over time	Information hazards	11.1.3
Point in time	Information hazards	11.1.3
Physical boundaries	Information hazards	11.1.3
Stakeholder organization		

Social		
Individual	Misapplication based on experience, knowledge- and perception about the system	11.2.8.1
Collective	Misapplication based on experience, knowledge- and perception about the system	11.2.8.2
Political	Overstepping moral or ethical principles (deontological viewpoint)	11.2.7.3
Participatory	Lack of or inappropriate communication (participatory viewpoint)	11.2.7.1.1
	The decision-making process might take a longer time when having many participants	11.2.7.1.2
	The decision-making process might be influences by a mix of different agendas	11.2.7.1.3
	Relying on layman's opinion for decision-making	11.2.7.1.4
	Participants might influence each other during the decision-making process (bandwagon fallacy)	11.2.7.1.4.2
Non-participatory	Neglect of stakeholder's opinions, and thus potentially disregarding important information	11.2.7.2.1

12 Discussion

12.1 Summary and interpretation of results

The results in this thesis should be interpreted on a general level, i.e., the results are not specific to any domain or decision-making context. Therefore, when using the results given in this thesis for specific purposes, there might be additional aspects to consider. For this, the model introduced in Figure 32 by (JCSS, 2008) could be used as a template on how to analyze consequences in specific contexts. It is believed that the hazard and system identification in this thesis, nevertheless, will help bring awareness to the categories that could be considered by stakeholders and decision-makers.

The main contribution of this thesis is the taxonomy presented in Figure 5. This figure shows the main constituents of decision-making rationales, which together with the system identification are answering this thesis's main research question and the related sub-questions 1-6, as presented in header 5.2.1. The presented taxonomy can be used as a generally applicable tool by decision-makers and stakeholders for various purposes. In principle the presented taxonomy could be read from any direction; however, the influence arrows indicate the direction of influence between the elements within the taxonomy. The perception of stakeholder preferences, physical boundaries, time conditions, and ethics make up the decision contexts system (as described in heading 9.5) which in turn could influence the selected approach and application. The bidirectional influence arrow between preferences and system information indicates that decision-maker(s) and stakeholder(s) preferences could determine the time conditions in which the decisions are being optimized for, as well as if the decision-maker(s) sees the decision-process as participatory or non-participatory. As further outlined in Figure 20, the bidirectional influence arrow between preferences and ethics suggests that the stakeholder and decision-maker preferences influence ethics and vice versa. The bidirectional arrow between approach and application indicates that the approach could influence the application of information, e.g., EUT is a normative application of information. The application of information derived from the decision context system could, in turn, have an influence on which approach seems more preferable for a decision-maker.

A smaller but still relevant contribution is Figure 7, which outlines the possible relations between stakeholder(s) and decision-makers(s). This model can be used to consistently categorize the relations between decision-maker(s) and stakeholder(s) on a group/individual level.

The Influence diagrams are outlined in heading 10 show the dependencies within the taxonomy. These dependencies can be used to analyze specific and general decision contexts to, e.g., derive

hazards or opportunities. The influence diagrams answered sub-question eight as presented in header 5.2.1

Finally, the hazards outlined in heading 11, and summarized in Table 5, answer the second part of the main research question and outline the hazards in decision-making based on the dependencies in Figure 5, thus also answering sub-question nine. Some of the hazards described in the hazard identification will only be considered hazards depending on which ethical/participatory standpoint is adopted by the decision-maker(s) and stakeholder(s). Furthermore, many of the hazards outlined will be more or less severe, depending on the perspective. In these cases, we have outlined from which perspective it could be considered a hazard in parenthesis in the headline. Some of the elements described within the system identification (and thus the taxonomy) do not have a related section in the hazard identification. For these sections, it is intended that the general hazards described in 11.1, which also answers sub-question 7, should be considered.

12.2 Discussion of implications

It is hoped that the system identification and the proposed taxonomy can provide inspiration towards developing a widely accepted framework that encompasses all the constituents of decision-making rationales. Such a framework would, if appreciated, provide a stronger premise as well as transparency for decision-making in a variety of contexts.

The thesis was made to provide decision-makers with a pragmatic tool that encompasses the relevant aspects of decision-making rationales. With this tool in hand, it is wished that decision-makers are made aware of the elements that could be considered in their decision-making. Furthermore, with the influence diagrams as well as the outlined hazards, we have attempted to facilitate increased awareness of the dependencies and gaps in decision-making. Namely, the hazard identification of the constituents within the taxonomy and general decision-making hazards could be used to increase general understanding of what to be aware of when making decisions. The influence diagrams could be used to identify where hazards and opportunities might occur in specific decision-making contexts.

