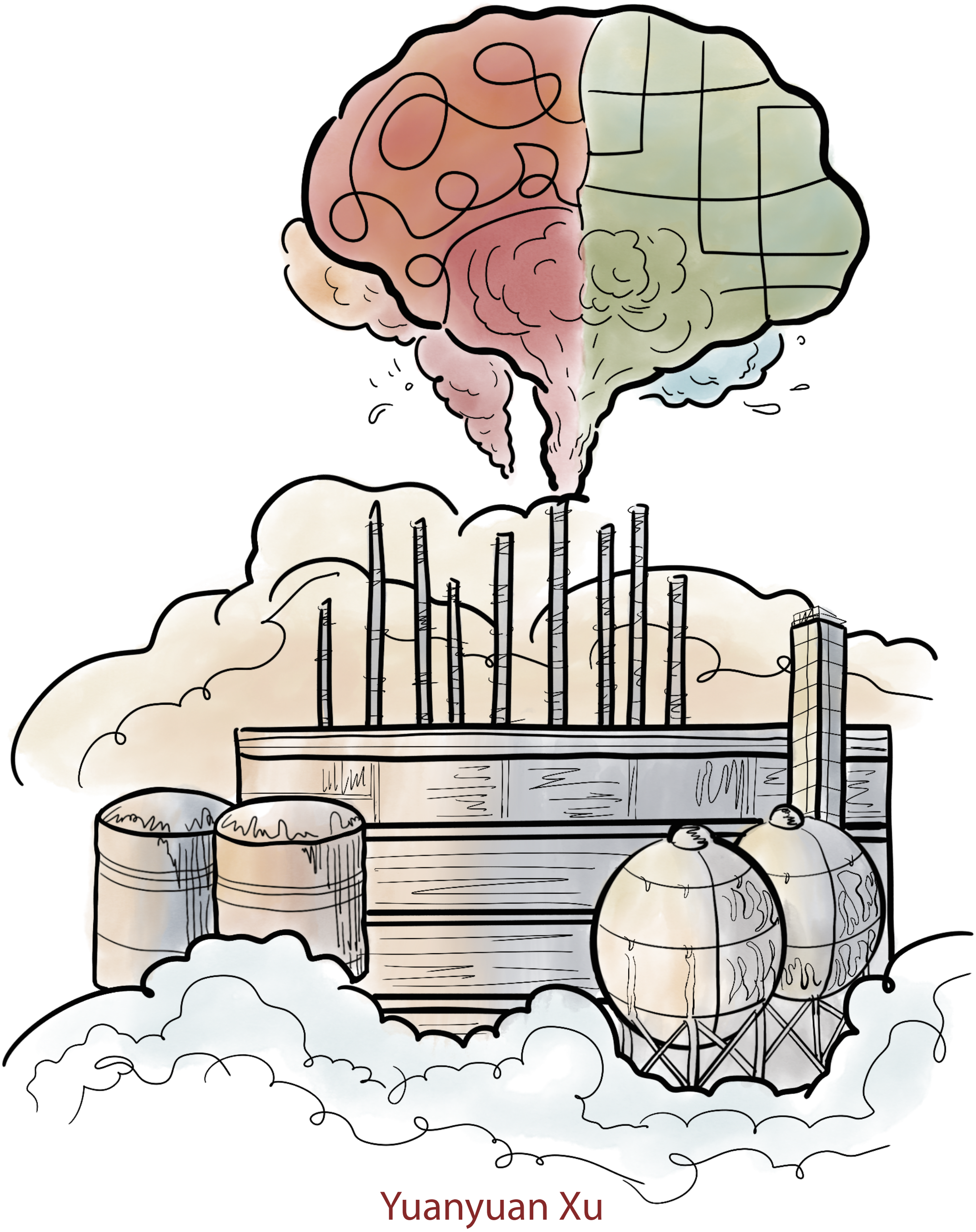
Towards an Integrated Rational and Emotional Risk Decision-Making Approach



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Towards an Integrated Rational and Emotional Risk Decision-Making Approach

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Towards an Integrated Rational and Emotional Risk Decision-Making Approach

Dissertation

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List of abbreviations and acronyms

AHP	Analytical Hierarchy Process
CON	Consultancy agencies
EHS	Employees of high-risk sectors
EMR	Emergency responders
ERA	Ethical Risk Analysis
EU	Expected Utility
FTA	Fault Tree Analysis
GOV	Government organizations and regulatory body
IAEA	International Atomic Energy Agency
INS	Insurance company
IRERDM	Integrated Rational and Emotional Risk Decision-Making
IRGC	International Risk Governance Council
MCDA/M	Multicriteria Decision Analysis/Making
MED	Media
MPT	Modern Portfolio Theory
NGO	Non-Governmental Organizations
NGT	Nominal Group Technique
PAF	Perception Affecting Factor
PCRSF	Person-Centered Risk Assessment Framework
PRA	Probabilistic Risk Assessment
PUB	Public
Q&Q	Quantitative and Qualitative
QALY	Quality-Adjusted Life Years Calculation

QRA	Quantitative Risk Assessment
RAF	Risk Assessment Framework
RES	Academic or research institution
RM	Risk Management
RPG	Role-Playing Game
RS	Risk Scenario
SAFR	Social Amplification Framework of Risk
SPSS	Statistical Package for the Social Sciences software
WTA	Willingness To Accept
WTP	Willingness To Pay

PART I INTRODUCTION

Chapter 1 Research Foundations

Risk management is vital to ensure a safe construction and operation of all kinds of infrastructure. The current risk management paradigm adopted by industry is based on a rational concept of risk[1] and struggles to fulfill contemporary societal[2] demands. With the advent of Industry 5.0, industrial processes gradually shift the focus from technical aspects towards sustainability, human-centricity, and resilience[3]. With the society's growing expectations for moral and ethical aspects to be involved in technology and innovation-related decision making, the mismatch between old-school industrial risk management on the one hand and social responsibility on the other, has become increasingly evident. This dissertation is devoted to developing and validating a new risk management approach to better meet societal demands. This chapter introduces the research problem, motivations and objectives, contributions, and the outline of the thesis.

[1] Typically, a rational concept of risk refers to the combination of probability of a risk event and its consequences.

[2] In this dissertation, "societal" is mentioned multiple times, referring to the macro social level. For instance, the term "societal demands" refers to the collective needs or expectations of a society or social group.

[3] Resilience is defined by ISO 22300:2021 Security and resilience as "ability to absorb and adapt in a changing environment".

1.1 Setting the scene

1.1.1 Problem statement

The expansion of industry is an important part of global economic growth and development. Industries play a significant role in shaping and enhancing modern life (Weiss 2010). The construction and operation of chemical and process industries for instance inevitably introduce various types of hazards, and the associated risks[4] have the potential to cause major accidents such as fires, explosions, and toxic releases (Khan and Abbasi 1999). To prevent industrial accidents and losses, Risk Management[5] (RM) evolved as an established scientific approach to identify, assess, evaluate, control and monitor risks (ISO 2018). A goal of risk management is to focus on managing negative aspects of risks, and RM provides structured information to assist policy makers to make decisions (Meyer and Reniers 2022). In spite of the efforts related to risk assessment and the design of risk management strategies, catastrophic events keep happening. Furthermore, the ever-increasing complexity and nonlinear causal relations in our world also exacerbate risks of which the severity and the extent of the consequences are not limited to the surroundings of the individual events but also include indirect impacts on society (Ekberg 2007, Aldawood and Skinner 2018).

Risk management not only involves technical activities; inadequate risk management can bring about a set of societal problems (Earle, Siegrist et al. 2010). A notable example is the Yucca Mountain nuclear waste repository (Slovic, Flynn et al. 1991). Despite multiple Quantitative Risk Assessments (QRAs) conducted by the U.S. Department of Energy, which concluded that the risks were negligible, public opposition remained strong. Concerns over the safe disposal of nuclear waste led to continuous protests and political resistance, ultimately resulting in the project's permanent abandonment. In 2011, an earthquake followed tsunami damaged the Fukushima nuclear power plant (Khadka 2023). Twelve years after the nuclear plant meltdown, Japan began releasing treated radioactive wastewater into the Pacific Ocean, in accordance with safety standards set by the International Atomic Energy Agency (IAEA). Nevertheless, the release triggered public fear and anxiety among those concerned about exposure, prompting protests both in Japan and South Korea. Environmental groups and marine biologists believe the risk assessment neglects the ecological impacts on water, sediment and organisms. For example, fishermen have

[4] Risk is defined as “the effect of uncertainty on objectives” by the ISO 31000:2018 risk management standard.

[5] Risk management is “coordinated activities to direct and control an organization with regard to risk.” ISO (2018). ISO 31000:2018-Risk Management: Guidelines..

told the BBC they fear their reputation has been permanently damaged and worry for their jobs. Similarly, in 2020, a major explosion happened at Port of Beirut triggered by ammonium nitrate, which resulted in 218 fatalities. The disaster intensified the scale of domestic protests and caused political unrest. Such consequences demonstrate that the significance of a risk cannot be captured solely by its immediate physical consequences.

Risk prioritization plays a vital role in the decision-making process of risk management, and it helps set risk management priorities and decide which risk should receive more attention (Xu, Yuan et al. 2024). Current risk management approaches adopted by industries are built on a technical and rational perspective, with the primary focus on reducing the severity of consequences and associated probabilities. Meanwhile, the management of industrial risks often involves several types of stakeholders with diverse, and often conflicting, concerns. Therefore, in order to ensure that the development of innovative technologies and industries is more societally responsible, it is vital for the current risk management paradigm to adapt to societal expectations (Hellström 2003).

1.1.2 Motivations and objectives

In 2022, the European Commission formally introduced the new vision of Industry 5.0 (Fifth Industrial Revolution) with the release of the document entitled "Industry 5.0: Towards a Sustainable, Human-centric, and Resilient European Industry" (Xu, Lu et al. 2021). It reinforced the role of industry in pursuing societal goals, such as social fairness and sustainability, beyond jobs and growth (Leng, Sha et al. 2022). In the risk management domain, there is a growing body of literature arguing for the inclusion of moral and ethical values in risk assessment (Reniers 2017). Risk management is an interdisciplinary filed, in fact, substantive academic work in the social sciences has advanced our understanding of the cultural and social aspects of risk (Hansen, Holm et al. 2003, Roeser and Pesch 2016, IRGC 2020). For example, cultural and emotional factors influence people how assess risk; experts and laymen perceive risk in a different way; risk communication is more effective when it is structured as a dialog instead of one-way communication (i.e., informing, education). However, social sciences research has largely focused on explaining why people have a "distorted" view of risk and how it diverges from the "real risk" produced by technical experts. Additionally, there are voices that fear public risk perception may influence risk decision-making in an inaccurate way (Jasanoff 1993). As a result, there is a lack of appropriate communication between the expert-driven risk culture[6] and socially oriented risk culture.

To bridge these gaps, the main objective of this dissertation is to develop an innovative industrial risk management approach that can systematically integrate economic, social, cultural, and ethical factors into rational risk thinking to support a more responsible risk management. The proposed approach will be tested and validated through case studies in the chemical industry and has the potential to be further adapted for use in other private and public organizations. The chemical industry will be taken as a case study since it requires trust and belief from the public and it is faced with increasing interdependencies and complexities, especially with the ever-increasing emergence of chemical industrial parks.

1.2 Research questions

After the introduction of the research background and identification of knowledge gaps of risk management, we identified the necessity of recognizing social and ethical factors in risk management. On this basis, the following main research question is formulated:

How can an integrated rational–emotional risk-based decision-making approach be designed and evaluated to combine technical risk assessment with diverse stakeholders' emotional and ethical concerns, thereby supporting transparent and acceptable prioritization of major-accident risks?

To answer this question, a list of sub research questions has been identified and that need to be addressed. Each question is related to a distinct chapter of the thesis.

SRQ1 (Chapter 2). *How do different disciplines define risk, and what approaches are employed to assess and manage it?*

Risk and its definition are the basis of risk assessment, and the results of risk assessment provide important input for risk decision-making. Nevertheless, public and societal values such as personal control, voluntariness, and distribution of risks and benefits are not manifested in formal risk assessments. The public or the authorities cannot obtain meaningful insights from purely rational risk descriptions. To achieve responsible and sustainable risk management, economic perspectives,

[6] "Risk culture" can be understood as the overall pattern of how risk is perceived and managed, including a set of values, cognitive frameworks, and behavioral practices through which risk is understood, evaluated, and responded to.

the social environment, values, and world views have to be determined. Risk is a multi-dimensional concept, and extensive theoretical and empirical research in the social science field has already been conducted to explore its societal and ethical dimensions. However, how these concerns are conceptualised across different disciplines, and how they relate to the assessment and management of risk, requires systematic examination. Therefore, integrating the rational concept of risk with the ethical and moral aspects require a comprehensive multidisciplinary examination and cooperation. A systematic literature review is conducted to answer the question.

SRQ2 (Chapter 3). *How to develop an approach that integrates stakeholders' concerns into risk management?*

Risk management can be viewed as a risk-informed decision-making process. A risk decision-making approach is to use scientific tools to calculate and guide decisions on how risks can be prioritised, and focused on this, preventive measures can be allocated. In spite of many questions and ambiguities in defining risk, from an ontological perspective, risk must correlate to reality (facts) and objectives (economic, societal aspects and values) (Blokland and Reniers 2019). Risk analysis involves value judgments in many aspects, such as framing the problem, defining risk indicators, and making assumptions (Bohnenblust and Slovic 1998). From this perspective, risk depends on the insights of stakeholders who are or who perceive themselves to be, affected by the risk or by risk management activities. However, "what we value?" is usually subjectively defined by experts without input from the public or the authorities. This raises the question of how stakeholders' concerns can be systematically identified and incorporated into the risk management process. In particular, it is necessary to consider how concerns expressed by different stakeholders can be elicited, structured, and translated into decision-relevant information, so that they can be considered alongside technical risk information in risk decision-making. Moreover, nowadays, public support and participation have become a core element of any technological development. To realize the responsible risk management paradigm, risk analysts must build bridges between the professionals and stakeholders and, in particular, create partnerships with the stakeholders. Involvement of diverse stakeholders and the public, enhancement of two-way risk communication, and proper use of risk perception can make risk assessment more credible and justifiable to the public. As a result, a new approach named Integrated Rational and Emotional Risk Decision-Making (IRERDM)[7] is proposed to integrate stakeholders' concerns into the risk management process.

[7] Here, the "emotional" approach refers to the layman's view of risk. The term "emotional" is used to differentiate it from the rational method and is not synonymous with "irrational".

SRQ3 (Chapter 4). *What are the variations among stakeholders' views and attitudes toward the proposed risk decision-making approach?*

Risk perception is a product of hazard characteristics, characteristics of risk perceivers, heuristics and biases and reflecting the socio-cultural process (Tversky and Kahneman 1974, Rohrmann and Renn 2000, Siegrist and Árvai 2020). Thus, the views and attitudes of different types of stakeholders may vary according to their roles and professional experiences. Currently, there is a lack of studies investigating the influence of the role and professional experiences of stakeholders on major risk management. Examining variations in stakeholders' views and attitudes can therefore provide insights into whether and how the identified social concerns are represented in stakeholder perspectives. Therefore, to adopt and further refine the proposed risk management approach, specific research is needed to examine stakeholders' perceptions, attitudes, and views toward major risk management, and to identify the common features that can be extracted from different stakeholder groups with diverse fields of expertise. As a result, a survey is conducted and analysed to elicit stakeholders' views and attitudes toward the proposed risk decision-making approach.

SRQ4 (Chapter 5). *How can the proposed approach for supporting risk decision-making, be validated?*

Before the proposed approach is formally applied to real-world risk management, it is essential to design an implementation method and to test its effectiveness. Risk ranking plays a vital role in risk assessment, and it helps to set risk management priorities and decide which risk should receive more attention. To meet the objectives of the study, a role-playing game (RPG) is employed as a potential engagement method to simulate and validate the risk management decision-making approach.

1.3 Thesis outline and scope

This dissertation consists of six chapters (including this one), and related chapters are grouped. Based on the content, the first two chapters can be grouped into an introductory part (Part I). Chapter 3 to Chapter 5 focusing on developing and validating the responsible risk management approach are grouped into the second part (Part II). Part III concludes the dissertation and discusses the future directions on improving the risk management approach. The structure of the parts and their relationship is illustrated in Figure 1.1.

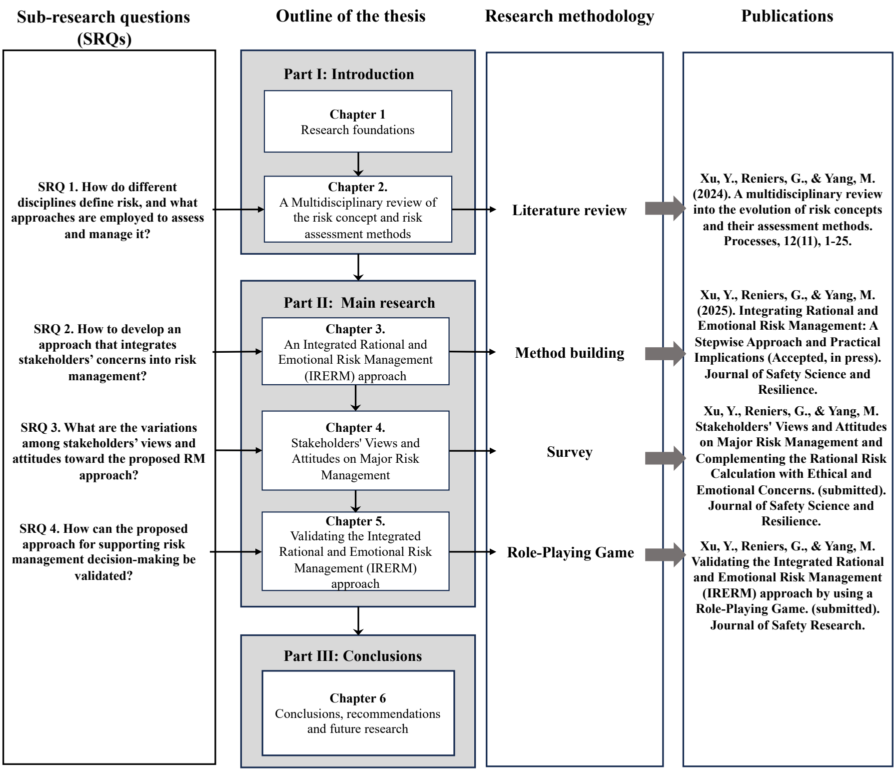

Figure 1.1 Flowchart of the thesis structure.

Part I contains the first two chapters of the thesis. Chapter 1 introduces the research background, motivations and objectives, research questions, and organization of the thesis. In Chapter 2, the historical background and development of risk concepts across major fields of study, definitions and interpretations of risk, and risk assessment methods are introduced. Moreover, a review of the current contributions in the scientific literature concerning integrated risk management approaches is presented. Current research gaps regarding interdisciplinary studies of risk are analysed.

Part II of the thesis consists of three chapters focused on the development and validation of a novel major risk management approach called IRERDM. Chapter 3 presents a process approach that is used for integrating stakeholders' emotional and ethical concerns into major risk management, as well as its application in a hypothetical ammonia plant site-selection decision problem. The chapter first redefined the risk characterization and risk description by the involvement of the "human" dimension, thus advancing the understanding of risk as both a technical problem and a societal issue. Moreover, the detailed steps of involving stakeholders in risk management are described. Finally, a hypothetical case study is applied to illustrate how the approach can be used to incorporate multi-stakeholders' concerns and enhance the acceptability of risk management and risk decisions.

Chapter 4 is an exploratory stage to confirm the validity of the risk management method proposed in Chapter 3. This chapter focuses on investigating the viewpoints and attitudes of stakeholders relating to major risk management towards the IRERDM method. The study is conducted using an online questionnaire and distributed to various types of stakeholders relating to major risk management at different national levels. Furthermore, we use descriptive analysis and Chi-square tests to analyse the influence of roles and professional experiences of stakeholders on the results. Finally, the results of survey responses are reported.

Chapter 5 aims to further validate the practicability and usefulness of the IRERDM approach in enhancing risk management. This chapter simulates the real risk management process by using the IRERDM approach when applying the Role-Playing Game (RPG) research design. The risk decision making process is performed by students instead of real stakeholders. First, the rationale of applying the RPG as an experiment to validate the IRERDM approach is elaborated. Then, a step-by-step implementation of the RPG and roles of facilitator and participants are described. Finally, a thematic analysis of the interaction among participants is presented. At last, the usefulness and findings are extensively discussed. The designed step-by-step process for conducting the game provides a replicable tool for future researchers and a way to include stakeholder engagement in the decision-making process of RM.

Finally, in Part III, Chapter 6 provides responses to the sub-research questions posed in Chapter 1. This chapter summarizes the main findings and contributions of the dissertation. Limitations of the performed research are also discussed and directions for future research are given.

Chapter 2 Literature Review

This chapter is modified based on the following published journal paper: Xu, Y., Reniers, G., & Yang, M. (2024). A multidisciplinary review into the evolution of risk concepts and their assessment methods. Processes, 12(11), 1-25.

Risk is a complex and multi-faceted concept defined and addressed differently across disciplines. This chapter provides an overview of the theories, approaches, models, and other fundamental aspects of different disciplines relevant to risk concepts, with the aim of exploring possible ways to advance risk assessment and management. First, we provide an overview of the historical development of risk studies in nine major disciplines. Then, definitions and interpretations of risk are reviewed and grouped into four categories, followed by detailed discussion of the connections between these definitions and their disciplinary backgrounds. In addition, a comparison analysis of current risk assessment methods is conducted. Current research trends are obtained based on systematic literature review. Finally, this chapter outlines future research directions, aiming to build a more comprehensive and integrated risk perspective combining insights from multiple disciplines.

2.1 Introduction

The risk concept is the foundation of the approaches and methods of risk management, as terminology can affect and become a part of the theoretical framework in which we study risk and how we cope with it (Athearn 1971). The practices of modern formal risk management have only emerged in recent decades, nevertheless, people have been dealing with risk problems for a long time. Since the 1990s, there has been an increasing interest in redefining and refining concept of risk and added substantial knowledge to this fundamental area (Greenberg, Cox et al. 2020). The distinction between risk and related concepts also received much attention, i.e., risk and hazard; risk and risk perception (Bohnenblust and Slovic 1998). Aven's work provides a historical perspective, showing how the definition of risk has shifted in recent decades from probability-based thinking to an emphasis on uncertainty (Merkelsen 2011). Boholm explored how Swedish Government agencies define risk and identified inconsistencies between usage and definitions (Aven 2012).

Modern society is increasingly occupied with preventing, managing, and mitigating all types of risk across a range of societal sectors, such as insurance, common law, natural disasters, epidemic disease, pollution, food contamination, building and fire codes, transportation accidents, and traffic injuries (Covello and Mumpower 1985, Beck 2006). The literature on formal risk studies has expanded across multiple disciplines, each contributing unique insights on the taxonomy of risk perspectives. For instance, Jasanoff identified "two cultures" divide in risk analysis: disciplines such as mathematics, biostatistics, toxicology, and engineering, contribute to quantitative risk analysis on one side, while law, psychology, sociology, and economics contribute to nonquantitative side (Jasanoff 1993). Althaus's multidisciplinary survey of risk literature uncovered conflicting attributes of risk across fields, with risk being viewed as objective or subjective, knowable or unknowable, individual or collective, and both rational and emotional (Althaus 2005). Similarly, Renn's review highlights a distinct divide between the technical and natural sciences, which focus on the physical impacts of risk, and the economic, psychological, and social sciences, which emphasize the relationship between risk and society (Renn 1992, Renn 2008).

In recent years, formal risk management is increasingly recognized in organizations as a systematic approach to avoid losses and disasters. Many risk management frameworks are developed to identify, assess and treat risks, from an organizational context to national safety and security. These frameworks—such as the COSO Enterprise risk management framework (Eckert 2006); the risk framework of the Dutch Government (Veiligheid 2023); and the ISO 31000 standard on risk management (ISO 2018), Cabinet Office (Office 2002)—cover a broad spectrum, including infectious diseases, ecological safety, cyber threats, major accidents, social and political stability, terrorism, international and military threats, economic, etc. Despite ongoing scientific debate on the multidimensional nature of risk, nearly all integrated frameworks are based on the rational idea that risk is a combination of probability/uncertainty and consequences, with little attention to contextual factors (Ale, Aven et al. 2009).

Nonetheless, many real-world risk problems are complex and multi-faceted, requiring a new risk management paradigm that bridges the disciplinary divide and allows for a more holistic approach to address the complexity of modern risks. While prior research has reviewed disciplinary perspectives on risk, there remains a need for studies that systematically analyze how definitions of risk are linked to disciplinary backgrounds, and how these different perspectives might collaborate effectively. This chapter re-examines the concept of risk from a multidisciplinary perspective, with a focus on risk definitions and assessment methods. This review will:

- Mitigate the tendency to view and assess risk without considering its context;
- Clarify the reasons why risk is understood and assessed differently across disciplines;
- Shed light on the intellectual origins of current approaches to risk;
- Provide a foundation for future interdisciplinary collaboration.

The literature review is organized as follows. Section 2 elaborates on the literature review methodology of this study. Section 3 explores the historical development of risk research in different disciplines, with a focus on the initial engagement of different fields in the study of risk and main contributions. Section 4 identifies and categorizes diverse definitions and interpretations of risk. Section 5 explores "how" risk is assessed according to these varied definitions and interpretations. Before concluding, Section 6 discusses the impact of multidisciplinary perspectives on current risk theories and anticipates potential future directions in risk management.

2.2 The review methodology

The objective of this study is not to provide a thorough review to cover all risk concepts and its assessment methods. It is unrealistic to cover all relevant studies for such a broad topic. The primary aim is to establish the perspectives and methods of major disciplines in addressing risks. Snowballing is a literature review method that identifies additional papers from a reference list or citations (Wohlin 2014). We utilized a structured approach that integrates a backward snowballing literature review (from the reference lists) approach, complementary database search, and personal knowledge in this study. The detailed flowchart of snowballing literature review process is shown in Figure 2.1.

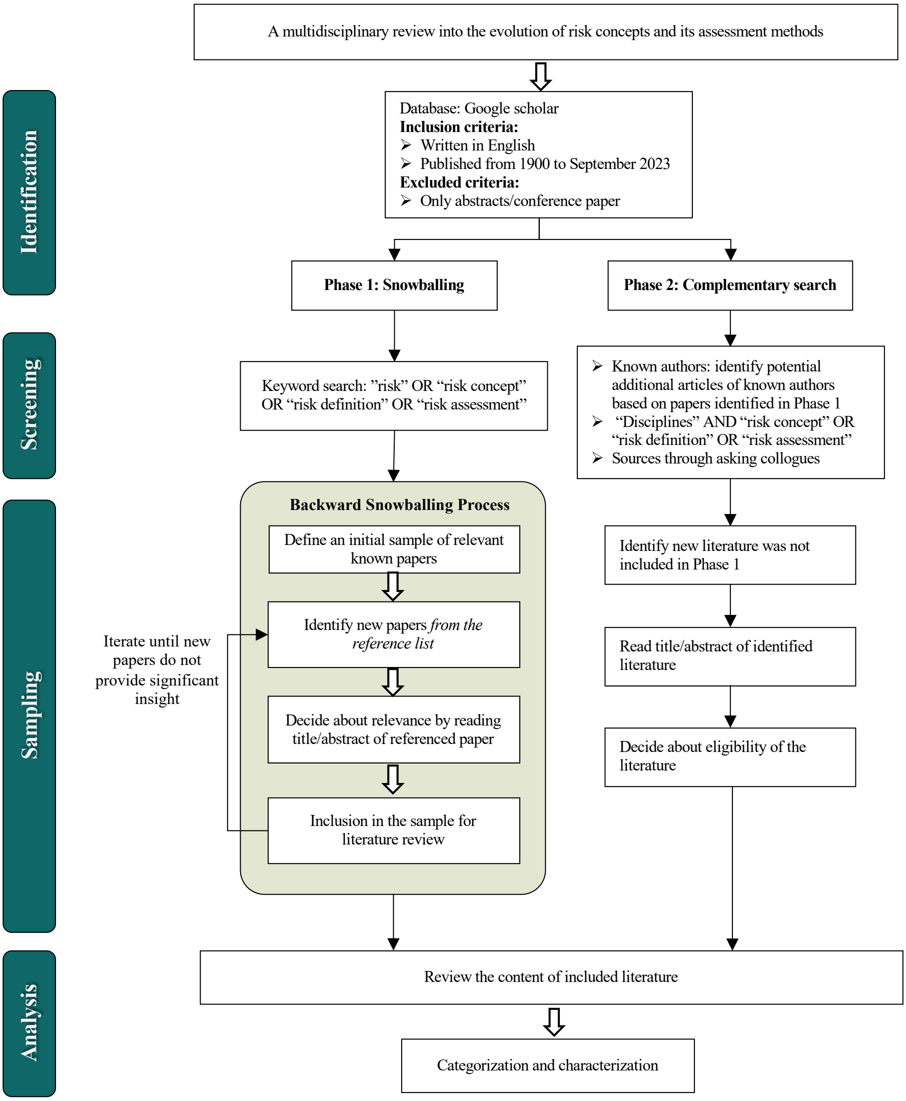

Figure 2.1 Flowchart of the snowballing literature review process.

The included articles are limited to the period of publication from 1900 to September 2023. Articles not written in English are excluded. To avoid bias that some publishers may be in favor of certain fields of study as well as to avoid overlooking some obscure papers, Google Scholar is set as the main database. The literature review study is divided into two phases. It starts with the snowballing sampling method. Firstly, the initial highly relevant and highly cited papers are identified using keyword search ("risk definition" OR "risk concept" OR "risk assessment") from the Google Scholar database. Then, the identified initial known papers are included in the snowballing sampling process. The backward snowballing process is an iterative process involves several steps. First, based on the screening results, the highly cited papers were selected for further review by looking at the title and abstract. Then, the references of the initial selected sample were reviewed and examined by reading the title and abstract. At last, the new set of relevant literature was included in another round of the snowballing process. The new set of literature underwent the same snowballing process until new papers did not contribute insight. To improve the after that, complementary database research is applied to identify articles that may have been omitted in the first phase. Finally, the identified articles are categorized by discipline for further characterization analysis.

2.3 Historical development of risk studies

Before diving into how risk concept is defined and assessed, it is essential to understand the origins and evolution of risk studies. A historical timeline that begins in 1600 is presented in Figure 2.2. The classification of disciplines mainly refers to (Althaus 2005). Nine disciplines—mathematics, philosophy, economics, anthropology, psychology, sociology, law, engineering, and medicine—are discussed. The upper markers along the timeline indicate the sequence of initial engagement of different fields in the study of risk. The notes below the timeline mark significant risk theories, approaches, or phenomena in certain periods.

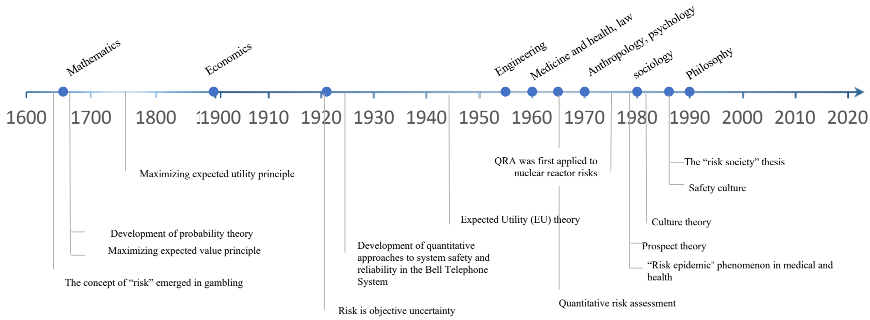

Figure 2.2 Timeline of multidisciplinary engagement in the study of risk and key milestones in development of risk theories and applications.

It should be noted that the aim of this section is to grasp a broad overview of how different disciplines approach risk, serving as a foundation for readers to understand the different disciplines approach risk, serving as a foundation for readers to understand the antecedents of various risk definitions and assessment methods. The in-depth discussions on perspectives of risk can be found in more specific studies on the topic.

2.3.1 Mathematics

Many documents (Jacobs 2000, Althaus 2005, Dein 2016) suggest that the concept of risk may have emerged from significant developments in social, intellectual, and economic life in the Middle Ages. In 1657, mathematician Blaise Pascal introduced probability theory. After that, the mathematical calculation of chance was soon applied to gambling and economic ventures, investments, and insurance (Boholm 2015). This heuristic was further enhanced by Pascal's work in proposed the maximizing expected value principle (agents facing risk would maximize the expected value) for calculating the fair price of a gamble (Peterson 2008). Daniel Bernoulli would later build upon this insight in 1738, when he introduced the concept of utility and formulated the maximizing utility principle that explained why people would pay only a small price for a game of infinite mathematical expectation (Schoemaker 1982). The probability theorems of 17th-century mathematicians provided the groundwork for the prevailing conceptions and practices of risk today (Dannreuther and Lekhi 2000).

2.3.2 Economics

The earliest discussion of risk in scientific economics evolved around the 1890s when research began to be undertaken on formulating a theory of distribution related to profit (Wood 1964). This sparked an interest in risk and risk-bearing, which manifested itself in the insurance literature. At the same time, applied mathematics sought to apply statistical methods to economics, resulting in the use of relative frequency as a measurement approach for risk. By 1920, the dispersion of a relative frequency distribution had been identified as risk (McGoun 1995). In 1921, to make a distinction between measurable uncertainty and unmeasurable one, economist Frank Knight defined risk as "objective uncertainty" that is measurable when enough evidence is collected (Knight Frank 1921). In the mid-1940s, building on Bernoulli's expected utility principle, John von Neumann and Oskar Morgenstern developed the Expected Utility (EU) Theory (Gollier 2001). Utility can be understood as benefit, advantage, pleasure, good, or happiness (Broome 1991). The Expected Utility (EU) theory is one of the most influential normative decision theories to specify how individuals make decisions under risk (Mangram 2013). It is built upon utility theory--people value risks subjectively according to the utility value of gains and losses, which is related to ones' wealth status (Tucker and Nelson 2017). Variations in individuals' responses to risk are therefore explained by differences in their utility functions. One important implication of this framework is risk aversion, which reflects an individual's general dislike of outcome variability rather than a specific sensitivity to losses. Since the Second World War, the EU theory has played a significant role in management (especially decision science), economics, and psychology (Schoemaker 1982). Within the EU framework, risk aversion implies a symmetric evaluation of gains and losses with respect to final wealth. However, empirical studies suggested that an individual tends to respond more strongly to potential losses than equivalent gains. Kahneman and Tversky use the term "loss aversion" to describe this asymmetry between the perception of gains and losses (Kahneman and Tversky 2013).

2.3.3 Engineering

With the development of industrial society, a growing number of large and complex systems combined with operational risks gave rise to scientific risk research of engineering to systems safety (Zio 2009). Around 1924, the development of quantitative approaches to system safety and reliability in the Bell Telephone System constituted an important building block for the emergence of Probabilistic Risk Assessment (PRA) in various fields of complex engineering systems (Zachmann 2014). After World War II (1939-1945), the profound development of technologies, especially in the chemical and nuclear industries, brought about potential catastrophic and long-lasting consequences, resulting in systematic attempts to study societal risks (Renn 1998). This led to the establishment of modern risk management studies in 1955 (Dionne 2013). Since the 1970s, as late modern societies began to pay more attention to the uncertainties accompanying the increasing ignorance and rapid development of modern technology and industry, risk research and risk management have become increasingly scientific issues (Rasmussen 1974). The engineering sector has been influenced by the statistical method in finance of calculating probabilities to develop the idea of risk (Zinn and Taylor-Gooby 2006). Engineering problems gave rise to a quantitative approach to system safety, which laid the foundation for the emergence of Quantitative Risk Assessment (QRA). QRA establishes connections between threats and consequences (Nateghi and Aven 2021). As a core method in engineering risk research, QRA was first applied to nuclear reactor risks in 1975 and has since been used in various non-nuclear situations (Bradbury 1989). Classic QRA methods such as Fault Tree Analysis (FTA) and Hazard and Operability Study (HAZOP) were developed in 1960s and 1970s in response to increasingly complexity in military, nuclear, and chemical industries (Amyotte and Khan 2020). Scientific methods for identifying causal links between adverse health effects and different types of hazardous activities and mathematical theories of probability jointly built the roots of modem risk analysis (Covello and Mumpower 1985).

2.3.4 Medicine

The disease panorama in Western countries has changed considerably over the last century, moving from acute to more chronic diseases, which caused a shift to more preventive medical activity (Rørtveit and Strand 2001). Meanwhile, calculating risk entrenched in the scientific world provides the theoretical bases for health-related decision-making in clinical settings. Widespread techniques and methods for the analysis of “risk” in the professional literature on health and healthcare have developed after the 1960s. Health Risk Appraisal/ Assessment/ Management began emerged in the medical field at that period (Hayes 1992). Since the 1980s, “risk” has appeared more often in medical journals, and especially in epidemiological literature. This phenomenon was defined by Skolbekken as a “risk epidemic” (Skolbekken 1995). In evidence-based medicine, efforts are made to gather the data of risk factors and how they lead to the outcome (Feinstein and Horwitz 1997). The emergence of Health Risk Assessment has also brought about many controversies, such as how to avoid over-medicalization and the fact that the human body is a non-linear system that cannot be adequately measured using the linear models on which risk assessment is based.

2.3.5 law

With the increasing moral anxiety of modern lawyers and the societal disappointment in their ethical regulation, legal systems underwent a dramatic change in the 1960s, and risk management norms gradually took over contemporary law and society (Alfieri 2005). Contemporary legislation developments turn to the preventive, future-oriented logic of risk. Modern law adopted the conception derived from economics that an action can be said to generate loss if it increases the probability of a loss (Priest 1990). The probabilistic process helps the legal system to adopt a broader and more expansive view of the sources of loss. It is devoted to risk control, with less focus on strict causation than on contribution to the occurrence of harm. The same trends could be seen in criminal law. Risk-driven law diminishes the appreciation of the moral choices facing lawyers in practice and the other-regarding obligations of lawyers in society (Alfieri 2005). Since the early 1980s, criminal law has attempted to act as a preventive force to control the risk of future crime. Risk-driven criminal law focuses on managing the risk of crime rather than the crime itself (Pratt and Miao 2019). Sentencing offenders as dangerous, rather than sentencing them for a specific offense, appears to have increased in recent years (MacAlister 2005).

2.3.6 Anthropology

Since the 1970s, an increasing number of anthropologists has shifted toward risks and hazards as they are aware that the populations' lives are affected by the environment (Faas and Barrios 2015). Technological progress has brought about many more man-made risks to modern society than traditional societies, so the scientific community has become more aware that social concerns must be considered while promoting new technology. This initiative allows cultural and social anthropologists to delve into previously unexplored territory (Velimirovic 1975). Culture is anthropology's leading innovation and core explanatory tool; it has proven to be key to understanding why and how people worldwide perceive and respond to risks (Boholm 2015). The concept of "culture" came to refer to the distinctions between thoughts and behave manners of people around the globe. In its deep and holistic framework, it incorporates kinship, subsistence, economics, politics, dress, food, exploitation of place, scheduling of time, arrangement of space, classification of humans, social roles and relationships, child raising, laws, rules, and more (Hoffman 2015). There are various definitions of "culture", generally, culture can be understood as "that complex whole which includes knowledge, beliefs, arts, morals, laws, custom, and any other capabilities and habits acquired by a (human) as a member of society" (White 1959).

In 1982, social anthropologists Douglas and Wildavsky proposed "culture theory" that assumes "risk" is created within a culture (Douglas and Wildavsky 1982). Cultural theory is an approach of interpreting how and why individuals form judgements about danger and threat. The point of cultural theory is that such judgments are formed dependent on social context, and related to rights to know, justice for those likely to be affected by damage or loss of peace of mind, and about blame, responsibility and liability. Thus, what is considered as risk? and how serious that a risk is thought to will be perceived differently among organizations or groups became the main focus of cultural approaches to risk (Lupton 1999).

Furthermore, cultural theory made valuable contributions to the deliberative process in risk management (Renn 2004). The normative implications of cultural theory in the context of risk assessment, particularly emphasizes "fairness" as the key to resolving conflicts between these different perspectives (Tansey and O'riordan 1999). The fairness is related to how to treat different groups appropriately and may involve consensus building, and appropriate use of compensation or liability rules. Pure technical concept of risk that focuses on "how safe is safe enough" may never get the satisfactory answer. The normative procedural recommendations of cultural theory are that "how fair is safe enough" is more important than "how safe is safe enough". Moreover, "trust" towards the institutions that create and regulate risk is of great interest (Tansey and O'riordan 1999). Cultural theory promotes and supports direct incorporation of citizens' viewpoints in the decision-making process.

2.3.7 Psychology

The interest in risk studies in psychology fields began with economic psychologists. Around the 1970s, a group of economic psychologists with a long experiment tradition rejected the rational choice theory of microeconomics (Zinn and Taylor-Gooby 2006). Under the rational choice theory of economics, people are risk-neutral to optimize the expected cost or profit (Jammernegg and Kischka 2007). However, the experimental evidence demonstrated that people making judgments under uncertainty do not fully adhere to rational thought based on assessing the likelihood and severity of outcomes; yet people follow a way of intuitive thinking that makes decisions quick and unwittingly (Tversky and Kahneman 1974, Smith 1991, Mathis and Steffen 2015). This was published in the seminal work by Kahneman and Tversky where they demonstrated that "cognitive illusion/bias" stem from heuristics (Tversky and Kahneman 1974). In the same work, they identified three main heuristic types, including representativeness, availability bias, adjustment and anchoring. To integrate these behavioural observations into rational decision theory, Kahneman and Tversky developed an alternative risk choice model: prospect theory (Kahneman and Tversky 1979). Zohar (Zohar 1980) introduced the concept of "safety climate" demonstrating that workers' risk perceptions can be shaped by organizational policies and practices. This study suggests that production workers within the same organization tend to share a relatively unified set of cognitions regarding safety.

The other main branch of psychology studies on risk emphasizes social and cultural influence on misperception of risk. This branch of work streamed from studies on risk acceptability (Starr 1969) and applied empirical psychometric approaches to quantifying risk (Slovic 1987). The distinguishing feature of the psychometric approach is using various psychometric scaling methods to produce quantitative measures of perceived risk (Slovic 1992).

2.3.8 Sociology

Since the 1980s, the notion of risk has become extremely popular in many areas of social science, from policy and theory to international relations and political science. Its effect is particularly marked in sociology, where a distinctive "sociology of risk" has emerged (Reith 2004). In the mid-1980s, social scientist Beck proposed the famous "risk society" theory to replace "industrial society", arguing that risk is becoming increasingly central to our global society (Beck 2016). These risks are not only connected with industrial activities but also to how actors deal with what they perceive as risks. Risk management is no longer limited to certain technological risks but has become integral to all aspects of social life. Sociology highlights the importance of context (social, material, economic, cultural) for understanding social life. The social construction of misperception of risk, the social amplification of risk, and the social construction of risk (Lidskog, Sundqvist et al. 2013). Thus, risk management focuses not only on how organizations deal with the technical calculation of risks but also with the actors they perceive as possible threats and potential risks to the stability of the organization. Meanwhile, the urgent need for managing today's risk has promoted the creation of a new discipline that is risk assessment (Slovic 1987).

In 1998, Kasperson et al. proposed the Social Amplification of Risk Theory (SART) (Kasperson, Renn et al. 1988). The SART framework explains how the information process, institutional structures, social-group behaviour, and individual responses determine the consequences and how the "ripple effect" of risk events introduces the temporal and geographical extension of impacts. The SART recognizes the role of engineering and science understanding of risk, however, it argues the deficiencies of technical risk analysis cannot provide information about social indirect impacts.

2.3.9 Philosophy

Philosophy is distinguished by the fact that it has linkages with every other academic discipline. In the 1990s, philosophers increasingly identified a wealth of risk-related issues in need of philosophical elucidation (Cranor 1990). Philosophers have illuminated new insights into the terminological clarification of risk, the ontological base and epistemic status of risk, risk and moral principles, its decision-theoretical aspects, the implications of risk in political philosophy, and various other topics (Asveld and Roeser 2009, Hansson 2012, Roeser 2012). Furthermore, the philosophers' argumentation analysis has also led risk experts in other fields to start examining the "value-laden" aspects of risk. For example, when is it ethically acceptable to expose other person to a risk (Ersdal and Aven 2008, Vanem 2012)? How to extend the risk definition with consideration of moral principles (Gardoni and Murphy 2014)? How can risk analysis take account of the possibility that risk analysis itself is "wrong" (Aven and Renn 2009)?

2.4 Definitions and interpretations of risk

After understanding the historical progression, the next step is to identify "what" risk means in different contexts. There is a wealth of literature discussing risk concepts. It focuses on analysing the linkage between the definition and the disciplinary background to uncover the reasons "why" risk is approached differently across disciplines. A range of definitions and interpretations of risk was first collected from the literature across different disciplines. To have a more coherent understanding of these definitions, they were subsequently grouped into four disciplinary categories: economics and decision science, engineering and science, social science, and philosophy. A list of definitions or interpretations of risk from diverse disciplinary literature was compiled and summarized in Table 2.1.

Table 2.1 Compilation of risk definitions and interpretations from the Literature.

Reference	**Year**	**Descriptions, definitions, and understanding of risk**	**Source**
(Haynes 1895)	1895	If there is any uncertainty whether or not the performance of a given act will produce a harmful result, the performance of that act is the assumption of a risk	Social science & medicine
(Knight Frank 1921)	1921	Risk is objective uncertainty	Risk, uncertainty and profit
(Domar and Musgrave 1944)	1944	Risk is expected loss	The Quarterly Journal of Economics
(Allais 1953)	1953	Risk is the variance of the probability distribution over the utilities of all possible consequences	Econometrica
(Nickerson and Feehrer 1975)	1975	Risk is expected value, encompassing both the outcomes of a decision and some representation of the probability of the outcomes	Decision making and training
(Libby and Fishburn 1977)	1977	Risk is the variance or dispersion of outcomes	Journal of accounting research
(Fishburn 1981)	1981	A function of the probability of loss and the distribution of losses	Theory and decision
(Kaplan and Garrick 1981)	1981	Risk is a set of triplets	Risk analysis
(Douglas and Wildavsky 1982)	1982	Risks are the dangers that societies define as troublesome	Risk analysis
(Beck 2020)	1992	A systematic way of dealing with hazards and insecurities induced and introduced by modernization itself	Theory, culture & society
(Rehmann-Sutter 1998)	1998	Risk is the relationship of responsibility for harms for which the action of some person was a condition	Risk: Health, Safety & Environment

(Rosa 1998)	1998	Risk is a situation or event where something of human value is at stake and where the outcome is uncertain	Journal of risk research
(Reventlow, Hvas et al. 2001)	2001	The statistical probability that an undesirable event – disease or death – may strike.	Scandinavian journal of primary health care
(Loewenstein, Weber et al. 2001)	2001	Risk as feelings	Psychological bulletin
(Malmfors and Rosing 2002)	2002	RISK=Replaces Incomplete Scientific Knowledge	Toxicology
(Ale 2002)	2002	Risk has two components: the extent of the damage and the probability or likelihood that such damage will occur	Safety science
(Slovic and Weber 2013)	2002	Risk is seen as a concept that human beings have invented to help them understand and cope with the dangers and uncertainties of life	Regulation of Toxic Substances and Hazardous Waste
(Boholm 2003)	2003	What is to be considered a 'risk' depends entirely on cultural settings and assumptions; risks are culturally defined and selected	Ethnos
(Hufschmidt, Crozier et al. 2005)	2005	Risk is a measure of the probability of adverse effects on health, property, and society, resulting from the exposure to a hazard of a given type and magnitude, within a certain time and area	Natural Hazards and Earth System Sciences
(Aven and Renn 2009)	2009	Risk refers to uncertainty about and severity of the events and consequences (or outcomes) of an activity with respect to something that human value	Journal of risk research
(Lidskog and Sundqvist 2012)	2013	Risks are always situated in a social context and are necessarily connected to actors' activities	In Essentials of risk theory
(Alaszewski 2018)	2015	The selection of risks reflects social and political relations within groups	Health, Risk & Society
(Goman 2018)	2018	Risk is a state of uncertainty, s.y. there is a possibility that involves loss or other undesirable outcome for an exposed actor	In Proceedings of the Central European Cybersecurity Conference

(Prabnakorn, Maskey et al. 2019)	2019	Risk =Hazard × Exposure × Susceptibility	Natural Hazards
(Blokland and Reniers 2019)	2019	Risk = reality + objectives	Sustainability
(Babic 2019)	2019	Risk + information entropy = k	Philosophy of Science
(Freeland, Knes et al. 2020)	2020	Risk can be defined as the range of all possible, but uncertain, outcomes from positive (most optimal) to negative (most suboptimal) in terms of both reward magnitude and probability	Current opinion in behavioral sciences

2.4.1 Economics and decision sciences

There are three main categories of definitions of risk in economic and decision sciences: risk=objective uncertainty, risk=variance, and risk=expected utility.