12.3 Limitations and uncertainties

During the investigation of the literature related to this thesis, the authors obtained a lot of new perspectives on decision-making. Such new perspectives have highlighted a host of scientific fields

that could be taken into account in decision-making. These scientific fields include but are not limited to, anthropology, philosophy, cognitive sciences, engineering, economy, and certain branches of mathematics, i.e., scientific fields in which the authors are not experts. During the investigation of these branches of science in relation to decision-making, the authors have realized that the knowledge base required to develop this thesis had to be both broad and deep. The notion: “The more you know, the more you realize you do not know” is a good description of the authors' experience when investigating the topics of this thesis. As a result, the authors acknowledge that there is room for future development of the work carried out in this thesis. Therefore, some of the conclusions derived from the system- and hazard identification might seem banal in the eyes of experts in the related scientific fields. Because of this, the authors have gained an increased admiration for the field of decision-making. Moreover, in the identification of the constituents of the decision-making taxonomy, there could be important aspects that the authors have not been able to identify. Furthermore, there are likely hazards related to the taxonomy that the authors have not been able to recognize. This is especially true for the unstructured approaches, as these were not the main focus of the thesis. Most of the literature used in the thesis is derived from a single source, i.e., the expert elicitation, consequently, there could be relevant literature that the authors’ have not considered in the context of decision-making rationales.

The goal in decision-making is to do what maximizes the utility for the decision-maker and/or the stakeholders. As such, it could be argued that all of the approaches in the taxonomy are ultimately sub-branches of utility theory. From that perspective, the subdivision of the approaches being structured and non-structured might seem irrelevant, i.e., the unstructured approaches (ad-hoc and anarchy) would be chosen because the decision-maker believes that these approaches would increase the utility of the decision-making outcomes. However, the authors chose to categorize the unstructured approaches separately in the taxonomy. This was done to highlight their principal differences and make the taxonomy more useable as a pragmatic tool.

13 Conclusion and further work

13.1 Conclusion

This thesis has answered the two research questions, what constitutes a decision-making rationale? And what hazards are related to decision-making rationales?

The first question was answered by analyzing literature suggestions from expert elicitation; the amount of literature was expanded based on the references provided by that literature. Based on the literature review, a system identification was done to identify the constituents of a decision-making rationale. The constituents have been categorized into a taxonomy. The taxonomy can be seen in the appendix; see heading 15.3.

The system identification gave the foundation for influence diagrams to be developed. The influence diagrams, together with the system identification, provided the basis for the hazard identification related to the elements within the decision-making taxonomy. The hazards related to the identified decision-making rationales are summarized in a table that can be found in heading 11.3.

13.2 Further work

Because decision-making is not exclusive to one field of science, there is a need for a holistic approach that considers every relevant aspect in further developing the presented taxonomy. Consequently, it is recommended, by the authors, that collaboration between a variety of scientific domains is commenced when identifying and describing the relevant aspects of decision-making. This collaboration should be done to avoid professional bias toward a specific decision-making domain and to outline the relevant aspect of decision-making with sufficient depth.

13.2.1 Non-structured approaches

The non-structured approaches were not the main focus of this thesis. Therefore, this branch of approaches could potentially be further investigated, and the findings could be integrated with the taxonomy. Consequently, if further categorization of the unstructured approaches is done, there might also be additional hazards to consider in the hazard identification of these.

13.2.2 Selection of decision-making rationale

In this thesis, we have attempted to identify the constituents of decision-making rationales in the proposed taxonomy and outline the related hazards on a general level. One of the future considerations that could be pursued is how to select a particular rationale for a given context and purpose. Selecting a rationale can be argued to be a structured decision-making problem in itself, and it could create value for decision-makers if a framework that facilitates such a selection is developed.

13.2.3 Mitigation of hazards

Much of the work on how to mitigate hazards in a variety of contexts has already been done. However, the literature is widely spread, and consequently, it can be easy to miss out on important aspects as a decision-maker. A future proposition could be to develop a paper that could suggest mitigation measures of the hazards related to each of the elements in the taxonomy.

13.2.4 Utility, memory, and experience

One of the questions the authors have debated with one another was the nature of utility. In his book Thinking Fast and Slow, Daniel Kahneman mentioned the two selves: the remembering self and the experiencing self. The remembering self is how we think back on past experiences, and the experiencing self is our actual experience at the moment. If there is a gap in how humans experience events and how we remember those experiences, then what we think we want for the future might be different from what we actually want. Because memories are all there is left from past experience, what is being optimized for in decision-making might just be future memory and not future experience.