The definition of risk has evolved over time. By 1920, the dispersion of a relative frequency distribution had been clearly identified as risk (McGoun 1995). However, this definition faced scrutiny since the late 19th century, particularly among authors in the insurance field (Haynes 1895). They observed that not all risks have reliable historical relative frequencies or statistical data. Thus, risk is still present even if quantifiable statistics are not. If risk is measured by relative frequency, then some risks are unquantifiable which creates uncertainty. Although scholars recognized the distinction between probability and risk, few scholars are able to specify the nature of the term by definition. Willett (Willett 1901) was the first scholar to separate and distinguish the various aspects of the problem of explaining the nature of risk. He thinks it is necessary to define risk with reference to the degree of uncertainty about the occurrence of a loss, not with reference to the degree of probability that it will occur. In his definition, risk is the objectified uncertainty as to the occurrence of an undesired event. However, he did not make an explanation about the term "uncertainty". Knight illuminate the ambiguities concealed in the notion of "risk" and "uncertainties" by employing the terms "objective probability" and "subjective probability" to designate the risk and uncertainty respectively. Risk is defined as "objective uncertainty" to make a distinction with "subjective uncertainty" (uncertainty). In Knight's definition, risk could be calculated precisely with certainty (the relative frequency) (Knight Frank 1921).

Financial economics is formed on the foundation of Modern Portfolio Theory (MPT). MPT is an investment model that describes how investors may balance risk and return in constructing investment portfolios (Holton 2004). The basic principle of risk and return trade-offs is that the riskier the investment, the greater the required potential return. In Portfolio theory, risk is synonymous with volatility, representing the chance that the actual return on an investment will be different than expected (Mangram 2013). The two most common ways of measuring volatility or risk are the calculation of the variance of an expected return and the standard deviation from an expected return. It should be noted that in investment context, decision under risk must be understood as a joint function of the expected return and variance. Sometimes investors will choose to bear greater risks in order to achieve higher returns.

Economics and decision science risk studies are closely related to the question of "how people should make decisions". Rational choice theory is essential in modern economics. It defines that a rational individual would seek utility-maximizing when faced with various alternatives (Weirich 1986, Sugden 1991, Mathis and Steffen 2015). Normally, the premise underlying pure rational choice theory under risk is that decision-makers do not know the precise outcome but have perfect knowledge of the likelihoods of various outcomes (March 1994). Additionally, the EU theory acknowledges that real life scenarios are a mixed risk and uncertainty. If individuals are risk-neutral, expected values can replace the definition of probability and utility (Tversky and Kahneman 1992). Compared with other economics definitions, it has the merit of encompassing people's subjective preference and attitude towards risk in the risk concept (Fishburn 1968).

2.4.2 Engineering and natural science

The quantitative definition of risk proposed by Kaplan and Garrick—conceptualizing risk as a set of triplets—has had a profound influence on the way risk is conceptualized, particularly within engineering disciplines (Kaplan and Garrick 1981). Engineers and scientists prefer quantitative approaches that focus on "operationalization" and "measurement". From the engineering and science point of view, risk can be interpreted from a systems-based perspective as a function of system states (Haimes 2009). They believe that risk could be defined and measured mathematically and free from subject bias. Different from the economics domains, engineering risk assessment is often associated with systems where data is insufficient or absent. Actuarial approaches are inappropriate for engineers. Risk calculations in engineering have to handle various uncertainties. Hence, experts have to judge the probabilities based on their experience and knowledge. The illustration of system-based definitions is shown in Figure 3.

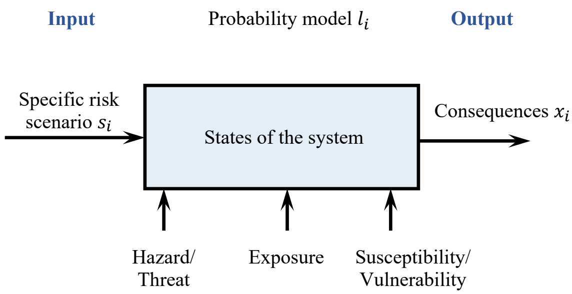

Figure 2.3 The illustration of quantitative "set of triplets" definition of risk. Hazard/threat, exposure, and susceptibility/vulnerability are represented as attributes of the state of the system rather than as independent elements of the triplet.

- s_i denotes scenario ith risk scenario;
- l_i is the likelihood of the scenario;
- x_i denotes the potential consequences;
- Susceptibility/vulnerability represents the inherent states of a system to adapt and respond to hazards;
- Threats could be seen as specific interruptions outside the system;
- Exposure can be defined as assets and values exposed to certain threats.

There are three main discourses in defining risk in engineering and science literature: probability-based, uncertainty-based, and moral-based. This probability-based definition still plays an important role in today's engineering risk management.

The probability-based definition has two branches. One is from safety and reliability engineering in which risk is defined as probability and consequence. The other one is defined by a combination of "exposure", "susceptibility/vulnerability", and "consequence". This is because safety and reliability engineering are primarily concerned with probability of failures in the operating system itself. The second type of definition is commonly seen in environmental and security science fields. Risks are caused by factors external (natural disasters, terrorist attack) to the reference system. This is what leads to the subtle difference in definition. But in "exposure", "susceptibility/vulnerability" are all calculated in the form of probability. Regardless of what variables are used to define risk, probability and the severity of consequences are two indispensable elements.

In the past decade, scientists with engineering backgrounds have paid attention to debates and discussions on the concept of risk. Scholars have focused on the distinction between risk concept and risk characterization and how to represent uncertainty accurately. They pointed out "probability" is just a way of characterizing "uncertainty", however, not the only way. Particularly, fruitful results have been yielded by introducing the "knowledge" dimension in characterizing the "uncertainty" component of risk (Aven, Renn et al. 2011, Aven and Reniers 2013). The concept of risk is shift from probability-based to uncertainty-based. Furthermore, the acknowledgment of the "time" scale of risk concept provides support for resilience works (Logan, Aven et al. 2022). According to the uncertainty-based definition, risk as a concept exists objectively, whereas risk assessment is dependent on the assessor and is therefore subjective.

Influenced by economic, science and engineering, psychometric, and social risk studies, Gardoni and Murphy proposed a synthesized risk ranking framework and applied it to dam risk assessment. The framework expands the two-dimensional risk definition to three-dimension with the addition of “source of risk” that emphasizes the moral differences between individuals. Specifically, voluntariness, distribution of consequences and causation are incorporated to represent equity and intentionality (Gardoni and Murphy 2014).

2.4.3 Social sciences (Anthropology, psychology, sociology, law)

Risk does not have a precise definition in social sciences, unlike fields such as economics and decision science, engineering and science. In social science literature, risk is a disputed concept that have comprehensive meanings. Social scientists argued that all human activity, including the physical sciences, relies on social, cultural, and political construction (Douglas 2018). Based on how “risk” is constructed, different disciplines can generate different interpretations in the social sciences field.

According to anthropologists, statistical probability is a mathematical concept that quantifies the chances of an event or occurrence, and it has limited relevance for explaining how people think and act in situations where there is an element of uncertainty. For example, the cultural theory assumes risk is a cultural phenomenon and what constitutes “risk” is entirely dependent on cultural settings and propositions (Boholm 2003). Risk is decided by a collective belief system thus it varies among culture and social context.

From a psychologist's view, especially social psychology, risk could be defined by any individuals who may be influenced (e.g., experts employ risk assessment to evaluate hazards, and laypeople rely on intuitive judgments) (Solberg and Njå 2012, Slovic and Weber 2013). However, cultural theory does not take into account individual differences in perceptions of nature. What is essential for anthropologists is to understand how groups select and frame risks. For example, some social misperception of risk studies concludes subjective attributes that influence individuals’ view of acceptability of risks, voluntariness, benefits (Starr 1969), dread, and familiarity (Fischhoff, Slovic et al. 1978). The subsequent studies of risk-seeking behavior studies in economic and psychology literature also explains risk can have desired outcome. Depending on the value actors attributed to the manifold issues at stake, an outcome can be positive and/or negative (Battistelli and Galantino 2019).

The sociology of risk evolved from psychological and anthropological perspectives. Works on the sociology of risk generally focus how the social and cultural factors that influence the selection of “risk”. In that sense, risk is also dynamic, continually modified by the societal environment. There are two major viewpoints of risk in sociology. The social construction of risk theory denies the “objective” elements of risk and regards risk purely shaped by social environment. Nonetheless, the SARF emphasizes public perceptions can amplify the real dangers and leading to risk perception deviated from risk assessment.

In the context of law, risk is used to conceptualize and address social problems, and as an incentive to reduce individual claims on collective resources (Baker and Simon 2010). While the law demands positive statements by scientists that a risk does exist or does not exist (Foster, Bernstein et al. 1999), the results of risk research are often ambiguous. This makes translating scientific data into something that can be used to make decisions in a legal context difficult (Kirk 2019). As such, studies in law do not emphasize probability as much as the field of engineering. Instead, the concentration of the lawyer is the causation and liability of risks (Rehmann-Sutter 1998, Valverde, Levi et al. 2005).

2.4.4 Philosophy

Philosophy provides a new perspective for risk definition research from the perspective of epistemology and ontology. Ontology denotes the state of reality, while epistemology represents the creation of knowledge and understanding. Ontology focuses on whether risk exists objectively independent of risk observers. There are many discussions on the ontology of the concept of risk. For instance, Shrader-Frechette proposed a scientific proceduralist approach that assumes risk is neither a social construct nor purely objective (Shrader-Frechette 2009). Solberg and Njå maintained that all risk claims are subjective. Risk as a possible state of affairs is a confusion between ontology and epistemology. They believe that when people think of risk, they always link it with specific activities or hazards. Hence, risk is a concept that we used to cope with the logically possible future states of affairs and risk does not exist objectively (Solberg and Njå 2012). Blokland and Reniers reasoned that when no objective can be attributed to reality, there is nothing at risk, and thus the concept of risk is not valid (Blokland and Reniers 2019). Peschard et al. argued that risk is based on objective facts, but risk identification and risk estimates are value-dependent processes (Peschard, Benétreau-Dupin et al. 2022). The epistemology of risk refers to the study of how we know and understand risk. From the epistemological aspect, risk is a state that something undesirable may happen, but we do not know whether or not it will. Risk is regarded as a state of lack of scientific knowledge or information. It therefore has a strong component of “uncertainty” (Hansson 2002). If uncertainty is not deemed as an element of risk, then it becomes fatalism.

2.5 Risk assessment methods

After reviewing the diverse understandings and definitions of risk, this section focuses on the different methods to measure and assess risks. We subjectively selected three standard risk assessment methods (Quantitative Risk Assessment, Multicriteria decision Making, and psychometric risk paradigms). Their scope of use, purpose, main methods, and advantages and some controversial points are discussed in the following context.

2.5.1 Quantitative risk assessment (QRA)

Quantitative Risk Assessment (QRA) is a widely used technique to identify and estimate hazards, especially in engineering and technical fields. It relies on engineering and scientific knowledge to aid "rational" decisions when the consequences of alternatives are uncertain. It aims to provide detailed quantitative information on consequences of specific hazards under uncertainty to aid decision-making regarding risks (Arendt 1990). By thoroughly examining how factors can interact, what scenarios can result, and what damage the scenarios can cause, QRA helps technicians apply quantitative approaches to handle risk aiming to provide actual values of probabilities and consequences. Through this process, QRA effectively answers three questions: What can go wrong (Scenarios)? How likely is it (frequency)? And what are the impacts? (The process of QRA is shown in Figure 2.4).

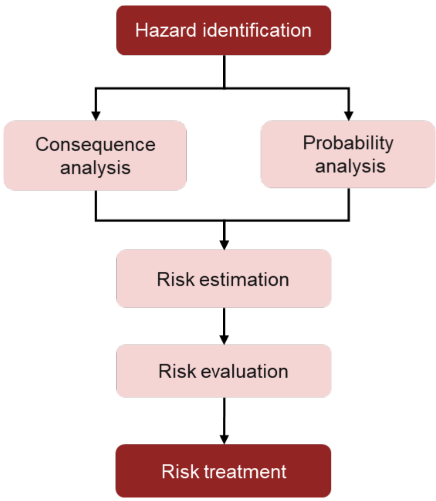

Figure 2.4 The basic process of quantitative risk assessment.

It should be noted that QRA was first developed in the nuclear engineering context. However, according to specific characteristics in other fields of engineering and science, such as chemical risk assessment and flood risk assessment, it may have different connotations and names. For instance, QRA in chemical risk assessment involves dose-response assessment, exposure assessment, and risk characterization (Haas, Rose et al. 1993). QRA in flood risk assessment involves hazard identification, vulnerability assessment, and exposure assessment (Apel, Thieken et al. 2004). But the similarities of these methods are that they all utilize quantitative approaches to estimate the level of risks.

Normally, the first step of QRA involves defining the scope and context of the analyzed system. Next, the possible hazards and potential linkage between causes and consequences are identified. After that, the frequency of the consequence is analyzed. The tools used for quantitative frequency analysis include historical data, Fault Tree Analysis (FTA), probabilistic modeling, subjective judgment and more. The fourth step involves the analysis of the outcome of the consequence. Tools for quantitative consequence analysis include subjective judgment, event tree approach, empirical physical model, experiments, and computational simulation. Next, the estimated risk is evaluated by probability-consequence diagram, i.e., F-N curves, risk matrix (Ale, Burnap et al. 2015), etc. Finally, political, procedural, and technical control and mitigation measures are identified and applied to treat risks.

There are many disputes on utilizing QRA for risk assessment. On the one hand, QRA has faced many criticisms on its proficiency of science. For example, QRA is questioned not deal adequately with data-scarcity scenarios. In dealing with “rare” events where there are substantial elements are unknown in quantitative risk assessment (Weinberg 1981). Only care about bottom-line numbers, not useful when they are highly uncertain, and risk analyst’ knowledge limitation (Apostolakis 2004), and human error in risk estimation (Freudenburg 1988).

On the other hand, quantifications tend to reduce the complex nature of risk and cannot reflect key social, cultural, and political realities. For instance, this also leads to another criticism as it concentrates on the direct impacts of consequences, such as physical harm to objectives, while ignoring the indirect social impacts (Kasperson, Renn et al. 1988). Besides, QRA may neglect emotional responses that importantly affect perceptions, judgments, and behaviors in response to real or perceived risks (Slovic 2000). Some maintains that simpler and more popular techniques such as the precautionary principle should be used instead of or in addition to QRA (Anthony Cox Jr 2007).

Despite of these, QRA does play a role in many real-world cases to help achieve preferred consequences. QRA is based on a rational idea of risk. Some studies have tried to address the limitations of risk assessment by introducing public values.

For example, Bohnenblust and Slovic proposed a framework to incorporate subjective factors such as risk aversion, willingness-to-pay, voluntariness to risk-based decision-making process (Bohnenblust and Slovic 1998).

$$R_m = \sum_{i=1}^{n} p_i C_i \varphi_i(C_i) \omega_i \tag{1}$$

Where R_m is the monetary collective perceived risk, n is the number of accident scenarios i, p_i is the probability of occurrence (per year) of scenario i, C_i are the consequences (fatalities) of scenario i, $\varphi_i(C_i)$ is the risk aversion factor as a function of C_i, and ω_i is the marginal cost or willingness-to-pay (million SFr/fatality).

In addition, some scholars suggested including societal values and ethical principles in risk evaluation tools (Johansen and Rausand 2014, Strouth and McDougall 2021). Reniers and Van Erp (Reniers and Van Erp 2016) proposed an integrated calculation formula for determining risk and obtaining risk prioritization by considering technical and non-technical factors.

$$R_i = \frac{p_i C_i^a}{\beta_i \left(E_i F_i^b\right)} \tag{2}$$

Where β_i is policy factor that varies with the degree of participation in the risk due to event/scenario i is voluntary, E_i is a parameter representing equity principle, and F_i is a parameter representing fairness principle, a is aversion factor towards consequences, and b is factor representing the availability of combination. It contains several implicit assumptions.

2.5.2 Multicriteria decision analysis (MCDA)

Multicriteria Decision Analysis/Making (MCDA/M) is a method that uses systematic analysis to evaluate and select alternatives based on diverse criteria to handle the uncertainty of diverse values and interests of individuals or decision-makers (Kiker, Bridges et al. 2005). It is a sound analytical method for risk management where multiple and often conflicting criteria are considered. It focuses on addressing multi-faceted decision-making problems in complex scenarios such as political or legal issues, social issues, project planning, etc.

The risk decision problem in MCDA is usually decomposed into a hierarchy of sub-criteria/indicators, and each criterion/indicator is called a “risk factor” which can be analyzed independently. It focuses on comparing the "risk factor" and calculate their rankings to identify risk management priorities. Generally, a MCDA analytical framework follows the serial process, as shown in Figure 2.5.

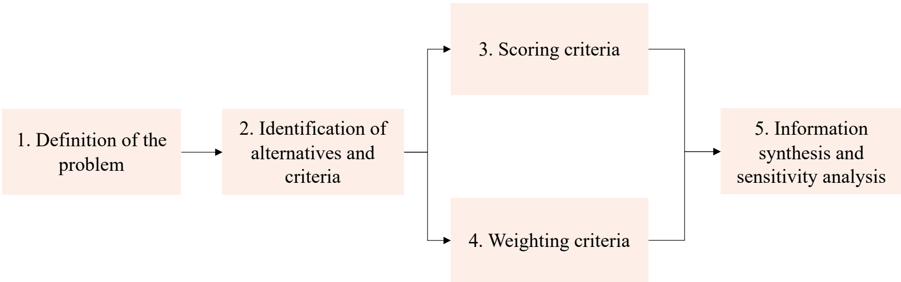

Figure 2.5 General steps of MCDA methods for risk assessment.

It starts with identification of the risk problem. The second step aims to identify risk determinants and potential choices. In some adapted MCDA approach for risk assessment, there is an additional step "identification of stakeholders" between step 1 and step 2. Stakeholders are included to gather views from them in identifying criteria and elicit priorities of the criteria. After alternatives and criteria are determined, a synthesis of knowledge and approaches, such as survey, focus group, consultation with experts, can be used to analyze the criteria. Then, the relative importance of criteria can be obtained through common approaches such as Analytical Hierarchy Process (AHP), Outranking, etc. (Saaty 2013).

MCDA as a tool aiding risk assessment has many advantages. First, a MCDA approach can take account into multiple dimensions of risk as well as various values of stakeholders simultaneously. Moreover, a MCDA approach can integrate various types of data. Besides, in MCDA, all risk factors are represented using metrics make the assessment process more transparent and accountable (Hongoh, Hoen et al. 2011).

However, there are also a number of deficiencies of MCDA for risk assessment. One of the most crucial limitations is that the results of MCDA can be sensitive to subjective judgments, particularly in the selection and weighting of criteria. MCDA is only suitable for decision-making processes that have sufficient time. Furthermore, MCDA usually based on simple additive and multiplicative logarithms regarding criteria scores and weights. However, the proxy-based models might give misleading results because aggregating risk factors into a single proxy can obscure their underlying relationships (Keisler and Linkov 2021). For example, in QRA, risk = probability ×

impact. The risk factors "probability" and "impact" are multiplicative. Then an equivalent formula as in MCDA should be log(risk) = log(probability) + log(potential impact). The choice of aggregation method therefore matters, as different aggregation structures can produce different representations and interpretations of risk.

2.5.3. Psychometric risk paradigm

The "psychometric paradigm" is a method developed to understanding and quantifying laypeople's opinions and attitudes toward risks (Slovic 1987). In addition to the pure aggregation of estimated likelihoods and consequences, risk assessments in psychology studies encompass more dimensions (Slovic 2000). Psychologists are interested in intuitive risk judgments (perceived risk), for example, risk aversion to certain hazards, the discrepancies between experts and laypeople towards risks, and the factors behind the perceptions. Psychometric risk perception research is mainly focused on how laypersons' "perceived" risk is departure form "actual" risk. Through psychophysical scaling and multivariate analysis techniques, risk attitudes and perceptions are expressed by "cognitive maps" or quantified representations by consulting participants to rate the riskiness of hazards (Slovic 1987).

Fischhoff et al. hypothesized 9 characteristics that influence judgments of risk perception. Expect the common probability of fatalities; it also contains knowledge about risk, to what extent are the risks known precisely by the persons exposed to those risks and to what extent are the risks known to science, control over risk, and novelty of risks, etc. They determined that "dread" and "novelty" are the two main factors influencing people's perceptions of risk based on an examination of survey data (Fischhoff, Slovic et al. 1978).

The psychometric approach has been continuously expanded to include more perception factors. Bassarak et al. proposed that disputed risk and morality should be captured as additional dimensions of risk judgments in addition to dread and novelty (Bassarak, Pfister et al. 2017). Psychometric risk paradigm is widely used in various fields to study different group' perception of specific risks (Jenkin 2006). Psychometric risk studies usually use questionnaire survey to rate possible hazards on various scales, e.g., voluntariness of risk (1=voluntary, 5=involuntary). Figure 2.6 shows an example of psychometric risk questionnaire.

Qualitative dimensions	Description	Score (1-5)
Voluntariness	The extent to which exposure to the hazard is voluntary	
Immediacy	The extent to which the consequences are noticed immediately	
Knowledge of exposure	The extent to which a person knows if he has been exposed	
Expert knowledge	The extent to which experts know about the hazard.	
Controllability	The extent to which a victim can control the severity of consequences due to exposure	
Novelty	The extent to which the hazard is new to society.	
Catastrophic potential	How many fatalities occur at once	
Dread	The extent to which the effects of exposure are dreaded	
Severity	The extent to which the consequences of exposure are severe	

Figure 2.6 An example of psychometric risk paradigm questionnaire.

The qualitative dimensions in the first column on the left side represent attributes or elements on how individuals perceive different risks. Those elements may vary according to specific context, various hazards investigated. Each dimension is presented in a short description, providing context for respondents. Respondents are asked to rate their perception of risk on a numerical scale (in this example from 1-5). The combination of qualitative dimensions, descriptions, and numerical scoring provides a structured way to approach individuals' assessment of different risks. The psychometric approach is effective in identifying differences and similarities among groups related to their risk attitudes and risk perceptions of specific risks. However, the results of risk perception and the approach itself are seldom directly applied in the domains of risk management.

There are many criticisms on using public risk perceptions to influence policy making. The arguments include such as public perceptions are noise/bias, public attitudes are prejudiced, managing risk merely entails managing public perceptions, the public is not homogeneous in its risk perceptions (Pidgeon 1998); some may worry about anything can become a determiner of risk perception (Slovic, Fischhoff et al. 1982).

By contrast, research on risk perception has played a pivotal role in promoting participatory decision-making processes. Although lay people may have little knowledge about hazards, however, their basic conceptualization of risk can be far more extensive. These perceptions reflect the real concerns of people which technological analyses often miss (Renn 2008).

For example, Florig et al. (2001) of Carnegie Mellon University proposed a deliberative risk ranking method. The method advocates gathering public input to help set risk management priorities. First, a set of risk attributes are identified by experts referring to risk perception literature. Then, risk is analyzed in terms of the attributes identified. After that, the selected participants are required to rank the attributes. At last, risk ranking is obtained applying the multi-attribute ranking procedure (Florig, Morgan et al. 2001, Morgan, DeKay et al. 2001).

Plattner et al. (Plattner, Plapp et al. 2006) built an integrated model for natural hazard risk evaluation, including scientific risk analysis, economic perspective, social environment, values, and psychological characteristics. Plattner stressed the importance of risk perception, specifically Perception Affecting Factor (PAF) and objective risk e_{eff} (probability times consequences), in conducting risk assessment and management. Furthermore, prospect theory has been proposed to explain how individuals make decisions under risk when their judgments deviate from the assumptions of rational decision-making. Based on expressed preference theory in psychometric studies, Plattner et al. developed a perceived risk r_{perc} formula with the integration of subjective deviation of risk perception and effective risk function e_{eff}:

$$r_{perc} = R_{eff} \frac{\sum_{i=1}^{n}(paf_i a_i)}{\sum_{i=1}^{n} a_i} \tag{3}$$

Where paf_i [0.5,2] is the value of the PAF, a_i [0,1] being the weight of each paf_i and n being the total quantity of relevant PAF. PAF includes voluntariness of risk-taking, individual reducibility of risk, knowledge and experience, endangerment, subjective damage rating, and subjective recurrence frequency perception.

Table 2.2 Overview of main risk assessment methods, their advantages, limitations, and main application field.

Risk assessment method	**Advantages**	**Limitations**	**Main application field**
QRA	● Help understand real damage and probabilities	● Neglect contextual issues ● Data scarcity	Engineering and natural science
MCDA	● Enrichment of risk assessment process ● Simplicity ● Transparent	● Results are sensitive to subjective judgments ● Not suitable for time-sensitive situations	Economics and decision sciences

		• The simple algorithm may result in misleading results	
Psychometric risk paradigm	• Understand public's concerns	• Public attitudes are prejudiced	Social sciences

2.6 Discussion

The concept of "risk" was first used in gambling and has now become part of our society. Its definition and connotation are constantly enriched with the development of society and science. Risk is interpreted and used in many contradictory ways, including distinctions between objective and subjective, and rational and irrational. However, after reviewing the literature from various disciplines, the emergence of these controversial points is mainly due to the different starting points for looking at risks and the different context settings they made.

Engineers primarily focus on the adverse consequences of malfunctions of the technical system, often neglecting human activities into the system. In contrast, social scientists emphasize risk management, risk perception, and risk communication, and social acceptance of risk. Despite the presence of these contradictory emphases in the conception and scope of risk, many socio-cultural approaches recognize the importance of a techno-scientific approach to risk. The emphasis in social sciences is to broaden the scope of technical risk assessment by incorporating more societal factors, making it more meaningful to view those socio-cultural approaches to risk as an extension of risk.

In recent decades, the growing body of risk research in philosophy has introduced ethical and moral challenges to the study of technology risks, which often overlook societal dimensions (Asveld and Roeser 2009, Van de Poel 2016). Our rapidly changing society is characterised by disputed risk problems that necessitate the inclusion of economic, moral, and ethical aspects in risk assessments (Reniers 2017). Effective risk management should not only aim to reduce the frequency and negative impacts of accidents but also promote justice and democracy (Meyer and Reniers 2022, Modarres and Groth 2023). The COVID-19 pandemic has highlighted the tension between risk decision-making and public acceptance, underscoring the need to consider not just the consequences and likelihood of risks but also their distribution and the importance of building trust among the public, institutions, companies, and governments (Ale, Slater et al. 2023).

Responsibility should be prioritized as a fundamental aspect of risk management rather than a secondary concern. This calls for the development of a novel integrated risk management paradigm that takes social, ethical, political, and economic aspects into account.

Over the past three decades, numerous efforts have been made to achieve this objective. Engineers and natural scientists continue to absorb social scientists' perspectives and improve current risk assessment approaches by encompassing public values, ethical principles, and utilizing deliberative processes. However, these approaches have yet to be fully integrated into risk management frameworks with established procedural steps.

Recently proposed integrated risk management frameworks, such as the one developed by the International Risk Governance Council (IRGC) (Florin and Bürkler 2017) and the SAFE FOODS framework for the governance of food safety (Knudsen 2010), emphasize transparency, inclusive communication, stakeholder involvement, and the consideration of broader economic, social, and political contexts. These frameworks represent significant steps toward inclusive risk governance (as illustrated in Figure 2.7).

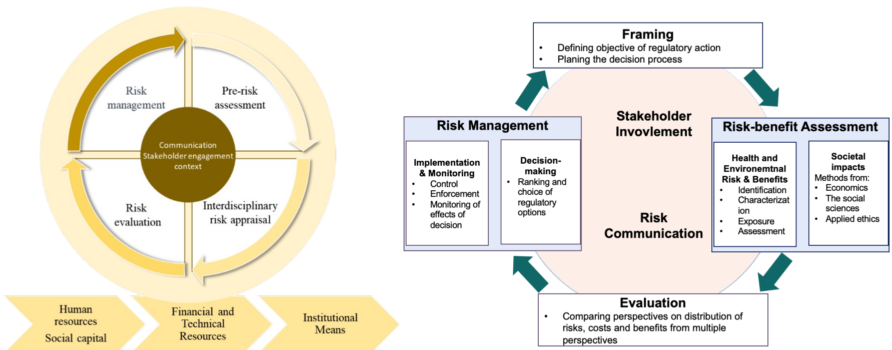

Figure 2.7 Integrated risk management framework. (a) IRGC risk governance framework; (b) The SAFE FOODS risk governance framework.

Both risk management frameworks show an iterative decision-making process with four main stages: framing (pre-risk assessment), risk appraisal (risk-benefit assessment), risk evaluation, and risk management. They both start with pre-risk assessment/framing that focuses on framing risk and identification of involved stakeholder groups. Then, risk appraisal/risk-benefit assessment is conducted to characterize risk. However, these frameworks diverge in their focus during this stage.

The IRGC risk governance framework not only includes technical risk analysis but also gathers stakeholders' concerns and opinions. In contrast, the SAFE FOODS risk governance framework emphasizes the importance of societal impacts within the risk assessment process. Following the risk appraisal, the outcomes of risk assessment are compared with specific criteria, to determine the significance and acceptability of the risk. Based on the results of risk evaluation, tolerable risks are then subjected to treatment. Despite these structured processes, several unresolved issues persist within both frameworks. Questions arise and remain unresolved, such as:

- How can public concerns be effectively measured or assessed, and in what ways do these concerns influence policymaking?
- What methods can be employed to rank risks while taking into account non-rational factors?
- How should decisions be made when conflicts arise between technical risk analysis assessments of public concerns?

Social sciences and philosophy studies help to identify and explain public concerns, economic, and psychological factors. A number of non-rational elements have been identified in the literature. For example, emotions and contextual factors—such as voluntariness, the distribution of risks and benefits, and the availability of alternatives—play an important role in risk-related judgments (Roeser 2006). Moreover, affective states, including fear, happiness, anger, and surprise, have been shown to be positively correlated with risk aversion (Nguyen and Noussair 2014). However, the results of these studies have rarely been applied in the formal risk management model. How to select and combine these aspects with the current technical concept of risk needs to be explored. In the future studies, it is necessary to expand the definitions of risk instead of focusing on one or two aspects to better cope and manage risks.

Prior studies have proposed various methods for assessing concerns and ethical issues separately as a supplement to the main risk assessment process. These qualitative assessments based on expert judgment are also called concern-driven risk management (Anthony Cox Jr 2007). For example, Hansson (Hansson 2018) introduced Ethical Risk Analysis (ERA) to assess ethical related decisions on risk. The method covers ethical issues such as agency, interpersonal relationships, and justice. Malsch et al. (Malsch, Tremblay et al. 2022) developed an innovative safety decision support system with the integration of ethical impact assessment into risk governance framework, in which social (e.g., equity, gender), economic, and environment-related values are included. Additionally, the UK Treasury method proposed an additional scale-based assessment method to take account into public concerns, such as familiarity, trust, dread, equity, and management (Treasury 2005). Generally, these contextual factors are assessed using non-quantitative methods.

Given the dominance of quantitative approaches in current risk management frameworks, further research is needed to investigate whether and how different types of information and data can be systematically integrated to support decision-making.

While there have been attempts to introduce stakeholders in the MCDA method, the approaches vary significantly from study to study. Despite many risk-related standards have stressed the importance of stakeholders, a systematic procedure for integrating stakeholders in risk management remains lacking (Florin and Parker 2020). A normative model that can systematically incorporate stakeholder involvement is necessary. Furthermore, scholars should explore ways to better manage diverse stakeholder opinions regarding risk, the interrelations between risk management and stakeholder management, and stakeholders' responsibility and roles in the risk management process.

The cultural approach, psychometric approach, and moral philosophy approach all advocate that people who be may affected by risk should have input in risk management. A fair decision-making process that incorporates stakeholder participation can lead to procedural justice (Renn 2015, Begg 2018). Stakeholder pressure is a significant factor influencing risk management strategies (Betts, Wiengarten et al. 2015). Over the past decade, there has been a growing interest in involving stakeholders in natural hazard risk management in Europe, particularly concerning flood risk management (Evers, Jonoski et al. 2012, Buchecker, Salvini et al. 2013).

2.7 Conclusions

This chapter presents a comprehensive review of the historical development, theories, and approaches of the risk concept used in different fields of research domain sciences when studying, discussing, and managing risks. The main conclusions are as follows.

There are wide variations and even competencies between and within disciplines regarding the notion of risk. However, many of the contradictive perspectives between the concept of risk are due to different standpoints. From a holistic point of view, the social science approach extends the concept of risk. The concept of risk in modern risk science has deep technical background that emphasizes the scientific nature of risk. However, a risk result from a technical system is not isolated and may bring indirect impacts to the broader social and societal system. Risk is not only to be identified through scientific methods but also constructed from social activities.

The concept of risk has never evolved in isolation; its development has been shaped by the integration of theories from various disciplines. For instance, early probability theory in mathematics has long served as the foundation for quantitative risk assessment. In recent years, more and more risk management studies tried to integrate “hard” and “soft” approaches and provide meaningful results. However, a normative procedural integrated risk management framework still needs to be explored.

To conclude, a comprehensive risk perspective with the integration of diverse values, including technical aspects, social and cultural response, individual cognitive processes, and what have you., may have the potential to deal with risks in a sustainable and responsible way.

PART II MAIN REREARCH

Chapter 3 Developing an Approach to Incorporate Emotional Concerns in Risk Decision-Making

This chapter is modified based on the following published journal paper: Xu, Y., Reniers, G., & Yang, M. (2025). Integrating Rational and Emotional Risk Management: A Stepwise Approach and Practical Implications (Accepted, in press). Journal of Safety Science and Resilience. https://doi.org/10.1016/j.jnlssr.2025.02.004

Traditional risk management-based on a "rational" idea of risk (the damage linked with probabilities for a certain scenario) often diverges from public perceptions, resulting in conflicts between expert-led evaluations and societal acceptance. Two research directions have emerged to bridge this gap: enhancing stakeholder participation in risk management and incorporating emotional factors into risk assessment. In this chapter, an Integrated Rational and Emotional Risk Decision-Making (IRERDM) approach is proposed to systematically integrate stakeholders' emotional considerations into formal risk management. First, we introduce a refined conceptualization of risk that incorporates human values alongside uncertainty and consequences. Second, based on this refined risk conceptualization, we develop a step-by-step stakeholder engagement process, with a detailed description of each stage. An illustrative example involving an ammonia plant site-selection risk problem is provided to demonstrate the applicability of the proposed approach. The proposed approach offers a potential way to resolve conflicts and enhance public trust in risk management.

3.1 Introduction

3.1.1 Paradigm shift in risk decision-making

People need to consider risks in the face of decisions in many situations, such as daily life, an investment, an operational system, etc. Naturally, people deal with risks implicitly and consider several alternatives without specific risk assessment training. However, with the increase in complex systems, human capability is limited to cope with numerous factors. In response, formal risk assessment emerges as a scientific field and offers a systematic and scientific way of decision-making in a complex and uncertain world (Aven 2010). Over the past 40-50 years, risk management has been widely applied to address hazardous exposures across state agencies, industry, the academic community, and other fields concerning public health and environmental safety.

The risk management process typically consists of similar key stages: establishing context, risk analysis, risk evaluation, and risk treatment (Ale, Aven et al. 2009). Typically, risk analysis is conducted by experts involving the estimation of probabilities and consequences of risk events. The risk analysis results will enter the risk evaluation stage, providing information to judge the acceptability of risk. However, many psychological studies of risk suggest a distinction between how experts and laypeople perceive and judge risk (Fischhoff, Slovic et al. 1978, Hansen, Holm et al. 2003). The skeptical attitude of laypeople toward science is often attributed to their lack of knowledge. In line with this view, much of the early research focused on educating the public to accept expert perspectives. Nonetheless, it has become increasingly clear that simply attempting to persuade laypeople to adopt expert viewpoints is not a practical approach. In recent decades, conflicts between scientific risk assessments and public perception have intensified, particularly in response to emerging technologies such as nuclear power and wind farms. A notable example is the Yucca Mountain nuclear waste repository (Slovic, Flynn et al. 1991). Despite multiple Quantitative Risk Assessments (QRAs) conducted by the U.S. Department of Energy, which concluded that the risks were negligible, public opposition remained strong. Concerns over the safe disposal of nuclear waste led to continuous protests and political resistance, ultimately resulting in the project's permanent abandonment.

In the past decades, many new initiatives and theories have emerged to reconcile conflicts between rational risk analysis and layperson risk judgment. We distinguished two prominent themes in contemporary studies: the involvement of stakeholders in risk management and broadening risk descriptions. Firstly, several social science and management literature assume that the discrepancy between experts and laypeople is due to a lack of communication. Consequently, approaches within this category advocate for enhanced collaboration with stakeholders in risk management to leverage transparency and procedural justice and ultimately improve their acceptance of risk decisions (Begg 2018). This method is commonly referred to in the scientific literature as participatory risk management, also described as collaborative, integrative, interactive, or comprehensive risk management (Almoradie, Cortes et al. 2015, Maskrey, Mount et al. 2016, Nouzari, Hartmann et al. 2020, Weale, Stuckey et al. 2022), etc. Unlike traditional risk management, which primarily highlights information delivery, participatory risk management focuses on dialog and co-determination between laypeople and experts. This approach, which combines scientific risk analysis and public deliberations, is also known as the analytic-deliberation model (NRC 1996, Renn 1999). Through communication with stakeholders, their societal considerations and risk perceptions can be obtained and propagated in the risk assessment process. Currently, stakeholder participation in risk management is implemented through various approaches. For example, stakeholders can contribute by identifying risks and uncertainties based on their personal and sector-specific experiences, analyzing major consequences according to their concerns, and jointly determining the most critical risks for risk control planning (Gerkensmeier and Ratter 2018).

Although many experts employ various methods to enhance the accuracy of risk analysis and minimize uncertainty, some sociologists pointed out that laypeople's distrust in science stems more from insufficient information and less from accuracy (Sjöberg 2001, Hansen, Holm et al. 2003). For example, social science studies have shown that the acceptability of risk is not only influenced by technical concept of risk but also by societal considerations, such as justice, distribution of adverse consequences, equality, rights, and more (Xu, Reniers et al. 2024). Psychometric theorists argue that laypeople's risk attitudes towards hazards could be explained mainly by three factors: dread, familiarity, and exposure (Fischhoff, Slovic et al. 1978, Slovic, Fischhoff et al. 2016). Moreover, some scholars have argued that emotional factors not only influence risk perception and ultimately affect decision making (Sjöberg 2007), but should also be considered as an integral part of decision making. For instance, Li et al. proposed a hybrid decision-making model, suggesting that analytical reasoning and emotional influences together shape how individuals perceive and respond to risk (Li, Ashkanasy et al. 2014). In that work, they first analyzed the discrepancy between rational decision models and the real decision-making process. Second, drawing on neuroscientific evidence and behavioral studies, they point out that individuals who are unable to generate normal emotional responses nevertheless retain intact logical reasoning abilities; however, they exhibit profound difficulties in real-life decision-making, such as prioritize alternatives. Finally, they proposed the hybrid model that combine rational and emotional decision-making system. The rational system is responsible for calculation, probability weighting, and logical comparison, whereas the emotional system rapidly filters options, provides directional judgment under uncertainty, and compensates for incomplete information. Traditional risk analysis, however, is primarily based on rational choice theory, which assumes that an individual makes decisions based on the utility of the desired outcome and the chance of that outcome occurring. Consequently, experts with scientific training tend to use rational methods of measurement (utility of the consequence and the probability of the consequences) as a primary basis for risk evaluation, risk treatment, and risk communication. In contrast, laypeople who make decisions rely more on emotional decision-making system and are influenced by "emotions" such as fear, anger, and surprise (Roeser 2006, Williams 2013, Kassam 2015). As a result, formal risk analysis, based on rational decision-making system, is sometimes insufficient to fully capture the general public's more encompassing and multi-facet values. Recognizing these limitations, scholars influenced by social science perspectives have proposed an alternative approach. The second branch of study advocates adding emotional considerations, such as voluntariness, equity, and fairness, into rational risk concepts, thereby broadening its scope and making risk analysis less blameworthy, see (Vlek 1996, Gardoni and Murphy 2014, Reniers and Van Erp 2016).

Aligned with the hybrid rational and emotional decision-making model, we refer to the layman's view of risk as the "emotional" approach in the following context. Here, "emotional" is used to differentiate it from the rational method and is not synonymous with "irrational". Moreover, in contrast to the rational influences—such as probability and consequences—emphasized in the utility-maximization principle of rational decision theory, we classify non-cognitive factors influenced by emotions, affect, heuristics as emotional factors.

3.1.2 Aims and scopes

However, implementing the two methods separately has several drawbacks and limitations. On the one hand, while stakeholder engagement allows diverse opinions to be voiced, formal risk analysis remains grounded in technical assessments, limiting the scope of inquiry to predefined scientific parameters. The judgment of "what needs investigation" is confined to technical language. On the other hand, introducing emotional factors in risk ranking or evaluation is a direct way to incorporate laypeople's attitudes in risk analysis. However, these methods lack generalizability and are limited to pre-set dimensions of risk. The emotional criteria introduced are typically based on experts' subjective judgment, which may not accurately capture the public's genuine concerns. To address this gap, Xu et al. (Xu, Yuan et al. 2024) proposed an integrated technical and societal risk ranking approach. Their method first identifies key stakeholders before conducting risk analysis, allowing them to define the primary risk indicators. Based on these stakeholder-driven criteria, risk assessment is then carried out, with final rankings determined through a Multi-Criteria Analysis (MCA) approach. Despite this advancement, a standardized risk management framework that systematically integrates rational and emotional perspectives is still lacking. To meet the above challenges, we aim to develop a method for systematically integrating stakeholders' emotional risk perspectives into the formal risk management process. More specially, the aim is to develop:

- A generalized risk conceptualization to capture emotional considerations within the risk decision-making approach
- A practical and systematic risk management procedure for stakeholder participation

The remainder of this chapter is structured as follows: we first propose a modified risk definition and a risk description which opens opportunities for broader risk characterization in section 2. Then, we present the foundations and the integrated rational and emotional approach for risk management in section 3. To demonstrate how to implement the approach, an illustrative example of a site-selection risk problem is presented and discussed in section 4. Before concluding, the significance of this study and its relevance to existing works are discussed in Section 5.

3.2 A modified conceptualization of risk

3.2.1 Risk definition

Current risk definitions fall short of stressing the role of human values. To illustrate, we introduced some representative definitions of risk that allow us to discuss:

(a) Risk is equal to a set of triplets (s_i, l_i, x_i), where s_i is a scenario identification or description; l_i is the likelihood of that scenario; and x_i is the consequence or evaluation measure of that scenario (Kaplan and Garrick 1981).

(b) Risk is a situation or event where something of human value (including humans themselves) has been put at stake and where the outcome is uncertain (Rosa 1998).

(c) Risk is uncertainty about and severity of the consequences of an activity with respect to something that humans value (Aven 2010).

(d) Risk is effect of uncertainty on objectives (ISO 2018).

It should be noted that definition (a) is commonly used in most safety management practices and related fields. The definitions have some variations in interpretations. But generally, most definitions can be attributed to three main components: an event A and consequences C, and uncertainty U about the event and consequences.

For simplicity, risk can be formalized to formula (1) without specifying the events:

$$R = (C, U) \tag{1}$$

This mathematical definition of risk will serve as the foundation for the following discussion. Now, let us revisit the four descriptive definitions. The key distinction between definitions (b) and (c) compared to definition (a) lies in the inclusion of ethical and emotional stakes related to human concerns. Such stakes can be interpreted as some state of reality of human concern or interest. Similarly, the term "objective" in definition (d) can be interpreted as "what individuals, organizations, and societies (as collectives of individuals) desire, need, pursue, or strive to achieve." Thus, it is also related to human stakes (Blokland and Reniers 2019). Following the definitions of (b), (c), and (d), when we judge whether we face risks, we introduce our values about consequences or outcomes. If human objectives (/values) are not attached to the potential consequence, even if the outcome is large, risk is absent.

However, when risk is discussed, e.g., in an operational system, we normally don't emphasize this line of thought. This does not mean that risk analysts ignore "human stakes" when conducting a risk assessment today. Instead, the definition of "what human values" is determined by experts' subjective judgment. Ultimately, the assessment of risk reflects the experts' values. In many cases, expert judgment is sufficient for decision-making, particularly when those conducting the risk assessment also bear the risks. However, in situations where decisions are highly complex, ambiguous, and uncertain—especially when they affect diverse stakeholders, including individuals, organizations, and institutions—it may be necessary to incorporate the perspectives of laypeople, policymakers, and the broader public.

This would bring new considerations to the risk assessment process: whose stakes should be considered? To address this consideration, we suggest that "human at stake" in risk events should be explicitly specified. We denote the people at stake in risk events as "η". Accordingly, a modified risk definition is suggested as:

$$R = (C, U)_\eta \tag{2}$$

For example, assume the specific risk event to be observed is a specific loss of containment accident. We are uncertain U about what consequences C will happen and when they will happen. To define risk, we need to specify people at stake η, e.g., the plant managers. Plant managers might focus on the financial state of a chemical process plant. In this case, the potential consequences might be formalized as reduced capacity of production, supply chain production, etc.

Furthermore, when communicating about risk, naturally, "when" and "where" the risk will happen is implicitly considered. For example, Logan et al. (Logan, Aven et al. 2021)proposed an adjusted risk definition that highlights the role of time τ in risk and risk analysis. In this study, however, our primary focus is on the role of emotions and values of humans in shaping risk and risk analysis.

3.2.2 Risk description

Risk definition and risk description are two different concepts. A risk definition helps determine whether a potential risk exists, while a risk description estimates the magnitude and the likelihood of the risk (Aven 2023). Several representative risk descriptions include:

(a) The combination of probability and consequences.

(b) Risk is a triplet (C', Q, K), C' concerns specified consequence, Q indicates a measure of uncertainty, and K is the background knowledge supporting C' and Q.

Basically, these descriptions are all developed from a technical analyst's perspective. However, these descriptions may not always fully capture the attributes of risks, particularly when societal and perceptual factors play a significant role.