Consequently, when modeling utility, we should ask which kind of utility we want to optimize for? The utility of the experiencing self or the utility of the remembering self? Moreover, how do we account for the differences when collecting preferences or model consequences? Of course, those differences might be more or less relevant depending on the context, but it seems like there may possibly be some work left to be done in bridging the gaps between happiness research, memory, preferences, and utility theory.

13.2.5 Information management

An additional perspective is that decision-making could be seen as the management of information put into action. As such, all of the identified hazards could be categorized as sub-branches of informational hazards. Furthermore, appreciation of how to manage information consistently seems to be lacking, even in professions where consistency should be expected. The tools provided by, e.g., Thomas Bayes (Bayes rule), Von Neumann and Morgenstern (Expected Utility Theory), Raiffa and Schlaifer, along with Benjamin and Cornell (Bayesian Decision Theory), could facilitate such management along with a solid basis of justification of selecting decision-alternatives. This lack of appreciation for information management, from the perspective of the authors, seems to produce

many of the biases and hazards within decision-making. The authors believe that education and awareness in this area are generally lacking among decision-makers and in the population. Decision-making is ultimately something every human being is exposed to on many levels throughout their lives. The implications of making universally better decisions, even on the individual level, could have prosperous implications that go beyond the authors' imagination. Societal decision-making in the face of globalization and increasing populations has higher stakes than ever, which is why we should start paying the necessary attention to information management. Educating people about information management and spreading awareness about the topic might be some of the most important work that is to be done in the field of decision-making.

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15 Appendix

15.1 Results of Web of Science search

Science-based					
Search term	Number of results	Search term	Number of results	Search term	Number of results
"science based evidence"	73	"science based policy"	136	"science based decision-support"	14
Results					
Environmental Sciences	13	Environmental Sciences	32	Agriculture Multidisciplinary	2
Food Science Technology	5	Environmental Studies	15	Biodiversity Conservation	2
Agronomy	4	Ecology	13	Environmental Sciences	2
Environmental Studies	4	Social Sciences Interdisciplinary	11	Geosciences Multidisciplinary	2
Nutrition Dietetics	4	Water Resources	11	Automation Control Systems	1
Pharmacology Pharmacy	4	Biodiversity Conservation	9	Energy Fuels	1
Agriculture Dairy Animal Science	3	Public Environmental Occupational Health	9	Engineering Aerospace	1

Agriculture Multidisciplinary	3	Veterinary Sciences	9	Communication	1
Plant Sciences	4	Economics	9	Ecology	1
Chemistry Medicinal	3	History Philosophy Of Science	7	Engineering Civil	1
Evidence-based					
Search term	Number of results	Search term	Number of results	Search term	Number of results
"Evidence-based policy"	2363	"Evidence-based decision-support"	114	"Evidence-based evidence"	65
Results					
Public Environmental Occupational Health	333	Health Care Sciences Services	15	Medicine General Internal	46
Social Sciences Interdisciplinary	227	Computer Science Information Systems	13	Family Studies	3
Health Policy Services	206	Medical Informatics	13	Health Care Sciences Services	2
Public Administration	194	Medicine General Internal	10	Critical Care Medicine	1
Health Care Sciences Services	185	Clinical Neurology	7	Dermatology	1

EnvironmentalSciences	132	Computer Science Theory Methods	6	Social Work	3
Political Science	110	Health Policy Services	6	Rehabilitation	2
Criminology Penology	107	Computer Science Interdisciplinary Applications	7	Education Scientific Disciplines	1
Medicine GeneralInternal	125	Public Environmental Occupational Health	7	Gastroenterology Hepatology	1
Economics	107	Oncology	6	Integrative Complementary Medicine	1
Risk-based					
Search term	Number of results	Search term	Number of results	Search term	Number of results
"risk-based policy"	37	"risk-based decision-support"	72	"risk-based evidence"	7
Results					
Environmental Sciences	6	Water Resources	17	Veterinary Sciences	5
Environmental Studies	5	Engineering Civil	14	Environmental Sciences	2

Public Environmental Occupational Health	5	Computer Science Theory Methods	6	Engineering Environmental	1
Operations Research Management Science	4	Environmental Sciences	6		
Food Science Technology	3	Construction Building Technology	5		
Political Science	3	Engineering Industrial	5		
Social Sciences Interdisciplinary	3	Public EnvironmentalOccupational Health	5		
Water Resources	3	Engineering ElectricalElectronic	4		
Public Administration	3	Engineering Multidisciplinary	5		
Computer Science Interdisciplinary Applications	2	Geosciences Multidisciplinary	4		
Risk-informed					