To illustrate, consider two risk scenarios: (1) T is exposed to second-hand smoke, and (2) T is exposed to smoke because he/she smokes tobacco products himself/herself. From an emotional perspective, scenario (1) is more blameworthy than (2) due to the exposure being involuntary. This distinction cannot be expressed through purely rational risk descriptions. Obviously, voluntariness cannot be reduced to a specific kind of consequence. However, the concept is related to the "sources" of risk events. In this context, the "source" of a risk refers to the agents involved in the creation or maintenance of a risk (Gardoni and Murphy 2014), including potential contributing factors to an accident.

Ideally, a risk description should reflect all the influencing factors, rational and emotional, on how an individual views two risk scenarios differently. If we regard risk as an event chain, hazards α may lead to an event A, and there is uncertainty U about what event may take place and when it will happen. The event A would result in uncertain consequences C. When we discuss risk, the important aspects may focus on α, U and C.

It is essential that all those considerations are expressed in risk descriptions. Based on the "risk" defined in formula (2), a more informative risk description R' can be defined as:

$$R' = (\alpha, C', U')_{\eta} \tag{3}$$

Where α are the specific hazards, C' are the specific consequence, and U' is a measure of uncertainty.

Moreover, in practice, discussions of risks cannot be separated from the reference system in which they are analyzed. One commonly used tool in risk management is the bow-tie diagram. As shown in Figure 3.1, an event may arise from several hazards and lead to potential consequences of human stakes. Safety management delivery systems and safety barriers are shown as controls to prevent events and mitigate consequences. In some cases, event A may take place, but its consequences are not severe due to the presence of effective mitigation barriers.

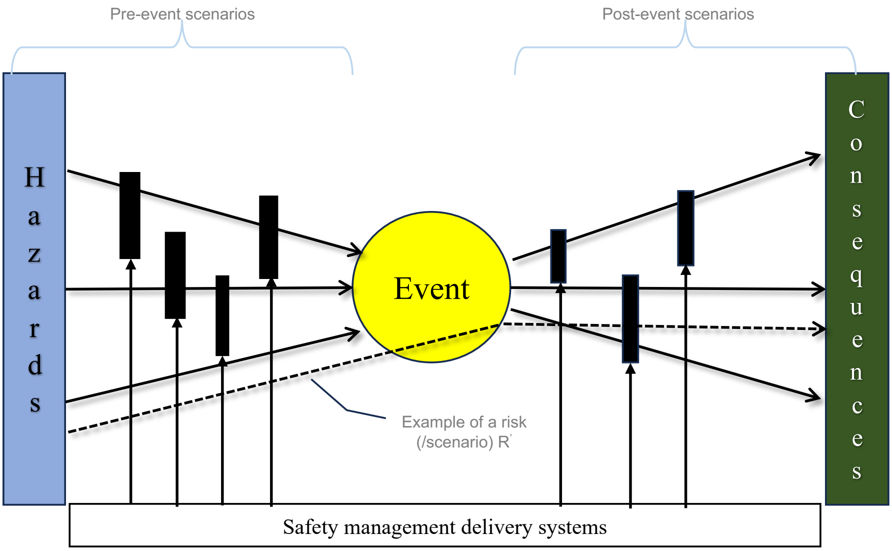

Figure 3.1 Bow-tie diagram representing risk scenarios. The black, white, and striped boxes represent different types of safety barriers.

Obviously, the consequences on the right-hand side of the bow-tie diagram depend on the manageability M of the consequences of the risk. Therefore, to denote a risk R' in a system with certain management controls M', we write:

$$R' = (\alpha, C', U', M')_{\eta} \tag{4}$$

M' is a measure of the extent to which the risk can be controlled or mitigated through management measures. To further illustrate the risk and risk descriptions, consider a risk assessment of a chemical process plant. The risk description is as follows:

- α: The causation of the event is considered, e.g., the risk event is caused by a terrorist attack.
- C': A supply chain production loss is considered, e.g., the company will lose 20 million euros.
- M': Mitigation barriers are considered, e.g., the emergency shutdown system works successfully.
- U': The uncertainty on α, C', M'.
- η : People at stake

3.3 Method

3.3.1 Foundations of the approach

Before presenting and discussing the suggested approach for risk management, it is important to clarify the underlying assumptions. Some of the assumptions face controversies in the risk field.

- *Definition of stakeholders*: The definition of "stakeholders" is not used constantly in the literature and may cause confusion sometimes. The definition of stakeholder is founded on Freeman's early stakeholder theory. In some management literature, distinctions are made between stakeholders and the public. To avoid ambiguity, this study adopts a definition adapted from IRGC (Florin and Bürkler 2017): “a stakeholder is an individual or an organized group that is, or will be, or might be, affected objectively or subjectively through perception by the outcome of the risk event or the activity, whether directly or indirectly, tangibly or intangibly, and immediately or with delay”. Thus, stakeholders include not only those directly affected (organized) groups but also directly affected (unorganized) public.

- *The role of stakeholders*: There are two main types of actors in conventional risk management--decision-makers who have responsibility for the decisions and risk analysts with expertise in risk problems. In this approach, stakeholders are the third type of actors, and they are viewed as people with experiential and value-based knowledge and can provide valuable insights to supplement rational analysis. Their preferences, interests, and values can provide the basis for experts to analyze the aspects. At the same time, they are invited to make decisions regarding risk ranking and prioritizing risk treatment strategies.
- *Subjectivity*: Some may be skeptical that the involvement of stakeholder's emotional perspectives of risk would introduce subjectivity to risk analysis. However, risk analysis is not a pure objective activity, encompassing value judgments (Fischhoff 2015). On the one hand, risk analysis relies on experts' experience, memory, and common sense and is susceptible to bias (Lichtenstein, Slovic et al. 1978, Pidgeon 1998). On the other hand, the judgment manifests itself in using generic categories of objectives to represent evaluation criteria, such as determining what consequence to analyze, which group is affected, and more. From a philosophical perspective, it is better to let those who may be influenced by adverse impacts decide what to analyze.
- *Legitimacy*: Some may be specious about laypeople who do not receive specific training to make "legitimate" decisions. A reasonable individual can be defined as who "exercises the degree of attention, knowledge, intelligence, and judgment that society requires of its members for the protection of their own and of others' interests" (Gardoni and Murphy 2014). Although laypeople may have more contextual considerations than experts, they should be able to make reasonable decisions for themselves and the communities they represent.
- *Uncertainties and conflicts*: Due to differences in how various types of stakeholder's value specific inputs, the increased uncertainties and ambiguities brought by the involvement of stakeholders in risk management are inevitable. Nevertheless, disagreements or cognitive conflicts among experts about physical facts are familiar even in traditional risk analysis. The participation of stakeholders is a way of helping resolve conflicts at the early stage, and it can be systematically addressed as part of the risk management process. The point is we should investigate how to employ negotiation and mediation methods and tools to deal with the newly brought societal conflicts. Furthermore, various conflict resolution methods can be found in scientific literature, such as round tables, mediation, alternative representative surveys, public hearings, focus groups, and more (Renn 2015, Florin and Parker 2020).

Risk is scenario linked to a future state of the world. Risk assessment is the description and measurement of risk scenarios, seen through the eyes of risk analysts and stakeholders based on knowledge, experience, and values. Risk assessment is, at least partially subjective and can cause normative conflicts among different parties. It may be impossible to reach a consensus among all parties on what needs to be investigated and what should be analyzed. However, it is still possible to reach a consensus on how to solve the risk problem through communication (Beatty and Moore 2010). The approach is not designed to seek the best answer, but to find a mutually acceptable solution.

3.3.2 Integrating rational and emotional risk decision-making

The starting point of this approach is that a decision-maker faces some decision points associated with the production, operation, and disposal of systems. For example, implementing a new technology, choosing a risk management policy, etc. The focus is on Type II risks. Type II risks are characterized by large uncertainties and potentially extreme consequences (e.g., explosions, fires, toxic releases) (Meyer and Reniers 2025). Typically, this type of risk has the characteristics of broad geographical dispersion and temporal extension and can affect a wide range of people and institutions. Risk assessments are considered valuable support for decisions in such situations.

The high-level objective of decision-making is not only to minimize the adverse effects on the environment, health, and safety but also to take into account human rights, and normative principles to ensure the decisions are socially acceptable. The stepwise decision-making process for risk management is presented in Figure 3.2. The approach contains six main steps. The detailed process of the approach is described in the following subsections.

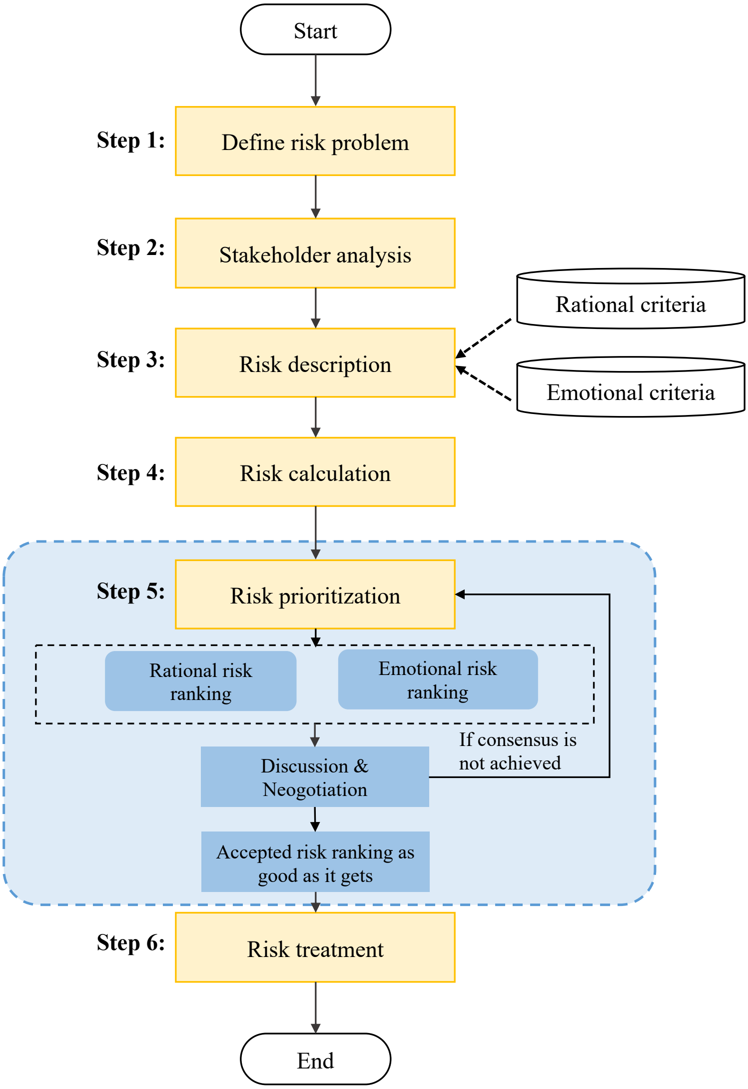

Figure 3.2 Overview of the Integrated Rational and Emotional Risk Decision-Making (IRERDM) approach.

3.3.2.1 Step 1: Define risk problem

In the preparation stage, it is essential to clarify what problems are to be solved, the context of the problem, and the boundaries you want to cover. There are three main steps in this stage:

Step 1. Define the risk problem and objectives

Step 2. Establish internal and external context

Step 3. Set the system boundaries

In the beginning, it is essential to have a clear scope of what to be analyzed. The selection of problems can be made through internal company meetings or by consulting external experts. When the decision problem is identified, the context that frames the problem should be established. The external context incorporates the economic, environmental, political, social, and technological environment that forms the context for the problem being analyzed. The internal context incorporates the elements of the industrial system, for example, establishment, layout, process systems, safety management systems, emergency systems, pipelines, storage tanks, etc. (Norway 2010).

To analyze the risk problem, it is necessary to specify the boundaries of risk assessment. For instance, the period over which the activities are observed, the length of time after an event occurs for which we evaluate the consequences of that event, geographical scope within which consequences are analyzed, etc. The discussion process and results, including diverse points of views should be formally documented and publicly reported.

3.3.2.2 Step 2: Stakeholder analysis

Stakeholder analysis is a newly brought step in this approach compared to the status quo. The aim of stakeholder analysis is to assign different tasks to different stakeholder groups. Generally, stakeholder analysis incorporates the following procedures:

Step 1. Identify stakeholders

Step 2. Establish contacts with stakeholders

Step 3. Determine stakeholders' participatory strategy

Identifying who has stakes in risk problems is the first task of stakeholder analysis. This could be done by brainstorming or look information from documents research articles through a series of meetings or focus groups (Reed, Graves et al. 2009). For example, in the safety management system, the type of stakeholders may include (Reniers, Ale et al. 2009):

- The plant (e.g., owners, managers, labor force)
- Public (e.g., affected people)
- Public authorities (e.g., local government)

- Emergency responders (e.g., firefighters, medical emergency responders)
- Others (e.g., business organizations, research institutes, NGO)

Once the general stakeholder groups are identified, it is time to establish initial contact with stakeholder groups. This could be done by public meetings. In the meetings, it is essential to decide on representing individuals of each stakeholder group that are expected to participate in the management process and ensure their willingness and availability to participation.

After stakeholders agree and accept the stakeholder participation plan, it is time to determine the targeted participatory techniques to support a practical stakeholder participation process. There are various participation techniques can be used to achieve this goal based on the aim of participation. For instance, newsletters, reports, presentations, public hearings, and internet webpage are suitable for informing or educating stakeholders about risk events. Interviews, questionnaires, surveys, citizen advisory panels, and Delphi techniques can help obtain stakeholder information. Multicriteria analysis, workshops, round tables, and focus groups are suitable for directly engaging stakeholders in decision-making (Renn 2015). Available time, budget, geographic locations, stakeholders' availability, and degree of complexity of participation are factors that need to be taken into account in determining participatory strategies (Jones and Preskill 2009). The determination of stakeholder participatory approaches should balance those aspects and communicate with stakeholders until all groups agree on the final engagement plan.

3.3.2.3 Step 3: Risk description

This step has two main tasks: (1) define how risk is described and represented in risk analysis, and (2) use scientific tools and methods to analyze those attributes to attain an overall picture of risk. The rational concept of risk based on frequency and consequences is still a necessary basis, but it may not be able to capture the complexity and diversity of risk. Risk description is assumed to open the opportunity to integrate rational and emotional factors in risk assessment.

Rational criteria. The actual damage linked with the occurrence probabilities of an event is the focal point of the rational concept of risk. Risk analysis based on the rational concept of risk is to capture the objective nature of risks (physical impacts). Therefore, the conventional description of the extent of damage and probability is appropriate to represent the rational concept of risk. Scientific risk analysis performed by experts is by many practitioners considered the most appropriate way to achieve safety goals. More detailed analysis and higher degree of qualification are helpful for meaningful results. Well-known approaches such as Quantitative Risk Analysis (QRA) are commonly used for risk analysis of type II events.

Emotional criteria. The emotional concept of risk highlighted the subjective risk perception that deviated from the rational risk concept. Societal, psycho-perceptual, and contextual concerns from stakeholders should be treated as valid inputs in the risk description process. It should be noted that the risk description in formula (4) only provides a simple framework that allows risk to be described rationally. Identifying more specific indicators associated with each dimension is necessary, allowing risks to be calculated and compared.

In practice, risk analysts should work closely with stakeholders to define how their perceptions can be quantified and integrated into risk assessments. Typically, the identification process involves directly soliciting stakeholder opinions through formalized deliberation approaches, such as a series of facilitated workshops or interviews. To avoid a fixed mindset, a list of pre-defined risk indicators can be provided to guide discussions while allowing stakeholders to modify, add, or remove indicators. Several scientific studies have explored the indicators, and those lists are not identical; see for instance (Starr 1969, Fischhoff, Slovic et al. 1978, Litai 1980, Treasury 2005, Gardoni and Murphy 2014, Slovic, Fischhoff et al. 2016, Achille, Ponnet et al. 2017). Some factors irrelevant to the industrial sector risk assessment for significant accidents are excluded. Some variables with similar meanings were merged into one indicator. Finally, we summarized and compiled a list of indicators for this study. Those indicators are grouped into four categories based on the risk description formula (4) previously introduced, aligning with its four key components: hazards, consequences, manageability, and uncertainty (as shown in Figure 3.3).

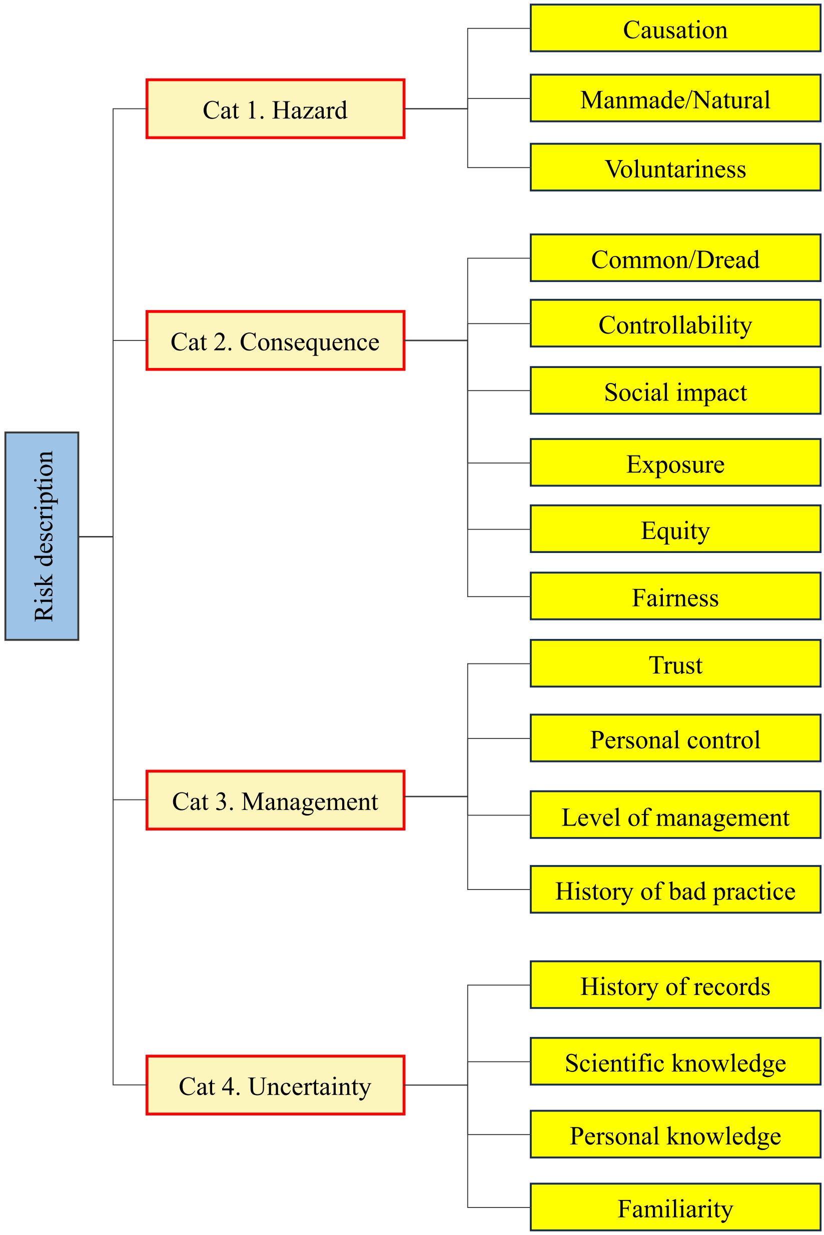

Fig 3.3 A non-exhaustive overview of criteria of risk.

Indicator cat.1 Hazard

- Causation: It distinguishes the ways in which cause harm or risk (intentionally, recklessly, or negligently). It is a concern relating to moral responsibility. From a moral perspective, intentional action is more unacceptable than negligent (Gardoni and Murphy 2014).
- Manmade/Natural: It concentrates on whether risks are induced by human factors or natural hazards. Risks induced by humans seem to be a greater worry than natural risks (Fischhoff, Slovic et al. 1978, Achille, Ponnet et al. 2017).
- Voluntariness: It concerns with an individual's ability to decide his/her exposure to a given risk. Voluntary risks are less troublesome than involuntary risks (Starr 1969).

Indicator cat.2 Consequence

- Common/Dread: It is a subjective concern associated with consequences. It refers to the emotional response to risks and can be called "fear of harm" (Fischhoff, Slovic et al. 1978, Achille, Ponnet et al. 2017). The fear of harm may be aroused from unusual experiences, ethical concerns, affect sensitive people, etc. (Treasury 2005).
- Controllability: It is related to whether risks are easily reduced or not easily reduced (Fischhoff, Slovic et al. 1978).
- Social impacts: Physical effects will interact with psychological, cultural, social, and institutional processes that amplify or attenuate public experience of risk and result in secondary (social) impacts (Kasperson, Renn et al. 1988). It includes economic, environmental, ecology, psychological impacts, etc.
- Exposure: It refers to the number of people exposed to the adverse effects. It might be possible to merge it into "dread" (Slovic, Fischhoff et al. 2016).
- Equity: Allocation of risks and benefits. It concerns whether risks and benefits are distributed equally (Achille, Ponnet et al. 2017).
- Fairness: It is related to the distribution of adverse consequences (equitable and inequitable) (Gardoni and Murphy 2014).

Indicator cat.3 Management

- Trust: It is defined as the public trust towards government, experts, and company. People are more concerned about risks when they don't trust the people or system that manages them (Treasury 2005).

- Personal control: It is related to the personal skills of the risk bearers to avoid adverse effects (Treasury 2005, Achille, Ponnet et al. 2017).
- Level of management: It refers to the ability and resources of the company to prevent or mitigate accidents (Treasury 2005).
- History of bad practice: It refers to the previous history of accidents related to the company (Treasury 2005).

Indicator cat.4 Uncertainty

- History of records: This is related to the frequency of occurrences of hazards in history. For instance, have accidents occurred in similar facilities in the past decades? (Treasury 2005, Achille, Ponnet et al. 2017).
- Scientific knowledge: This indicator concerns to what extent the risks are understood by the scientific community, e.g., lack of knowledge about precisely which factors may influence the consequences or likelihood of a given risk (Treasury 2005).
- Personal knowledge of experts: It refers to the experts' knowledge about the mechanism of risk (Achille, Ponnet et al. 2017).
- Familiarity: It is related to the public's knowledge of the mechanisms of risks. It can also be referred to as personal experience and associated with accessibility to information (Fischhoff, Slovic et al. 1978, Achille, Ponnet et al. 2017).

It is worth noting that the identified list of indicators is intended to provide guidance for practitioners. In practical applications, other unidentified factors may exist. The identified indicators will be used as supplement criteria to the rational concept of risk and together as the main criteria in the following risk assessment steps.

Some information about the criteria is evident, such as whether the risk event is manmade or natural-induced. However, some require detailed risk analysis and expert judgment. When "consequences" appear in the rational approach, it usually refers to the outcome or the events that have happened. Typically, it is calculated as the direct impacts brought by physical changes (i.e., pressure changes, temperature changes). Since emotional values are also regarded as aspects of the nature of risk in this category, some input to societal and psycho-perceptual variables in risk analysis may come from affected stakeholders. Those variables may not easily be quantifiable, but there exist some specific approaches to measure this type of data indirectly using indicators such as willingness to pay (WTP), willingness to accept (WTA), quality-adjusted life years calculation

(QALY), and the alike. However, some may prefer to utilize social science techniques such as focus group discussions, surveys, questionnaires, and interviews to keep the richness of the criteria.

3.3.2.4 Step 4: Risk calculation

The aim of this step is to define whether a risk is acceptable and to identify what scenarios/risks require further risk treatment.

The rule of risk evaluation behind the rational approach is that "the calculated risk is sufficiently low." The premise is that there is a standard risk acceptance criterion that can be used to compare a calculated risk level with this absolute criterion. A risk is unacceptable if the risk value exceeds the criterion. Generally, social risk acceptance criteria are deemed appropriate for this type of problem, as risk acceptance criteria are usually focused on the numbers of fatalities and frequencies. For instance, the absolute risk criterion, which is used more often, is "the frequency of death due to a specific hazard shall not exceed 10^{-6} per person-year" (Vanem 2012). Instrumentally, the risk matrix and FN curves (frequency versus numbers of fatalities) can be used as visualization tools to better understand risks (Ale, Aven et al. 2009).