Search term	Number of results	Search term	Number of results	Search term	Number of results
"risk-informed policy"	4	"risk-informed decision-support"	14	"risk-informed evidence"	0
Social Sciences Interdisciplinary	2	Engineering Civil	6		
Development Studies	1	Engineering Mechanical	4		
Green Sustainable Science Technology	1	Engineering Multidisciplinary	2		
Nuclear Science Technology	1	Mathematics Interdisciplinary Applications	2		
Regional Urban Planning	1	Water Resources	2		
		Computer ScienceInformation Systems	1		
		Engineering Electrical Electronic	1		

		Instruments Instrumentation	1		
		Engineering Chemical	1		
		Geosciences Multidisciplinary	1		
Resilience-based					
Search term	Number of results	Search term	Number of results	Search term	Number of results
"Resilience-based policy"	2	"Resilience-based decision-support"	0	"Resilience-based evidence"	0
Environmental Sciences	2				
Environmental Studies	2				
Ecology	1				
Energy Fuels	1				
Economics	1				

Sustainability-based					
Search term	Number of results	Search term	Number of results	Search term	Number of results
"Sustainability-based policy"	1	"Sustainability-based decision-support"	3	"Sustainability-based evidence"	0
Economics	1	Construction Building Technology	2		
Energy Fuels	1	Engineering Civil	2		
Environmental Sciences	1	Materials Science Multidisciplinary	2		
Environmental Studies	1	Engineering Environmental	1		
		Environmental Sciences	1		
		Green Sustainable	1		

		Science Technology			
Integrated risk, resilience, and sustainability					
Search term	Number of results				
Integrated risk, resilience and sustainability	459				
Environmental Sciences	223				
Environmental Studies	171				
Green Sustainable ScienceTechnology	166				
Water Resources	54				
Engineering Civil	42				
Geosciences Multidisciplinary	35				
Engineering Environmental	20				
Meteorology Atmospheric Sciences	40				

Ecology	34
Urban Studies	16

15.2 Literature list and summary of literature

15.2.1 10th Lecture: Bayesian Probabilistic Nets in Risk Assessment (Faber M. H., 2007)

This paper is an educational tool designed for engineering students. In the 10th lecture of the paper, the topic of Bayesian Probability networks is and their uses in risk management are addressed. The topic of causality is discussed and a general explanation of probability networks its notes is made, with the integration of discrete states. The implications of BPN's in general risk assessment and sensitivity analysis as well as their uses in fault trees and event trees are outlined through examples. The application of BPN's in large-scale risk management for urban structures under the hazard of an earthquake is discussed and a framework that also integrates Geographical Information Systems (GIS) Is proposed.

15.2.2 13th Lecture: Risk Acceptance and Life Safety in Decision Making (Faber M. H., 2007)

This paper is an educational tool designed for engineering students in the field of risk and safety. In the 13th lecture of the paper, the topics of life safety and risk acceptance in decision making is addressed.

Farmer diagrams, their usage, and their related problem with inconsistency to total risk is outlined.

The commonly used tools for risk acceptance is outlined and explained in detail topics such as:

As low as reasonably possible (ALARP)

Fatal Accidental Rate (FAR)

Potential loss of life (PLL)

The revealed risks in society are discussed as the degree of experienced life safety risks in various activities based on the rate of death versus the degree of voluntarism and the degree of personal influence on success.

A list of risk reduction costs per saved life for several risk reduction measures in society is outlined.

Tools for evaluating societies performance in various aspects, and how they are related and calculated, is outlined and their implications are discussed for:

Human development index (HDI)

Gross domestic Product Index (GDP index)

Education Index (EI)

Adult literacy index (ALI)

Life expectancy index (LEI)

Gross enrolment Index (GEI)

Modeling of acceptable socio-economic risks with the use of Life Quality Index (LQI) and Societal Willingness to pay (SWTP) and their implications is outlined and discussed. The term Societal value of a statistical life (SVSL) is outlined. An example of the acceptable strength of a hypothetical steel rod based on LQI as a risk acceptance criterion is formulated.

Lastly a section of sustainable decision-making outlines:

The indicators of sustainability,

The consequences to economy and society and

The consequences to the environment

These factors are integrated into a model/equation for the optimization of intergenerational decision-making.

15.2.3 On the governance of global and catastrophic risks (Faber M. H.)

The article outlays a problem with best practices in decision-making saying it is often theoretically flawed or at best targeted for specialized purposes.

This article focusses on enhancing governance of global catastrophic risks by defining three building stones for this

Identifying the most relevant hazards in a holistic global perspective and a categorization of these in view of different strategies for their treatment.

A theoretical and methodical framework for the identification of robust societal decisions on risk management in the face of large uncertainties.

A concept supporting decision-making on the allocation of economic resources for global life safety and health improvements.

The articles outline the concept of risk as to qualify, quantify and communicate the threats, perils or, more generally uncertain events perceived to be associated with adverse consequences.

The articles context is on normative decision-making where the preferences is taken as an aggregation of individuals, thus not an individual. The normative approach is required when the aim is to support decision makers. The usage of risk is describing as a characteristic of decisions for the purpose of two tasks

Ranking decision subject to uncertainty.

Assessment of the consequences of decisions.

Moreover, risk is defined as the expected value of utility based on economic decision theory and the axioms of utility theory. From these two theories two steps is required to assess the optimal decision, (i) identify preferences and associate them with utility, and (ii) accounting for uncertainties affecting a given decision problem, the expected value of utility must be estimated for each considered decision alternative.

The article categorizes risk with the mechanisms which appear to be driving them, though it is not easy to set boundaries between the categories since there always is some interaction between them:

Natural.

Technological.

Pandemics, disease, and malnutrition.

Malevolence and war.

Economic instability.

Deterioration.

Human and organizational errors.

A categorization of different hazard event types is also proposed

Type 1: Foreseeable large scale averaging events.

E.g., natural hazards, economic and industry induced risks.

Type 2: ‘Seepage’ events; losses of continuous and generally unnoticed intensities.

E.g., the release of radioactive material, ageing infrastructure, growing oil consumptions and the, for laymen, confusing and lengthy discussions like the scientific causes behind climatic changes.

Type 3: Unforeseeable or simply very large scale, discrete point in time events.

E.g., Eruptions of super volcanoes, asteroid impacts, outbreaks of pandemics, out of control technological developments, global war, and social instability.

The article outlines some critical issues in risk management.

Organizational and human errors are in general not included as significantly contributing hazards.

Risk assessments does not consider cognition biases and ‘seepage’ events.

There is a need for a framework for risk informed risk management which considers the three different types of hazards events and facilitate decision making regarding allocation of available economic resources for purpose of health and life safety improvements at small and large geographical scales. The frame should also address sustainability systematically and consistently – it should be balanced between “what we would like to have and what we can afford”.

Requirements are outlined as to what a normative risk management framework must fulfil:

Facilitate modeling of the system so that all relevant events leading to loss may be represented with their interdependencies.

Consistently account for the level of available knowledge as well as natural variability.

Facilitate decision making at a scale of system representation necessary to support the decision in question.

Quantify risks in a marginal as well as a non-marginal sense, i.e., be able to represent the effect of losses due to a given event on economic growth and the living conditions for future generations.

Specifically address decision making in the situations before, during and after hazard events.

Facilitate standardized procedures for systems representations in risk assessments.

Account for information which might become available in the future and facilitate those options for future decisions are included in the decision optimization.

Facilitate for consistent risk aggregation whereby it is ensured that the result of independently performed risk assessments can be and applied to assess and manage the risk in a larger context-portfolios.

Facilitate decision optimization and the assessment of the acceptability of decisions.

Enhance risk communication and risk management documentation.

15.2.4 Issues in utility modeling and rational decision making (Maes & Faber, 2004)

The article outlines the rationale behind the expected utility analysis and describes issues/critique of this rationale. The main rationale behind the maximum expected utility theory is referred to as the independence axiom (Von Neumann & Morgenstern, 1953) and the issues/critique is the common consequence effect, the common ration effect and oversensitivity to tail changes or changes in small probability events. Moreover, issues regarding the maximum expected utility theory covered by cognitive science describe people as risk-averse and in general irrational, e.g., if presented with a drug that can save your life with 50% chance people are more willing to take the drug, than if presented with a 50% chance of dying. The issue of incomplete information will always be present, however, can be mitigated by consulting experts. The bias of one's own experience is described as having precedence over objective data. Epistemic uncertainties are also an issue raised where the Ellsberg's paradox is used as an example, i.e., people tend to use probabilities they know instead of unknown probabilities even if the known probability gives a bad outcome. For decision-makers who know that unknown probabilities sometimes should be used the issue of applying Bayes' theorem/Bayesian updating is not applied correctly, i.e., the weight of prior information in the updating is too low compared to new data.

When using the maximum expected utility theory assumptions two assumptions are made, (i) decision-makers can calculate probabilities and (ii) decision makers are willing to and capable of updating the utility functions they use.

Rationale: The independence axiom is what addresses rationality in the expected utility analysis.

The article provides "violations"/competing views of the independence axiom, e.g., the Allais paradox.