However, the absolute risk criteria lose their meaning when stakeholders' input is considered. Additional criteria, in addition to probabilities and consequences, will influence the acceptance of risk. Risk perceptions play an important role in this context. For example, the calculated level of a risk may be situated below certain risk acceptance criteria, but it may be judged unacceptable due to its unequal distribution of adverse effects. Different from the rational approach, which focuses on the expected utilities, in this approach, additional focus should be paid on the moral/ethical rightness of the risk action or the consequences. From the physical aspects, "the uncertainties and possible consequences (e.g., loss of lives) are required to be reduced to a level that is as low as possible." The residual criteria can be evaluated through weighing the burdens and benefits (Hansson 2003). For example, exposure of a person to a risk is deemed acceptable if and only if one or more normative rules are satisfied (Hansson 2003):

- The exposure is outweighed by a more significant benefit
- This exposure is voluntary or works to his/her advantage
- The exposure is part of an equitable social system of risk-taking
- The exposure can be avoided by adopting precautionary measures

In theory, there can be universal normative rules among certain groups or specific members. Hence, instead of applying objective risk criteria so everyone receives the same treatment, risk analysts can consult the affected groups through negotiation and mediation methods to define risk acceptance criteria.

3.3.2.5 Step 5: Risk prioritization

Risk prioritization is conducted to systematically compare different risks (/scenarios) to decide which risks (/scenarios) are more important. The objective of this step is to reconcile perspectives among experts and stakeholders to obtain a generally accepted risk ranking. It starts with risk ranking based on a rational concept of risk (rational risk ranking). Then, a risk ranking with additional emotional considerations is conducted. We refer to it as "emotional risk ranking" to distinguish it from rational risk ranking. Finally, the two risk ranking results will enter a negotiating process until a final generally accepted risk ranking is achieved among stakeholders. There are many different types of consensus methods that may be used to synthesize stakeholders' opinions. Delphi, Nominal Group Technique (NGT), and consensus development panel approaches are the most commonly used formal consensus methods in group decision-making (Humphrey-Murto, Varpio et al. 2017). An integrated risk ranking methods is needed to this end.

Expected value is a commonly used method in standard risk ranking. It is established on a rational concept of risk probability and consequences. For instance, the expected value of a risk can be interpreted as the center of gravity of the probability distribution of the weighted average of all possible outcomes. Mathematically, for a risk-neutral decision maker (aversion factor=1) it can be written as:

$$R^t = \sum_{i=1}^{n} p_i^t C_i^t \tag{5}$$

Where n is the number of accident scenarios i, p_i is the probability of occurrence (per year) of scenario i, C_i are the consequences of scenario i, t is the specific time which the risk scenario is considered.

The rational risk ranking procedure according to the rational approach is straightforward. After determining the scenarios, the probabilities and consequences of the scenarios need to be determined. Furthermore, the data are integrated based on a risk calculation formula consisting of probability and consequences which can be prioritized.

If stakeholders require additional emotional aspects to be considered in risk ranking, approaches that could combine rational and emotional attributes are needed. There is no unique method to tackle this problem. Those methods vary according to whether the outcome is semi-quantitative or qualitative. We summarized some key methods and their main steps to tackle this problem.

Qualitative risk scale is a method proposed by Gardoni and Murphy (Gardoni and Murphy 2014) and in this work, they first proposed adding a "source" dimension to the risk definition. Qualitative risk scale is a simple and quick approach focusing on crude grading for each risk. It is conducted by combining all the levels of each attribute to create a composite scale. Risk ranking according to the qualitative risk scale can be performed based on the following procedure. Firstly, each criterion of risk should be classified by some type of categorization system, e.g., low, moderate, high. The classification of levels can be derived based on experts' or stakeholders' opinions. Secondly, the possible combinations of the dimensions are grouped and ranked and form a specific risk scale. Ultimately, risks can be compared and prioritized using the developed risk scales.

The integrated Quantitative and Qualitative (Q&Q) risk index is a method developed by Reniers and Van Erp (Reniers and Van Erp 2016) to combine emotional and rational considerations. The emotional factors could be seen as influencing factors that amplify or attenuate rational risk.

$$R_i = \frac{p_i C_i^a}{\beta_i \left(E_i F_i^b\right)} \tag{6}$$

Where β_i is policy factor that varies with the degree of participation in the risk due to event/scenario i being voluntary, E_i is a parameter representing the equity principle, and F_i is a parameter representing the fairness principle, a is aversion factor towards consequences, and b is a factor representing the level of recklessness of a risk decision. In the integrated Q&Q risk index approach, the qualitative data are calculated by a scoring system (0.1-very low, 0.5-low, 1-medium, 1.5-high, 2-very high). In theory, this approach should be based on an empirical analysis and represents the realistic link between quantitative and qualitative data. Nevertheless, in the current situation where theoretical and empirical data are insufficient, the relationships between parameters are largely based on subjective assumptions. For example, it assumes that a higher level of voluntariness, equity, and fairness results in a lower level of risk. This is true because the acceptability of such criteria is higher and consequently such risks will be prioritized lower than risks with lower voluntariness, equity, or fairness for decision-making. Secondly, β, E, F are dimensionless parameters, and the determination of their ranges of values would have significant effects on the risk value. The suggested value range of these parameters is from 0.1 to 2. It implies that involuntary risk (β=0.1) is 20 times higher than voluntary risk (β=2). However, some psychology surveys reflect different outcomes; this number in (Starr 1969, Litai 1980) is 1000 and 100 respectively.

This method is established as a function of the expected value and weighted sum of the scores of subjective considerations. The rational aspects are similar to the standard approach. The emotional elements are calculated as a composite score obtained by multiplying scores and weights. Mathematically, it can be written as:

$$R^t = P_i^t C_i^t \sum w_i \times X_i \tag{7}$$

Where w_i is the weight of each criterion of risk, X_i is the score of each criterion of risk. Typically, weighted scoring can be conducted according to the following steps. Firstly, the variables need to be classified into several categories by communication between risk analysts and stakeholders. Then, each category needs to be assigned a score (i.e., 1, 2, 3) for further calculation. To assign weight to an attribute, a range of Multi-Criteria Decision Analysis (MCDA) weighting methods can be used (i.e., AHP, swing weights) (Morgan, DeKay et al. 2001, Plattner, Plapp et al. 2006). Specifically, researchers from Carnegie Mellon University developed a standard procedure of deliberative risk ranking, and the weights are derived based on stakeholders' preference (Florig, Morgan et al. 2001). This approach is much easier compared to conventional MCDA methods. At last, the overall scores and weights are calculated to derive the overall value of risks.

3.3.2.6 Step 6: Risk treatment

Risk treatment comprises (1) decision-making and (2) implementation of risk treatment strategies. The focus of decision-making is to compare and select the most optimal risk treatment strategies by weighing the impacts brought by the alternatives on risks. Decision-making is an iterative process; this step often requires reassessing the impact of risk treatment measures when new risk treatment strategies are to be compared. There are many decision tools that can be used to assess risk treatment options. Generally, the cost of implementing the risk treatment strategy is the only criterion in addition to risk in the standard approach. When it comes to emotional-based approaches, sometimes other ethical and societal factors also need to be compared. There are many other criteria that may be considered. Examples include cost, timing, equity, fairness, administrative efficiency, compatibility, individual freedom, etc., and to deal with this variety of normative criteria, negotiation tools such as workshops, focus groups, MCDA and what have you, can be applied.

Implementation involves reviewing the decision process as well as implementation of the decision. In practical implications, the outcome of decisions usually cannot keep everyone satisfied. Review is a step to review the decision procedure, the result of decision, and the decision itself. For instance, when reviewing, issues that should be focused on may include (König, Kuiper et al. 2010): are the decision processes documented and traceable? Are all the relevant stakeholders identified? Are there some concerns from stakeholders that have not been considered? In theory, the decision should ensure that no critical protest exists. The opinions of the minorities or the presence/absence of controversy over the issue should be documented. If there is no critical protest towards the decision, implementation of the final option can be carried out.

3.4 Illustrative application of the proposed approach

The proposed stepwise approach is applicable to a number of Type II risk problems (major accidents that occur with low frequencies and high consequences) (Reniers and Van Erp 2016). This section aims to use an illustrative example to demonstrate the applicability of the approach to fundamental modeling instead of its application to a specific case. Thus, we do not go into detail about every step of the approach. The primary focus is on how risk is described and prioritized with consideration of emotional factors. Nevertheless, to make the example more concrete, a hypothetical site selection problem for an ammonia plant was chosen to provide further details. The rationale for selecting this risk problem is that site selection involves multiple factors and requires a combination of scientific risk assessment, ethical considerations, and stakeholder participation, by which the proposed risk management approach can be clearly illustrated and compared.

3.4.1 Problem definition

The example considers the problem of deciding where to locate an ammonia plant. After a preliminary site screening of land policy, regulations, traffic conditions, public facilities, and other issues, three alternative locations are being considered for the following risk assessment and decisions:

- Location A: an industrial park
- Location B: a suburban area
- Location C: a flood-prone area

To analyze and compare the risks of major hazards of each location, three representative accident scenarios are selected for further risk assessment based on regulatory requirements, historical data, and environmental characteristics: (1) location A: a domino effect caused by the neighboring plant in the industrial park leading to damage of the ammonia containment and a gas cloud of ammonia; (2) location B: a major accident within the plant leading to an ammonia cloud to a residential area;

(3) location C: a large-scale leakage of ammonia caused by a flood. In the following context, they are referred to as RS1, RS2, and RS3.

3.4.2 Stakeholder analysis

One of the primary goals of the approach is to reconcile different values between scientific risk assessment and stakeholder risk perception. A broader risk characterization that can reflect the concerns of stakeholders is required. In this example, five groups of stakeholders, including the ammonia plant, the local government, Non-Government Organizations (NGOs), residents, and the neighboring plant, are involved in the risk management process.

On one hand, the plant itself, including owners and managers, consists of an important type of stakeholders. The local government has a financial stake by funding a part of the construction costs of the plant. Another important group are the Non-Government Organizations (NGOs). When it comes to major accidents, their stakes are primarily focused on environmental protection, public health, and social justice. Local residents are crucial stakeholders in the operation of ammonia plants, as they are vulnerable to major accidents. Their stakes involve various aspects of safety, environment, and social well-being. Finally, the neighboring plant in the cluster park will also be threatened by major accidents that could have a negative impact on production and the economy.

3.4.3 Risk description

The approach focuses on reconciling different values and interests to reach a consensus among stakeholders. Broader risk characterization that can reflect the concerns of affected groups and the public is required. Following the procedure in Section 3, we assume that a list of concerns, in addition to rational criteria, has been gathered through dialogs among stakeholders:

- History of records: it concerns the history of accidents regarding similar facilities
- Social impacts: it denotes the greatest environmental impact in a single event
- Controllability: it examines if risk is easily/not easily reduced
- Knowledge: it refers to current scientific knowledge of the cause-effect mechanism of the risk scenarios at hand
- Dread: it refers to an emotional response towards risks

To determine the level of the emotional criteria, a crude qualitative risk analysis (low, moderate, high) can then be carried out by risk analysts. The categorization of different variables can be conducted through a series of questions posed to stakeholders. For instance, how many deaths do you think should be rated as low, moderate, and high? To illustrate, we assumed a categorization system was established to classify risk attributes into three levels based on stakeholders' risk appetite (as shown in Table 3.1).

Table 3.1 Hypothetical criteria developed for this example.

Criteria	Rating		
	Low	Moderate	High
History of records	History provides no records	History evidence is recorded but from a considerable time ago	History evidence is recorded within the past few years
Controllability	Easily reduced	Partially controllable	Difficult or impossible to control
Social impact	Minimum and negligible environmental damage	Moderate and immediate environmental damage	Large-scale and long-lasting environmental damage
Knowledge	A large amount of information and historical data are available	Some factors and variables are unknown, but the model used is reliable	Information and historical data are very limited or absent
Dread	Only employees or workers within the plant/park are impacted	Many people, including the local community, will be affected	Widespread impact beyond the local community, potentially affecting a large population.

3.4.4 Risk calculation

After the criteria of risk analysis are determined, risk analysts conducted a risk analysis to collect data regarding the criteria. The rational criteria of risk that probability and consequences can be estimated based on the classic QRA approach. Those emotional aspects are assessed by a scoring system: low=0.1, moderate=1, high=2. Since our purpose is to demonstrate how the decision process works, the risk analysis has been simplified, assuming the value of those risk criteria are known. The illustrative results of risk analysis are listed in Table 3.2.

Table 3.2 Illustrative risk analysis results.

Criteria	Risk Scenario (RS)		
	RS1	RS2	RS3
Frequency (year)	$1*10^{-7}$	$1*10^{-4}$	$1*10^{-5}$
Consequence (€)	$1.5*10^{8}$	$2*10^{6}$	$1.2*10^{8}$
History of records	0.1	2	0.1
Controllability	2	1	2
Social impact	1	1	2
Knowledge	2	1	1
Dread	1	1	2

For the sake of clarity, the underlying assumptions of rating of emotional criteria are illustrated below:

3.4.4.1 History of records

A score of 2 has been given to RS2 because the accident database shows the record of major ammonia accidents in the past few years. By contrast, a score of 0.1 has been given to RS1 and RS3 because there is no evidence of similar accidents in history.

3.4.4.2 Controllability

A score of 2 has been assigned to RS1 because the multiple chemical plants in the industry park increase the complexity of managing the interactions among different facilities. A score of 1 has been given to RS2 because the complexity of a single event is relatively moderate, and the event can be partially avoided. A score of 2 has been given to RS3 because the flood may damage the safety control system, and floods may accelerate the spread of chemicals and expand the geographical area of pollution.

3.4.4.3 Social impact

A score of 1 has been given to RS1 and RS2 because the release of ammonia will affect a large area of soil and cause harm to the ecosystem but not necessarily a catastrophic one. A score of 2 has been given to RS3 because the spread of ammonia contamination might affect a broader geographic area.

3.4.4.4 Knowledge

A score of 2 has been assigned to RS1 because domino effects are a kind of complex and highly uncertain process. It is hard to give an accurate prediction of the occurrence probability and consequences. A score of 1 has been given to RS2 and RS3 because although similar accidents don't occur often, the knowledge of the cause-effect mechanism of a single event is higher than domino effects.

3.4.4.5 Dread

A score of 1 has been assigned to RS1 because the large-scale release of ammonia may cause casualties in nearby chemical plants. A score of 1 has been given to RS2 because it can directly affect the vulnerable populations living nearby. People may feel dread when facing such events. A score of 2 has been given to RS3 because the impacts brought by the leakage of chemical substances into a flood is highly unpredictable. The influence may be long-lasting and cannot be observed.

3.4.5 Risk prioritization

3.4.5.1 Rational approach

The focus of the rational approach is on safety and technical aspects. The natural way is to perform QRA on the criteria of consequences and associated probabilities, see formula (5). The ranking is expressed in ordinal order, with 1 being the highest-ranked risk.

Table 3.3 Results of standard risk ranking approach.

Risk scenario	Risk value	Risk ranking (1=highest risk; 3=lowest risk)
RS1	15 €/ year	3

RS2	200 €/ year	2
RS3	1200 €/ year	1

From the results, the rankings of different risk scenarios can be observed. Following the rational risk ranking, RS3 is the highest-ranked risk. From risk management point of view, location A, an industrial park, would be the most appropriate site to construct the ammonia plant. Based on the criteria defined, location B is the second-best selection, and location C is the worst choice.

3.4.5.2 Emotional approach

When applying an emotional approach, it is essential to consider stakeholders' emotional criteria across different risk scenarios. To illustrate, the risk index method (see formula (6)) is applied to measure and integrate emotional factors into risk ranking. In this example, we assume that the history of records, severity, social impact, and dread are positively correlated to risk value, while controllability and knowledge are negatively related to risk value. For example, the risk value of risk scenario is calculated as follows:

$$R = \frac{1 * 10^{-7} \times 1.5 * 10^{8} \times 0.1 \times 1 \times 1}{2 \times 2} \approx 0.4$$

Finally, the overall risk scores are obtained following the procedure mentioned in chapter 3.3.2.5. Based on the scores, a ranking of risks is obtained (Table 3.4).

Table 3.4 Results of emotional risk ranking approach.

Risk scenario	Risk value	Risk ranking (1=highest risk; 3=lowest risk)
RS1	0.4	3
RS2	2	1
RS3	0.8	2

Based on the results, the rankings of different risk scenarios can be observed. In both ranking approaches, RS1 achieved the lowest score, but the rankings of RS2 and RS3 changed. Despite RS3 receives higher score than RS2 when only probability and consequences are considered. However, with additional consideration of the emotional factors assumed above, RS2 receives the highest score among the three scenarios. Accordingly, if emotional risk ranking is applied, location A might be the best construction site. In contrast, suburban areas became the least favorable option.

3.4.5.3 Discussion and negotiation

After obtaining the results of two different risk ranking strategies, risk analysts and stakeholders should discuss the results and reach a consensus as good as it gets. Different opinions regarding categorizations may exist. As mentioned in Section 3.2.5, some mediation techniques can help to achieve consensus. Due to this being an illustrative example, we assume that the stakeholder groups reached an agreement on how risks are prioritized through the consensus methods. The three illustrative risk ranking results are listed in Table 3.5.

Table 3.5 Comparison of standard, emotional-based, and final generally accepted risk ranking of major risk accidents of the three locations.

Risk scenario	Rational risk ranking	Emotional risk ranking	Accepted risk ranking
RS1	3	3	3
RS2	2	1	1
RS3	1	2	2

After discussion, a final generally accepted risk ranking is developed. RS2 has the highest risk and is considered the least suitable location for ammonia plant construction. RS1 receives the lowest risk level. Accordingly, location A is considered the most suitable place to construct the ammonia plant.

3.4.6 Risk treatment

At this stage, the risk assessment process is completed. While risk prioritization provides a primary basis for decision-making, the final decision may also need to consider additional factors, such as timing, costs, and implementation constraints. These considerations need to be integrated at risk treatment step to arrive a final decision. Given that this example is hypothetical, this step is not discussed in further detail.

3.5 Discussion

Technology risks brought by human activities may constitute adverse impacts on the safety and well-being of individuals, social groups, and non-human entities. The conflicts between scientific risk analysis and laypeople's risk perception are increasingly intensified. Prior studies suggested that public distrust in science can be attributed to a lack of communication and insufficient information. The expert-lay discrepancies can be explained as the differences between rational and emotional manner of thinking. In this study, we propose a stepwise integrated rational and emotional risk management approach that enables stakeholders to obtain scientific information related to risk decisions that may affect them.

Firstly, a modified risk definition is proposed with the involvement of the element "human at stake." The modified risk definition acknowledges the physical components of risk but also objectively or depends on human judgments. The social science approach to risk believes risk is constructed within cultures and societies (Xu, Reniers et al. 2024). The concept of risk is always linked with groups' values and interests and shaped by human interventions and social organizations (Renn 2008). What is deemed worthy of investigation may vary depending on the stakeholder group being considered. Based on the Bow-tie model, risk is represented by four dimensions: hazards, consequences, management, and uncertainties. Compared with earlier scientific works on extending risk descriptions, see (Florig, Morgan et al. 2001, Gardoni and Murphy 2014, Reniers and Van Erp 2016), this work provides a more dynamic and adjustable approach without loss of generality. Contrary to pre-define the attributes, our definition provides a general framework that allows stakeholders to develop more specific risk descriptions. This indicates that risk description should not be viewed as homogenous in a society. Rather, we emphasize individuals' sovereignty in risks that affect them. Risk is very dynamic (both short and long run); values are dynamic and can change with the development of society. Changes in constraints of political, economic, and social boundaries would introduce new characteristics in risk descriptions. In the proposed framework, these dynamics are addressed by allowing risk information, stakeholder preferences, and decision criteria to be revisited and updated throughout the risk management process.

Secondly, to target major hazards involving potentially high risk and multiple conflict interests, a systematic risk management procedure with the engagement of stakeholders is developed. This approach distinguishes itself from conventional risk management in three aspects: (1) a *stakeholder analysis* step that allows affected groups and the public to engage in risk management process; (2) a *risk description* step in which the stakeholders can interpret their concerns to determine what to be analyzed in risk assessment; (3) a *risk prioritization* step which is designed for resolving the conflicts between scientific risk analysis and laypeople's risk judgments. In the long run, the approach helps reconcile conflicts between stakeholders and experts to ensure the solution can be socially acceptable. This could be seen in the illustrative example. Obviously, risk ranking based on pure rational thoughts yields a different outcome compared with risk ranking considering additional emotional aspects. The plant managers and experts may not be interested in emotional considerations such as dread and knowledge in risk ranking. However, NGOs and residents may prefer to have a more comprehensive description of risk to make a more informative judgment. By involving stakeholders in risk decision-making process, their concerns and values can be clearly expressed and observed. Meanwhile, they also learned about the results of the scientific risk analysis. This decision is co-determined by stakeholders and risk analysts, which is believed to be accepted by the plant, local government, NGOs, residents, and neighboring plants.

This approach is not intended to replace the traditional risk management framework but to extend it. In the past, risk management norms considered laypeople's risk perception to be "heuristics and biases" that deviated from rational risk analysis (Plattner, Plapp et al. 2006). However, many risk perception studies suggest that layman emotional risk assessment actually provides rich perspectives for managing risks. Yet, many of these studies have limited their research findings within the social science field without direct application in the domains of risk management (Slovic, Fischhoff et al. 1982, Pidgeon 1998). Some of today's risk management guidelines, for example, Managing Risks to the Public: Appraisal Guidance (Treasury 2005) and IRGC risk governance framework (Florin and Bürkler 2017), do acknowledge the importance of emotional considerations in decision-making. However, they advocate that risk perceptions and societal considerations are assessed in "concern assessment" to supplement "scientific risk analysis" to avoid introducing biases to the system. While it is true that a layman's perception can be biased or an error, risk analysts are not immune to mistakes, especially when provided with inappropriate data. As mentioned earlier, in situations where data is scarce, experts often use model outputs as heuristic tools to generate missing information. This reflects the reality that laypeople usually have unequal access to scientific risk information when facing some of today's risks compared to experts. By systematically involving stakeholders in risk decision-making, they have the opportunity to voice their views and gain a deeper understanding of the scientific perspective. Early engagement helps to address and resolve potential conflicts between expert assessments and lay perceptions from the start rather than after decisions have already been made.

While this study proposes a possible way to reconcile conflicts between science and societal acceptance by integrating rational and emotional perspectives, there are several limitations that require future development and improvement. The current model represents an initial attempt to incorporate public values, such as fairness, equity, and emotional response, into formal risk management. The model is relatively crude, with simplified assumptions about how stakeholders express their values and interests and how various stakeholders reach a consensus on an emotional risk ranking. Furthermore, the details of this methodology remain conceptual and high-level, such as how to identify key stakeholders, and the interplays of negotiation and discussion process. More detailed methodology may enhance the applicability of the approach. The case study utilized in this chapter is hypothetical and intended to demonstrate the potential of the proposed approach. The practicality of the approach should be tested with real-life scenarios in future studies.

In summary, this approach offers a potential solution for reconciling expert-lay conflicts and enhancing public trust in risk management by integrating rational and emotional concepts of risk. While the approach may not always lead to desired results, the negotiation process is meaningful for narrowing down the gap between experts and the public.

3.6 Conclusions

This chapter aims to propose a normative risk management model aimed at resolving conflicts between scientific risk analysis and public risk judgments. The article explains the reasons behind the discrepancies between expert and lay perspectives and highlights the importance of incorporating stakeholders' emotional considerations within risk management.