15.2.5 Consequence modeling based on stated preferences (Maes & Faber, 2007)

The articles focus is on the way consequences are assessed and perceived by individuals and corporate or public entities when decisions must be made, and several decision-makers (more than one) have different preferences and values. This is based on observations where individual and corporate decision-makers have different values on almost identical decision-alternatives and consequences. Disagreement between decision-makers of all levels is common, and the article raises the concern that if no rational framework is used to accommodate variable preferences and taste the result can be unsettling. A framework is outlined which has the objectives to (i) provide basis for rational analysis of alternatives and decisions that accounts for different views regarding the modelling, perception of consequences and preferences with consequences and (ii) be able to assist the subsequent decision-making based on stated preferences, even when these preferences turn out to be different and irreconcilable.

The article outlines ten separate reasons of difference in opinions and preferences about consequences

Decision-makers does not act rational, i.e., they do not adherence to the maximum expected value framework.

Decision-makers does not act in good faith and show bias, i.e., they have hidden agendas and are more interested in making a decision that give themselves value instead of the stakeholders.

Decision-makers does not respect the rules of preference ranking, i.e., decision-makers are not updating the utility function they use, with the correct use of preference ranking.

Different decision-makers appraise specific consequences in different ways, i.e., if the consequences cannot be measured in monetary value, and thus, is based on a subjective appraisal of the consequence, e.g., the value of a life.

Decision-makers omit long-term consequences, i.e., some decision-makers might not consider the long-term consequences, and some do.

Decision-makers ignore follow-up consequences, i.e., it is different how the decision-makers take the systems spatial or physical boundaries into account.

Decision-makers combine different types of consequences in different ways, i.e., decision-makers have different views on the outcome of the combination of different consequences.

Decision-makers find it hard to represent the views of a large organization or (part of) society, i.e., it is difficult for decision-makers to represent the preferences of large groups.

Decision-makers are affected by the way preferences are solicited, i.e., the presentation of decision problem can affect the perception on the problem and thus, create different assignments of probabilities.

Decision-makers use different or “home-made” priors in a Bayesian analysis, i.e., when dealing with a new development with no prior data the opinion of an e.g., expert may be influential in determining the posterior distribution.

Hereon after the articles describes a framework to include these variations in preferences by different decision-makers. The framework relies on the use of preference distributions, hyper parameters of mixing distributions, and multinomial likelihoods over subsets of the preference space.

15.2.6 Protocols for Communication and Governance of Risks (Vrouwenvelder, Lind, & Faber, 2015)

This paper argues the need for a common communicative framework for discussing public risks. The framework should take into account Risk analysis, risk management, and risk communication. Moreover, the framework should be as widely applicable as possible and should give the basis for a uniform language in the communication and use of risk metrics.

The terms uncertainty (including the understanding and distinction of aleatory and epistemic uncertainty), probability, and risks should be well defined in the framework. The call for a uniform methodology is also addressed and should refer to relevant ISO standards or JCSS protocols.
In risk management, the measures of risk reduction should come from best practices and only be deviated from, if best-practice methods are justified to be inappropriate. The decisions could be based on methods such as ALARP in the context of the costs of reducing risks to acceptable levels. In low-risk scenarios metrics such as LQI or other methods addressing marginal life-saving costs should be implemented. It is of importance, that the protocol should account for different approaches and make recommendations on how to use the methods in distinct risk-management circumstances.

In risk communication, the various entities involved should be able to understand each other clearly, even though they might be on a laymen level in the understanding of each other’s fields. This calls for careful consideration of wording and presentation of propositions. Risk perception of various stakeholders should be considered. The paper concludes that there is an urgent need for two separate protocols for communication of risk: (i) a protocol for risk professionals to communicate to authorities, and (ii) a protocol for authorities to communicate risks to the public.

The need for such a framework is backed up by various historical examples, as well as scientific literature on the topic.

15.2.7 Objectives and Metrics in Decision Support for Urban Resilience (Nielsen, Glavind, Qin, & Faber, 2019)

The article proposes a framework for the representation of human welfare which considers interrelations and dependencies between society, individuals, technology and the qualities of the environment. The framework builds on the idea that a system cannot be resilient if its capacities are exhausted and thus, need help from a different system to recover. The framework provides the possibility to quantify resilience and sustainability in probabilistic terms, moreover decisions alternatives may be assessed relative to their effects on the probability of resilience and sustainability failure.

15.2.8 Faith and fakes – dealing with critical information in decision analysis (Nielsen, Glavind, Qin, & Faber, 2019)

(Nielsen, Glavind, Qin, & Faber, 2019) is concerned with the issue of information management in decision-analysis.

The paper describes the concept of ‘fake news’ and its implications in decision-making. Philosophical propositions concerning truth, knowledge, and information are outlined. Information is treated from the consequentialist perspective as ‘the difference which makes a difference’ in decision-making contexts throughout the proposed frameworks in the paper. A model of the information flows in decision-making is introduced and related notes with respect to ‘state of nature’, ‘stakeholders’, ‘decision-maker’, and ‘risk specialist’. The information’s system of origin and how it relates to decision-making from a consequentialist perspective is discussed. A categorization framework for conditions of information and their implications in decision-making is outlined. A framework for the optimization of decision alternatives with respect to system choice is done with explanatory examples. Lastly, a tool for assessing the robustness of decision-alternatives with respect to decision-rankings and system candidates is formulated.

15.2.9 HOMO EFFECTIVUS: toward a unified model of human cognition for the study of social-ecological systems (Levine, Chan, Satterfield, & Slingerland, 2011)

Homo effectivus merges available knowledge about human cognition to make a unified model to describe the human condition. It is formulated as a shared framework, with a common vocabulary,

for describing how people think and behave. The proposed framework embraces humans' inclination to analogical thinking, namely that humans match an object of attention with priors to make best guesses and assumptions. The framework could provide knowledge about how humans reason about their environment. The model has several suggested implications in the field of socio-ecological systems and resource management.

The model is very general and could be applied in cases concerning mental models with related behavior outcomes.

15.2.10 Normative models of judgment and decision making (Baron, 2004)

The paper addresses the topics of normative judgment in decision-making. Normative models in the paper are discussed as a result of philosophical reflection and should not include behavioral characteristics. The normative models are used to extract biases found in decision-making by comparing the decisions with the normative model. The exclusion of behavioral characteristics such as data and intuition about what people are ought to do, is important, as those are also subject to criticism (bias). Although no data is used, normative models need to consider who we are as humans, i.e., we have desires, feelings etc.
Rules about when to apply the normative framework and when not to is also of importance.

To understand biases, descriptive models and/or theories are made. Descriptive models/theories account for both behavior and reflective judgment. With both normative and descriptive models, the biases can be corrected with the use of prescriptive models to better align with the norms. Prescriptive models are an applied field that seeks to correct the biases that occur in the implementation of normative models. Furthermore, the term utility is discussed, with its implications and challenges.

The normative models described in the paper include Expected Utility Theorem (EUT). The normative rules on EUT that must be followed are discussed, e.g., how utility theory must include all relevant consequences. Furthermore, the article argues that to make improvements, normative models, like scientific models should generally be refined over time.

15.2.11 Affordable Safety By Choice: The Life Quality Method (Nathwani, Lind, & Pandey, 1997)

This paper is a summary of the book Affordable Safety By Choice: The Life Quality method. The summary is done to reach a broader audience and to spread knowledge in the area of societal decision-making. The main content is regarding the tool Life Quality Index (LQI) and its uses and implications in decision-making. The underlying principles of LQI are outlined, i.e., the accountability principle, the principle of maximum net benefit, the Kaldor-Hicks compensation principle, and the life measure principle. The LQI is described as a coherent and unified rationale

for decision-makers in managing societal risks based on objective quantitative factors. Examples of the use of LQI and how it could improve the allocation of societies' resources in balancing cost, benefit, risks, and related uncertainties.

15.2.12 Philosophical Devices: Proofs, Probabilities, Possibilities, and Sets (Papineau, 2012)

(Papineau, 2012) approaches the world in the logical context of sets, where everything in the world can be seen as a set of something, i.e., the world is a set with everything in it, when you do something, you select some things from this set and form a subset in which you interact. Moreover, (Papineau, 2012) introduces A priori and A posteriori. A priori knowledge is described as independent from experience where A posteriori knowledge is described as based on empirical evidence.

15.2.13 Understanding Utilitarianism (Mulgan, 2007)

(Mulgan, 2007) introduces the different two different types of utilitarianism, (i) the actualist utilitarianism which focus on what is the actual right answer when maximizing happiness and pleasure, even if you do not know the answer before you have to make a choice and (ii) the probabilistic utilitarianism which focus on maximizing happiness and pleasure is considering the values of each outcome and its probability (Mulgan, 2007) describes three ways to evaluate actions based on the probabilistic utilitarian approach is (i) maximin (ii) expected value and (iii) maximax where the first and third is described as dubious since one would either take so few risk that life would not be worth living or so many risks that one’s life would be destroyed. The expected value approach is described as the one most utilitarians prefer.