By updating the risk definition $(C, U)_\eta$ with involvement of people at stakes η, this chapter emphasizes the indispensability of human values in shaping the concept of risk. The modification of risk definition provides a reasonable basis for stakeholders to participate in risk management. Following this, the chapter introduces a stepwise, integrated approach that combines rational and emotional perspectives in risk management, specifically designed for risks with high consequences and significant uncertainties. An illustrative example is presented to demonstrate the approach's applicability, showing that following this systematic procedure enables the effective integration of stakeholder input into rational risk analysis, ultimately supporting the policy-making process. Including stakeholders and incorporating their perspectives into risk assessment is expected to help bridge the gap between scientific risk analysis and public concerns.

In the future, the challenge will be utilizing more precise tools and approaches to manage risks with the approach.

Chapter 4 Stakeholders' views and attitudes on the Integrated Rational and Emotional Risk Decision-Making (IRERDM) Approach

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This chapter is modified based on the journal paper: Xu, Y., Reniers, G., & Yang, M. Stakeholders' Views and Attitudes on Major Risk Management and Complementing the Rational Risk Calculation with Ethical and Emotional Concerns. (submitted). Journal of Safety Science and Resilience.

As an exploratory stage to examine the validity of the Integrated Rational and Emotional Risk Decision-Making (IRERDM) decision-making approach, this chapter reports on a questionnaire designed to elicit stakeholder views on major risk management, including perceptions of the meaningfulness of stakeholder participation, risk attitudes, decision-making styles, and the perceived importance of emotional risk factors. The results of the questionnaire are presented, followed by a discussion of the main viewpoints expressed by stakeholders, the relationship between stakeholder roles and their opinions, potential conflicts in participatory risk management, and challenges in promoting the IRERDM approach. The final section concludes with reflections on incorporating stakeholders' perspectives into the management of major risks. Although no significant differences were observed in most perceptions, attitudes, and practices related to major risk management across groups of stakeholders, there was not always a complete agreement between them. These findings suggest that promoting the IRERDM approach could be beneficial.

4.1 Introduction

Major risks, also called "Type II risks", are a kind of undesired events with high level of uncertainty and huge consequences (e.g., multiple fatality accidents) (Meyer and Reniers 2025). Risk management as a structured tool to deal with uncertainty and adverse impacts is accepted in many areas, such as the oil industry, food safety, construction management, etc. However, recent years have seen a decline in public trust in experts and risk management organizations. Modern society increasingly demands greater transparency and the integration of economic, moral, and ethical considerations in risk assessments (Reniers 2017). Currently, the research and policy-making activities in risk management are mostly concentrated on the more rational side. The traditional risk management process consists of three distinct parts: establish objectives/context, risk assessment (risk identification and risk evaluation), and risk treatment (Ale, Aven et al. 2009). Establishing objectives and context involves the definition of the key objectives to be met or key problems to be solved in risk management. This could relate to protecting public safety and health, environmental protection, and more aspects. Risk assessment focuses on systematically identifying hazards/risks and objectively estimating and evaluating all the information to support decision-making. Risk treatment aims to reduce or transfer risks when a certain risk is deemed acceptable. The earlier research on risk perception and communication revealed that laypeople's risk assessment is a complex and multi-faceted issue. People make decisions not only influenced by probability and consequences (which are the basis of the current risk management framework), but also by substantial emotional elements, such as psychological factors (Fischhoff, Slovic et al. 1978), ethical and moral principles (Roeser 2006), emotions (Sjöberg 2007), heuristics and biases (Tversky and Kahneman 1974).

Many efforts have been made to bridge the gap between scientific risk assessment and the public's voice (Ale, Slater et al. 2023). A comprehensive review of previous work can be found in (Xu, Reniers et al. 2024). Building on these pioneering studies, an Integrated Rational and Emotional Risk Decision-Making (IRERDM) approach designed for major risks, was proposed as outlined in chapter 3 (Xu, Reniers et al. 2025). The IRERDM approach is intended to bring stakeholders together, listen to their views on risk, and give them responsibility for making decisions. In IRERDM, stakeholders are defined as individuals or groups that may be affected by the adverse effects of risk. The public is also a special type of unorganized stakeholder. The IRERDM consists of 6 main steps: problem identification, stakeholder analysis, risk characterization and analysis, risk calculation and ranking, risk evaluation, and risk treatment. There are several features of the IRERDM approach that need to be emphasized. First, the process aims to achieve a certain degree of consensus, or at least agreement, by collecting stakeholders' views on the decisions. The ultimate risk ranking is achieved by weighting rational risk ranking and emotional risk ranking. Second, the IRERDM process is designed to have widespread applicability towards decision-making across many types of major risks. The main difference between current approaches is that emotional factors are incorporated into risk assessment and treatment through stakeholder participation.

The effective enforcement of the IRERDM process requires a strong partnership with different types of stakeholders. Particularly, stakeholders' decision-making process can be modified by their concerns and perceptions, which influence actual exposure indirectly (Lupo, Wilmart et al. 2016). According to the social construction of risk theory, risk perception and acceptability of risk are influenced by many factors, such as worldviews, culture, societal values, media influence, and more (Xu, Reniers et al. 2024). Consequently, what is considered to be risk and what is considered to be an acceptable level of risk will vary depending upon the roles and experiences of stakeholders being considered. Therefore, it is significant to understand the meaningfulness of participatory risk management and the significance of emotional risk factors perceived by stakeholders, and how stakeholders make decisions.

Prior research has offered valuable research on how experts and laypeople differ in their understandings and perceptions of various hazards (Rowe and Wright 2001, Hansen, Holm et al. 2003). Only a few studies have compared the differences in opinions among various types of stakeholders to risk management practices, and they are mainly focused on risk perceptions. Studies on attitudes towards participatory risk management were concentrated on specific fields of risk management, such as food safety, natural hazards, and construction industry (see (Vari, Linnerooth-Bayer et al. 2003, Van Kleef, Frewer et al. 2006, Stezar, Ozunu et al. 2014, Lupo, Wilmart et al. 2016)). Hence, the insights taken may not be readily transferred to general major risk management. To the best of the author's knowledge, stakeholders' risk attitudes and their decision-making styles for major risks have never been examined before. Meanwhile, the definition and criteria for the classification of stakeholders differ across specific contexts. For example, a majority of studies made a distinction between the public and stakeholders (Florin and Parker 2020). In some studies, e.g. (Sjöberg 2003), stakeholders are not identified solely by their involvement in interests or special concerns. Only those who actively engage through self-reporting or other observed activities are considered stakeholders. In the context of the IRERDM approach, the scope of stakeholders has a different focus. Stakeholders can be defined as groups or individuals who are or will be affected or do perceive to be affected by an event or activity from which a risk originates, and/or who have an influence on that event or its outcomes, including the risk management options implemented to address the risk (Florin and Parker 2020). Hence, those research findings may not be applicable to our context. Given the IRERDM is a newly brought approach, what is considered important in the decision-making process done by stakeholders need to be explored.

The objective of this study was to use a questionnaire survey to extract some common profiles of stakeholders relating to attitudes toward the IRERDM approach and emotional risk factors, as well as key factors that influence how they make decisions in risk management. Specifically, the objective is translated into three research questions:

(1) What are stakeholders' opinions regarding the meaningfulness of participatory risk management, and the significance of emotional risk factors? What are stakeholders' risk attitudes and decision-making styles?

(2) Are roles and experiences of stakeholders associated with their attitudes and views on major risk management?

(3) Is there potential for conflicts of views among stakeholders? What are the challenges of promoting the IRERDM approach?

The following context of the study is structured as follows: section two describes the materials and methods that were applied to collect and analyze the survey data. The questionnaire survey results are discussed in section three. The exploratory findings are summarized and discussed in section four. Finally, the conclusions are given in section five. The survey sample and supplementary data can be found in Appendix A.

4.2 Research methods

In carrying out this study, a survey was conducted through a sociological questionnaire which was sent to stakeholders involved in 10 principal fields (see later in section 2.1) of major risk management. Given that the research is of exploratory nature (a relatively new area of study), it was decided not to impose a theoretical model or framework on the data acquisition and analysis. It is designed to provide some descriptive evidence (describing patterns of phenomena) on how stakeholders perceive risks and key interests under specific uncertain circumstances rather than determining cause and effect relationships.

4.2.1 Study design and sampling

An online survey was set up to investigate the similarities and differences between the attitudes and views of stakeholders in various fields regarding integrated rational and emotional risk management. There are a variety of categorizations of stakeholders in previous literature. The stakeholder categories chosen for this study were based on existing literature (Reniers, Ale et al. 2009) and authors' experience and expertise. Stakeholders involved in filling the questionnaire are: (1) employees of high-risk sectors, (2) representatives, investors, and shareholders of high-risk sectors, (3) government organizations and regulatory body, (4) Non-Governmental Organizations, (5) academic or research institution, (6) emergency responders, (7) insurance company, (8) consultancy agencies, (9) media, and (10) public.

Sociological surveys differ from sociological empirical research to obtain information from experiments and have a high degree of control of the analyzed variables (Stezar, Ozunu et al. 2014). Due to the practical reasons and exploratory nature of this work, a non-probabilistic sampling was utilized. Non-probabilistic sampling tends to be cost-effective and time-efficient but may give some biased results (Hartono, Sulistyo et al. 2014). It may result in lack of representativeness, inaccurate or false information, overrepresentation of certain groups. Furthermore, individuals selected for the sample may differ significantly from those who don't. However, in the circumstance when the sample frame is difficult to drawn, non-probabilistic sampling is preferred (Emerson 2015). The survey was distributed in two ways. First, invitations requesting participation in the proposed online questionnaire were sent electronically to stakeholders based on their availability at different national levels. Second, the questionnaire was distributed through a snowballing strategy, where the first wave of respondents distributed the questionnaire to their connections.

4.2.2 Data collection

Responses from the stakeholders were collected using an online anonymous questionnaire created, hosted, and shared using Qualtrics™. Appendix A1 provides a sample of the survey form. The time required to respond to the questionnaire was approximately 5-10 min. Responses to the following parts are collected and analyzed:

(1) Demographic information of the respondent, including gender, geographic regions, and stakeholder groups (3 close-ended questions).

(2) Attitude towards stakeholder participation in major risk management (1 close-ended question).

(3) Response to a question about various stakeholders' weights in risk management (1 close-ended question).

(4) Seven strongly worded statements were used to elicit respondents' risk attitudes; each rated on a 5-point Likert scale reference) from "strongly disagree" to "strongly agree" (7 close-ended questions).

(5) Risk decision-making styles, including objectives, principles, and constraints (3 close-ended questions).

(6) Perceived importance of nine emotional risk factors, each rated on a 5-point Likert scale from "not important" to "very important" (9 close-ended questions, 1 open-ended question).

(7) Solving conflicts in risk decision-making process (1 semi-open-ended question).

(8) Respondents' comments and suggestions (1 open-ended question).

In total, the questionnaire contained 27 questions (with 89% close-ended, 7% open-ended, and 4% semi-open-ended).

To identify which category of stakeholders the participants belong to, respondents self-reported their profiles by answering the question, "which of the following best describes the group you belong to in the context of risk management?". Questions for risk attitude (defined as propensity for risk-aversion or risk-taking) towards major risks were designed and adjusted according to the existing scientific literature (Sjöberg 2003). In this study, risk attitude is not treated as a personal trait but regarded as decision behavior under certain circumstances. It may vary according to the type of risk, available information, and the circumstances in which a decision is made. Respondents were asked to indicate how much they agreed with the proposed statements, from strongly disagree to strongly agree using a 5-point Likert scale which is a type of Likert scale that is most widely used in various social studies (Tanujaya, Prahmana et al. 2022). A higher agreement level indicates a higher risk attitude score, which corresponds to a stronger tendency toward risk aversion. Questions for asking risk decision-making styles are multiple choice questions, designed according to (Meyer and Reniers 2022). Perceptions of the importance of emotional risk factors to some extent resemble the notable psychometric risk model; however, there are important differences. It includes not only psychological factors but also factors such as "social impact," which has been found important in the famous social amplification of risk framework (Kasperson, Renn et al. 1988). Furthermore, the factors measuring moral and societal problems, e.g., “fairness” and “trust,” are included beyond the psychometric model.

Before the questionnaire is formally distributed to respondents, the questionnaire was reviewed by an expert in the field of safety management and was slightly adapted based on the remarks. Meanwhile, a draft of the questionnaire was pre-tested by 12 persons belonging to a different group of stakeholders to evaluate the length of the questionnaire, understandability of questions, and mobile friendliness of the online system.

To improve response rates and protect respondent confidentiality, anonymous and voluntary responses are highlighted in the survey consent form. No answer to the questionnaire was mandatory. Each of the respondents was asked to fill in answers to questions based on their experience in the field (e.g., each question started with “From the perspective of your stakeholder role…”). These responses were completed independently and individually.

The initial invitation to participate in the survey was sent on 16 December 2024. The survey was open for responses until 15 January 2025. Upon completion of the survey, all collected data were coded and double-checked to eliminate procedural errors.

4.2.3 Data analysis

Response data gathered in Qualtrics™ were exported into a Microsoft Excel spreadsheet. Statistical data analysis was conducted using a Statistical Package for the Social Sciences software (SPSS) (version 20). Given the small number of responses to the open-ended and semi-open-ended questions, qualitative data extracted from the open questions were analyzed using a summary analysis to capture the key points and insights.

Each variable was described in terms of frequency distribution. A Chi-Square test is typically used to see if there is a relationship between two categorical variables. However, in larger contingency tables (greater than 2×2) where some expected counts are less than 5, the standard Chi-square test may produce inaccurate P values(Nowacki 2017). In this situation, the Monte Carlo method is feasible to produce an unbiased P value(Mehta and Patel 2011). Therefore, the Monte Carlo simulation-based Chi-Square test (two sub-groups when the expected number of observations was less than 5), with P=0.05, was applied to determine significant differences between the frequency distributions of stakeholder types and other dependent variables. If $P \leqslant 0.05$, we reject the null hypothesis, suggesting that there is a statistically significant relationship between the variables. If

P > 0.05, it suggests that the observed data does not show a statistically significant relationship between the variables.

Particularly, to address the issue of multiple responses (e.g., risk decision-making styles), we first applied binary (0, 1) encoding to the data. "1" represents the presence of a response, and "0" means its absence. Subsequently, we conducted separate Monte Carlo simulation-based Chi-Square tests for each binary-coded response pair to examine the associations between the type of stakeholder and the variables. In addition to performing chi-square tests on the binary-encoded responses, we also considered an alternative approach by reformatting the data into a multiple-response format and conducting a chi-square test on the aggregated responses. Finally, principal component analysis was applied to all multiple questions to see if there was clear clustering between different answers from respondents.

For risk attitude (4), the data was first viewed categorically with 5 scales and examined with Monte Carlo simulation-based Chi-Square test to determine if there are significant differences. Then, the data were judged quantitatively on a five-point scale (1=strongly disagree, 2=disagree, 3=neutral, 4=agree, and 5=strongly agree), and a total score was computed by averaging the seven items. The agreement between risk attitude was assessed using Cronbach's Alpha test (reliability test).

For part (6), the ranking of emotional risk factors was quantified as the ratio of the preference score of that particular emotional risk factor to the total preference score for all factors (Junaedi 2018). Firstly, questionnaire results were compiled in a table where columns were stakeholder categories, rows were Likert categories (not at all important, somewhat important, important, very important, and extremely important), and cells contained counts of responses. For columns that belonged to the same emotional risk factor, the counts in all cells were then pooled, and the proportion was scaled between 0% and 100% by dividing the pooled value in every cell by the number of samples:

$$\mathrm{Pr} = \left(\frac{f}{n}\right) \times 100\% \tag{1}$$

Where Pr=proportion data, f=pooled count responses for each risk factor in each Likert category response, and n= total number of respondents. The proportion data were converted to preference scores by weighting the values based on the response categories using equation (2):

$$\sum_{i=1}^{n} \mathrm{Pr}(x_i)x_i \tag{2}$$

Where $\mathrm{Pr}(x_i)$ = the probability of proportion data value in a cell (cell value/100) andx_i= 1 for not at all important, 2=somewhat important, 3=important, 4=very important, and 5=extremely important. At last, the preference score for each emotional risk factor was obtained by summing all values within that emotional risk factor. The relative preference score (as a percentage) of a particular emotional risk factor is simply the ratio of the preference score of that emotional risk factor and the total preference score of all emotional risk factors (total data column).

4.3 Results

4.3.1 Profile of respondents

A total of 122 questionnaires were collected, and after excluding invalid responses, 90 valid questionnaires remained. The frequencies and proportions of overall responses received from respondents can be seen in **Table 1**. Male respondents accounted for 76.7%, whereas female respondents represented 21.1%. A majority of respondents come from academic or research institutions (N=38), followed by employees of high-risk sectors (N=19), government organizations and regulatory body (N=12), media (N=5), public (N=5), emergency responders (N=3), consultancy agencies (N=3), representatives, investors, and shareholders of high-risk sectors (N=2), insurance company (N=2), and Non-Governmental Organizations (N=1). Out of the 90 respondents, they were mainly from Central and East Asia (77.8%), followed by Western Europe (13.3%). Other regions are North America (4.4%), South and Southeast Asia (2.2%), West/middle East Asia (1.1%), and North Africa (1.1%).

Table 4.1 Descriptive statistics of the characteristics of the respondents in the sample.

Items	Description	Frequency	Percentage
Gender	Male	69	76.7
	Female	19	21.1
	Prefer not to say	2	2.2
Region	East and Central Asia	70	77.8
	South and Southeast Asia	2	2.2
	West/Middle East Asia	1	1.1
	Western Europe	12	13.3
	North Africa	1	1.1

	North America	4	4.4
Stakeholders	Employees of high-risk sectors	19	21.1
	Representatives, investors, and shareholders of high-risk sectors	2	2.2
	Government organizations and regulatory body	12	13.3
	Non-Governmental Organizations	1	1.1
	Academic or research institution	38	42.2
	Emergency responders	3	3.3
	Insurance company	2	2.2
	Consultancy agencies	3	3.3
	Media	5	5.6
	Public	5	5.6

4.3.2 Attitude toward integrated risk management

4.3.2.1 Perceived meaningfulness of stakeholder involvement

Appendix A2 shows respondents' perceived meaningfulness about stakeholders' participation in risk management. Out of the 90 respondents, 42 (47%) strongly agree and 34 (38%) agree that stakeholder participation is meaningful in managing major risks. Those who strongly disagreed with this action represented 10% (N=9). 5 respondents (6%) answered that they neither agreed nor disagreed with the statement. These perceptions did not differ across variant stakeholder groups (P=0.31).

Figure 4.1 provides an overview of how different stakeholder categories perceive the meaningfulness of stakeholder participation in major risk management.

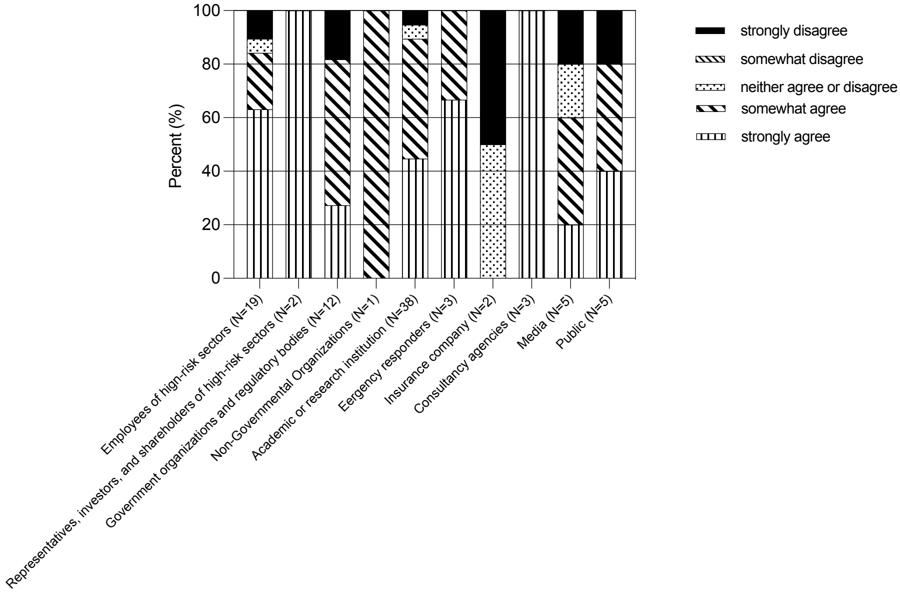

Figure 4.1 To what extent do you agree with the statement “stakeholder participation is meaningful for the management of major risks”?.

All respondents from the categories of representatives, investors, and shareholders of high-risk sectors, Non-Governmental Organizations, emergency responders, and consultancy agencies selected either “somewhat agree” or “strongly agree” toward the issue. In particular, all respondents from both the representatives, investors, and shareholders of high-risk sectors and consultancy agencies categories selected “strongly agree.” However, a higher proportion of insurance company respondents (50%) than in the other fields strongly disagree that involving stakeholders in managing major risk is meaningful. This may be due to a lack of responses.

4.3.2.2 Stakeholder’s responsibility in major risk management

For the question “which stakeholder group do you believe should have more influence or weight in the risk management participation process?”, respondents were asked to choose no more than four categories of stakeholders from a list of 10 options. The frequency of multiple-choice selections for each stakeholder category is visualized in Figure 4.2. In the histograms, the variables on the y-axis are ranked based on the proportion of participants selecting each variable. The variable with the highest response frequency appears at the top, followed by the remaining variables in descending order according to their relative frequencies among all participants.

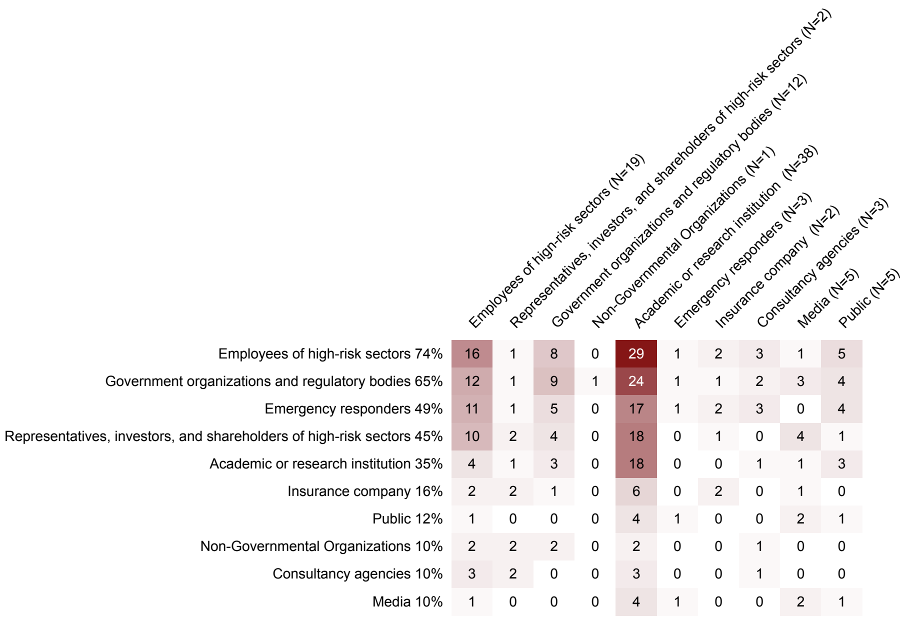

Figure 4.2 Which stakeholder group do you believe should have more influence or weight in the risk management participation process?

Regardless of the type of stakeholders, over three-fifths indicated that employees of high-risk sectors (66; 74%) and government organizations and regulatory bodies (59; 65%) should have more influence in risk management. More than a third of respondents believed that emergency responders (45; 50%), representatives, investors, and shareholders of high-risk sectors (41; 45%), and academic or research institutions (31; 35%) should be responsible for major risk management. Other stakeholders, e.g., insurance company (18; 16%), NGOs (9; 10%), public (11; 12%), and media (9; 10%) are less cited. This opinion did not vary between stakeholders (P=0.99).