15.2.14 Theory of games and economic behavior (Von Neumann & Morgenstein, 1953)

Von Neumann and Morgenstern explains the expected utility model as a mathematical model for examining the behavior of individuals making decisions under uncertainty. Von Neumann and Morgenstern argues that people, when facing uncertainty, make decisions based on expected value of utility rather than expected value. Thus, people do not prefer a specific outcome because it generates a higher expected payoff, but because it generates a higher expected utility. The expected utility theory is a compact way to summarize information about preferences by assigning numerical payoffs to, e.g., different outcomes. For the expected utility model to apply four axioms must be followed, (i) completeness, (ii) transitivity, (iii) independence (iv) continuity (Spaniel, 2016).

Completeness

A preference ordering is complete if and only if, for any two outcomes X and Y, an individual prefers X to Y, prefers Y to X, or is indifferent between the two.

Transitivity

For any three outcomes X, Y, and Z, if X is preferred to Y, and Y is preferred to Z, then X must be preferred to Z. Transitivity rules out preference cycle.

Independence

If P is a probability between 0 – 1 and X, Y, and Z is outcomes or probability distributions over outcomes. Then independence would prefer X to Y if and only if I prefer pX + (1-p)Z to pY+(1-p)Z.

Continuity

If you prefer X to Y to Z then there exists a unique probability between 0 -1 which makes one indifferent between the lottery pX + (1-p)Z and Y with certainty.

15.2.15 Prospect theory: An analysis of decision under risk (Kahneman & Tversky, 1979)

The prospect theory laid out by Kahneman and Tversky explains that humans in general process gains and losses differently. The prospect theory argues that the feeling of loss is two-three times greater than the joy felt from an equivalent gain, e.g., if one gain 100 US Dollars the person should be as happy as if the person received 200 US Dollars and lost 100, since the net gain is 100 US Dollars.

15.2.16 Judgment under Uncertainty: Heuristics and Biases (Tversky & Kahneman, 1974)

Kahneman and Tversky argue that decisions made under uncertainty rely on heuristic rules which allow people to simplify complex decisions and thus, make decisions faster. While the heuristics are described as useful, they are also described as something that can lead to systematic errors. The three heuristics outlined in the paper is (i) representativeness, (ii) availability, and (iii) anchoring. In the paper, Kahneman and Tversky argue that people overweight similarities and overlook other important factors. In general people's perception of the world is skewed by what people think and want and thus, link similar things together using the representativeness heuristic. The availability heuristic deals with how things are retrieved from memory or from imagination. The human mind is designed to avoid effort; thus, people overestimate probabilities based on what is easiest to recall. The anchoring heuristic occurs when a reference point is given as a starting point making the human brain estimate answers from this point and not straying afar from it. Thus, the starting point and how something is presented is important.

15.2.17 Summary of literature review

Authors	Science field	Models
(Faber M. H., 10th Lecture: Bayesian Probabilistic Nets in Risk Assessment, 2007)	Engineering	Human development index (HDI) Gross domestic Product Index (GDP index) Education Index (EI) Adult literacy index (ALI) Life expectancy index (LEI) Gross enrolment Index (GEI) Life Quality Index (LQI) Societal willingness to pay (SWTP) Societal value of a statistical life (SVSL)
(Faber M. H., 13th Lecture: Risk Acceptance and Life Safety in Decision Making, 2007)	Engineering	BPN, sensitivity analysis, fault tree, event tree.
(Levine, Chan, Satterfield, & Slingerland, 2011)	Cognitive science	Common framework for how people thinks and behave.
(Nielsen, Glavind, Qin, & Faber, 2019)	Decision theory, cognitive science, philosophy.	Framework for the classification of conditions of information.
(Faber M. H.)	Decision theory, cognitive science	Categorization of hazards, Bayesian pre-posterior decision analysis framework. Life Quality Index.

(Faber, Qin, & Nielsen, 2019)	Decision theory, Mathematics	LQI, framework for resilience, modeling and quantification, GDP,
(Maes & Faber, Consequence modelling based on stated preferences, 2007)	Decision theory, mathematics, cognitive science	Framework that includes several decision makers with different preferences and values.
(Vrouwenvelder, Lind, & Faber, 2015)	Decision theory	LQI, GDP, HDI
(Baron, 2004)	Decision theory	Normative-, descriptive- and prescriptive models
(Nathwani, Lind, & Pandey, 1997)	Decision theory	LQI
(Mulgan, 2007)	Philosophy	N/A
(Von Neumann & Morgenstein, 1953)	Mathematics, economic	Expected value of utility
(Kahneman & Tversky, 1979)	Cognitive science	Prospect theory
(Tversky & Kahneman, 1974)	Cognitive science	Heuristics and Biases

15.3 Representation of the decision rationale taxonomy