While there is no collective pattern of disparity across all response combinations, there are distinct preferences or variations between certain options and stakeholder categories. For example, employees in high-risk sectors ranked this option the highest among all choices, while a significantly lower proportion of respondents (1 out of 5; 20%) from the media group selected it

(P=0.02). Moreover, although consultancy agencies only account for 10% of total responses, all respondents from representatives, investors, and shareholders of high-risk sectors (2 out of 2; 100%) believe that more influence should be in the hands of consultancy agencies (P=0.02). Similarly, a higher percentage of interviewees of representatives, investors, and shareholders of high-risk sectors (2 out of 2; 100%) view NGOs (P=0.02) and insurance companies (P=0.01) as key players. A higher proportion of respondents (2 out of 2) from insurance companies selected the insurance company (P=0.01). All respondents from the group of insurance company, consultancy agencies, and public considered employees of high-risk sectors should have more influence in risk management activities. Particularly, no respondents from the group of representatives, investors, and shareholders of high-risk sectors, government and regulatory bodies, NGOs, insurance companies, or consultant agencies considered the public and media as deserving of greater influence in risk management.

4.3.3 Risk attitude

In the present section, seven risk attitude items were designed to include five scale-worded assertions regarding the statement regarding major risks. The statements are:

1. "I believe that the risk associated with industrial major accidents is much higher than what is reported in industry."
2. "I am not willing to accept major risks with compensation, such as chemical leakages, gas explosions, or large-scale industrial accidents, even if the proposed benefits or compensations are substantial."
3. "The adverse impacts of major risks (e.g., loss of lives due to chemical plant explosions) should be minimized at all costs (e.g., time, money), even if the likelihood of their occurrence is minimal."
4. "I believe the long-term consequences of chemical plant accident scenarios can still be largely ignored by current science."
5. "Even when a chemical industrial company meets all safety standards, I still feel concerned about potential consequences of an adverse event."
6. "I still pose a negative attitude towards an undesired event with high consequences, even when an expert tells me that the likelihood is low."

7. “In situations when not all major risks are fully understood, I believe it is possible to stop operations until further assessments can be made.”

The frequency of responses for each item, ranging from “strongly disagree” to “strongly agree,” is presented in Appendix A2. Out of the 90 respondents, the “most frequent” answers to this group of seven statements were “somewhat agree” and “strongly agree.” A Monte-Carlo simulation Chi-square test was conducted, with stakeholder types as the independent variable and their responses as the dependent variable. The majority of responses in the seven statements did not vary between stakeholders, except for statement 4 (P=0.03). Government organizations and regulatory bodies are more likely to select “strongly disagree” for statement 4, while NGOs and consultancy agencies tend to choose “somewhat disagree.” Respondents from academic or research institutions are more inclined to select “somewhat agree.”

The Cronbach alpha was 0.62, which indicates the seven questions are moderately related and consistent. For a further analysis of the responses, the mean scores of the seven statements for different stakeholders are calculated. The composite score of the seven items was grouped into one index: risk attitude to major risks. Five levels of risk attitude are formed based on the mean scores of the seven items (from strongly risk seeking to strongly risk averse). Higher scores indicate a propensity for greater risk aversion. The range of score level and distribution of risk attitudes (Weber, Blais et al. 2002) across participants can be seen in Table 4.2. The mean risk attitude score of the total participants is 3.87, and the standard deviation is 0.54.

Table 4.2 Distribution of risk attitudes across respondents.

Risk attitude	Range of score level	Frequency of respondents
Strongly risk seeking	1.00-1.79	0
Moderately risk seeking	1.80-2.59	3
Risk neutral	2.60-3.39	11
Moderately risk averse	3.40-4.19	46
Strongly risk averse	4.20-5.00	24

As observed in Table 4.2**,** out of the 90 respondents, the majority of respondents were risk averse, either moderately (51%) or strongly (27%). This was followed by risk neutral respondents, who accounted for 12%. Only three participants (3%) were classified as risk-seeking, while no participants fell into the strongly risk-seeking category. A Monte-Carlo simulation Chi-square test was run, with stakeholder types as the independent variable and risk attitude levels as the dependent variable. The results indicated a weak relationship between stakeholder types and risk attitude levels (P=0.40).

Figure 4.3 provides a clearer visualization of the different risk attitude levels among various stakeholder groups through a histogram.

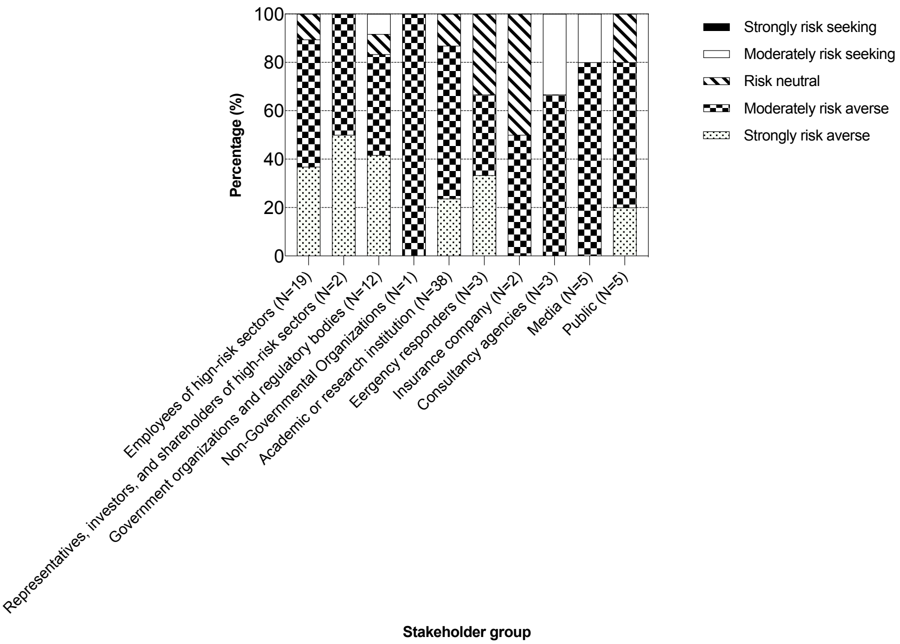

Figure 4.3 Distribution of risk attitudes across different stakeholder categories.

The majority of stakeholder groups exhibit a similar distribution of risk attitudes to the overall trend, with risk aversion being the predominant characteristic. However, some variations exist, particularly among consultancy agencies, media representatives, and government organizations, where the proportion of risk-seeking participants is slightly higher.

While the distribution of risk attitudes across respondents was about the same for all statements, For a further analysis, frequencies of the responses to seven statements are given, see Table 4.3.

Table 4.3 Response frequencies to risk attitude statements by all respondents.

Statement	Risk attitude				
	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
1	0	3	16	42	29
2	2	6	10	27	45
3	4	14	12	25	35
4	5	10	20	35	20
5	0	4	12	49	25
6	0	16	26	36	12
7	0	7	18	44	21

A majority of respondents selected "somewhat agree" or "strongly agree" for most statements. Compared with other statements, large number of respondents did “strongly disagree” in statement 2 (N=45;50%) and statement 3 (N=35;39%). There are very few risk seeking participants, with at most five (6%) appearing at statement 4. While most statements received high agreement levels, certain statements showed a more diverse distribution of opinions. In particular, Statement 6 showed a relatively higher proportion of “somewhat disagree” responses (N = 16, 18%) as well as a higher level of neutrality, together with Statement 4, compared to other statements.

4.3.4 Risk decision-making styles

To analyze risk decision-making styles, respondents were asked to choose the most important objectives, principles, and constraints (no more than four options) in the risk management process. According to a variation of responses, the distribution of responses across different stakeholder categories are shown in **Fig 5**. The variables are ranked on the y-axis of the heatmaps according to the frequency of each variable responses relative to the total number of participants, with the highest-ranked variable at the top, followed by the others in descending order of the proportion of participants selecting each variable.

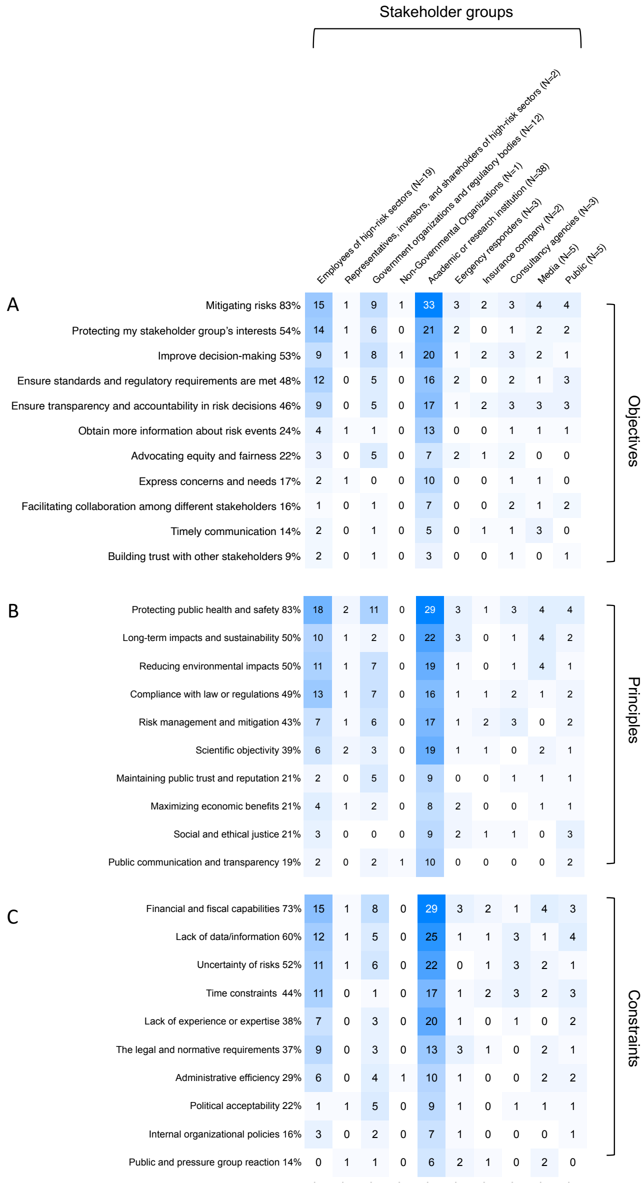

Figure 4.4 A-C Distribution of opinions regarding main objectives, principles, and constraints in participating in risk management.

4.3.4.1 Risk decision-making objectives

Regardless of the role of stakeholders, more than four-fifths of interviewees (N=75; 83%) regarded mitigating risks as their main objective. At the same time, over half of the respondents (N=49; 54%) indicated protecting stakeholder groups' interests as their main objective. Around half of the respondents reported that improving decision-making, ensuring transparency and accountability in risk decisions, as well as ensuring standards and regulatory requirements are met (48; 53%, 43; 48%, 41; 46%, respectively) are their main objectives. Nearly one in fifth respondents believed that obtaining more information about risk events (N=22; 24%), advocating equity and fairness (N=20; 22%). Somewhat fewer respondents emphasized other objectives, such as expressing concerns and needs (N=15; 17%), facilitating collaboration among different stakeholders (N=14;16%), timely communication (N=13; 14%), and building trust with other stakeholders (N=8; 9%). Types of stakeholders were not significantly associated with these opinions (P=0.98).

Some descriptive variations can be observed across fields. In the media sector, a higher proportion of respondents (60%) compared to other fields considers "timely communication" one of their main objectives. The same pattern is also evident to some extent among consultancy agencies: Those who identified facilitating collaboration among different stakeholders (67%) and building trust with other stakeholders (33%) as key objectives account a higher proportion compared with other fields. Likewise, among representatives, investors, and shareholders of high-risk sectors, a higher proportion obtain more information (50%) about risk events, express concerns and needs (50%). 67% emergency responders and consultancy agencies believed advocating equity and fairness should be the main objectives. Furthermore, it is worth noting that all respondents from insurance companies and consultancy agencies regarded ensuring transparency and accountability in risk decisions as their main objectives.

4.3.4.2 Risk decision-making principles

The second question asked respondents to choose the main principles of risk management. As shown in Figure 4B, out of the 90 respondents, 75 (83%) reported "protecting public health and safety" as one of the main principles. Following this, "long-term impact and sustainability" and "reducing environmental impacts" were selected by 45 (50%) respondents. Just under half of all respondents (N=44; 49%) thought they should comply with laws or regulations. Risk management and mitigation and scientific objectivity each received 43% (N=39) and 39% (N=35) responses respectively. The items "maintaining public trust and reputation," "maximizing economic benefits," and "social and ethical justice" received an equal number of selections, each accounting for 21%

(N=19) of the respondents. The lowest ranking was given to public communication and transparency (N=17; 19%). This opinion did not vary between different types of stakeholders (P=0.64).

Some descriptive variations could be observed from the results. All respondents of representatives, investors, and shareholders of high-risk sectors (N=2) believed scientific objectivity should be one main principle that needs to be considered. Similarly, emergency responders gave more emphasis to maximizing economic benefits (67%), as well as long-term impacts and sustainability (100%) than respondents in other fields. In the government organizations and regulatory body sector, a higher proportion of respondents (42%) than in other groups considered maintaining public trust and reputation as one of their main principles in risk decision-making. A higher percentage of public (60%) selected "social and ethical justice" than other groups. By contrast, in a sample of 12 participants, none of the stakeholders from government organizations and regulatory body considered "social and ethical justice" as a principle that should be taken into account in decision-making. Although "protecting public health and safety" was ranked in first place across all stakeholder groups, significantly fewer responses were observed in the sector of NGOs, and this may be due to a lack of responses (N=1).

4.3.4.3 Risk decision-making constraints

The third question asked the respondents to choose the main potential constraints in the risk management decision-making process. As shown in Figure 4C, regardless of the types of stakeholders, the highest percentage was registered for "financial and fiscal capabilities" (N=66; 73%), followed by "lack of data/information" (N=54; 60%), "uncertainty of risks" (N=47; 52%). Other constraints were "time constraints," "lack of experience or expertise," "the legal and normative requirements," and "administrative efficiency," each accounting for 44% (N=40), 38% (N=34), 37% (N=33), 29% (N=26). Significantly, the least essential constraint was attributed to public and pressure group reactions (N=13; 14%). This opinion did not vary between various types of stakeholders (P=0.80).

67% (2 out of 3) of emergency responders chose "public and pressure group reaction" emergency responders (P=0.02). Although respondents from all stakeholder groups consider financial and fiscal capabilities the most critical constraints in risk decision-making, significantly fewer interviewees in the Non-Government Organizations (0%) consultancy agencies group (33%) selected this item as their main constraint. All interviewees from the insurance company (N=2) and consultancy agencies group (N=3) regarded "time constraints" as their main constraints. A higher proportion of respondents from academic or research institutes (20 out of 38; 53%) selected "lack of experience or expertise" compared to other groups.

4.3.5 Emotional risk factors

This section asked respondents to rate the importance of emotional risk factors in risk management. Appendix A2 shows respondents' perceived significance of nine emotional factors. Among emergency responders, almost all emotional risk factors are perceived as important, very important, and extremely important. Furthermore, the main strong negative responses towards emotional risk factors came from two groups of respondents: employees from high-risk sectors and government organizations and regulatory body.

The graphical distribution of responses of total respondents is shown in Fig 4.5. Explanation of emotional risk factors can be seen in Table A1, Appendix A2.

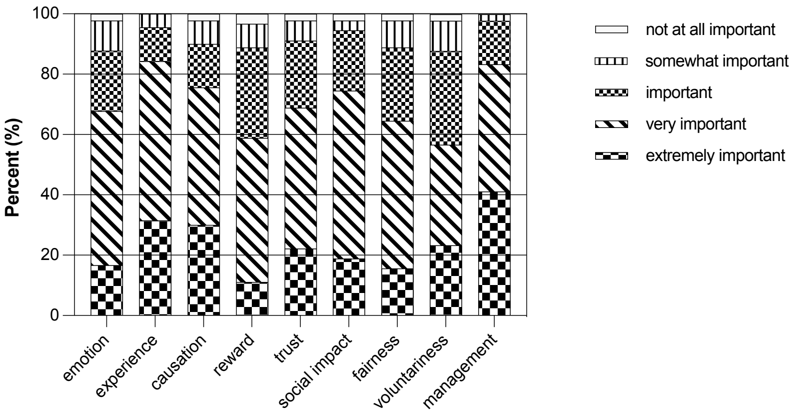

Figure 4.5 To what extent do you believe these factors are important in risk management?

As can be seen from Figure 4.5, regardless of the role of stakeholders, over four-fifth of interviewees indicated all emotional factors are important, very important, and extremely important. Notably, no respondents selected "not at all important" for either the item "experience" or "management". Furthermore, more than four-fifths regarded "experience" and "management" as either vary important or extremely important. The majority of these perceptions of the importance of the emotional factors did not vary between various roles of stakeholders, except the trust towards government, experts, and companies (P=0.02). Respondents from government organizations and regulatory bodies (8 out of 12; 67%) were more likely than other groups to consider trust as extremely important. In contrast, respondents from insurance companies (1 out of 2; 50%) were more likely than other groups to view trust as somewhat important.

For a further analysis of the ranking of these risk factors, see Table 4.4. In this table, relative preference score (%) of the items are given for various types of stakeholders and for total respondents without considering their demographic categorization (all data).

Table 4.4. Relative preference score (%) for all emotional risk factors.

Items	Stakeholder group										
	Employees of hign-risk sectors	Representatives, investors, and shareholders of high-risk sectors	Government organizations and regulatory bodies	Non-Governmental Organizations	Academic or research institution	Eergency responders	Insurance company	Consultancy agencies	Media	Public	All data
Management	12.46	11.76	12.92	10.34	11.7	11.61	13.24	11.24	12.27	13.22	12.19
Experience	11.54	13.24	11	13.79	12.15	11.61	13.24	13.48	10.43	12.07	11.9
Causation	10.92	10.29	11.48	13.79	11.63	10.71	13.24	10.11	9.82	12.07	11.39
Social impact	10.77	11.76	11	10.34	11.33	11.61	10.29	12.36	11.04	10.92	11.2
Trust	10.77	13.24	12.44	10.34	10.67	12.5	10.29	11.24	11.04	9.2	11.04
Emotion	12.46	8.82	10.29	6.9	11.26	9.82	7.35	8.99	11.66	11.49	10.75
Fairness	10.46	10.29	10.77	6.9	10.37	9.82	10.29	12.36	12.27	10.92	10.62
Voluntariness	10.62	8.82	10.29	13.79	10.3	10.71	11.76	10.11	11.04	12.07	10.59
Reward	10	11.76	9.81	13.79	10.59	11.61	10.29	10.11	10.43	8.05	10.33
Total	100	100	100	100	100	100	100	100	100	100	100

Across all stakeholder groupings, “management” had the highest relative preference score, meaning this emotional risk factor was the most important among respondents. However, there was no clearly dominant perception type, and there was little variation in the relative preference scores across perception types.

In addition to the predefined options, three respondents provided additional insights regarding important factors not listed in the questionnaire (see Table 4.5).

Table 4.5 Respondents’ statements about additional emotional risk factors.

Respondent's statement		Demographic		
		Gender	Region	Stakeholder
(1)	The predictability of the risk and the completeness of emergency response measures	Male	East and Central Asia	Representatives, investors, and shareeholders of high-risk sectors
(2)	The concealment of risks and the gap between the risk perceived by managers and the actual situation	Male	East and Central Asia	Representatives, investors, and shareeholders of high-risk sectors
(3)	The awareness and professionalism of company managers and the changes they have made for safety	Male	East and Central Asia	Government organizations and regulatory bodies

4.3.6 Solving conflicts

During the decision-making process, an important aspect is the interaction between different stakeholders; thus, the question “How would you handle potential conflicts with other stakeholders?” was addressed. Appendix A2 shows the frequency of responses of participants. Out of the 90 respondents, most respondents choose mild conflict-solving strategies when making decisions, e.g., “I prioritize collaboration and consensus building” (N=30; 33%) and “I try to find compromises while protecting my interests” (N=29; 32%). An equal proportion of respondents (N=12; 13%) selected “I avoid conflicts and defer to experts to resolve the conflict.” However, a small portion chooses to hold strong attitudes when meeting conflicts. 12 out of 90 respondents chose “I focus on achieving my goals, even if conflicts arise”. 6% (N=5) interviewees answered that they would step back from decision-making process if the conflict became too intense. The type of stakeholders did not significantly associate with these responses (P=0.60).

The distribution of responses among different stakeholders is illustrated in Figure 4.6.

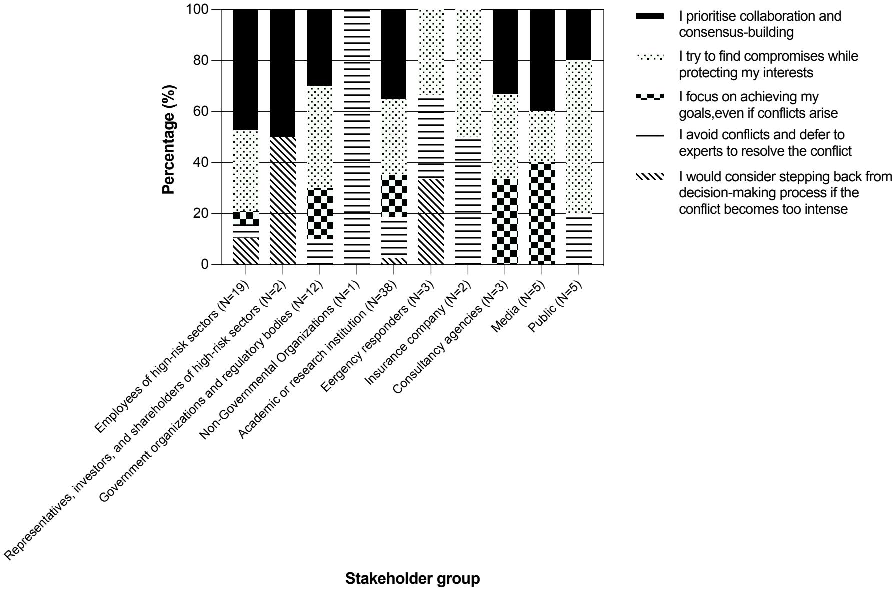

Figure 4.6 How would you handle potential conflicts with other stakeholders?

In addition to the five approaches to solving conflicts, the respondents were requested to indicate other means if not included. Apart from the given choices, two respondents provided alternative responses (see Table 4.6).

Table 4.6 Respondents’ statements about other ways of conflict solving.

Respondent's statement	Demographic		
	Gender	Region	Stakeholder

(1)	The degree of interest varies, leading to differences in compromise or refusal to cooperate.	Male	East and Central Asia	Representatives, investors, and shareholders of high-risk sectors
(2)	I maintain a minimum level of safety as a boundary to any results.	Male	Western Europe	Government organizations and regulatory body

One respondent from employees of high-risk sectors reported that "interest" is important. This statement suggests that stakeholders' willingness to collaborate or resist risk management decisions is largely dependent on their perceived self-interest. In contrast, another respondent from a government organization highlighted a safety-first approach in decision-making. Government organizations or regulatory bodies, they may rely on rules and procedures in order to cope with uncertainty. According to government respondent, decision-making is constrained by safety thresholds that cannot be compromised, regardless of other competing interests.

4.4 Discussion

In the previous chapter, arguments were given to show the importance of involving stakeholders and including emotional factors in risk management. This chapter 4 focuses on extracting the stakeholders' perceptions, risk attitudes, decision-making preferences, and conflict-solving traits in relation to the management of major risks, for 10 types of stakeholders. Given the initial and exploratory nature of this study, and the limited number of responses, the results must be interpreted with caution.

4.4.1 Stakeholders' attitudes and views toward major risk management

Before examining stakeholders' attitudes and views toward major risk management, it should be noted that the stakeholders from employees of high-risk sectors (N=19) and academic or research institutions (N=38) account for 63% of the respondents. Thus, the general attitudes and views may be overrepresented by these two groups.

In this study, there appeared to be a general positive attitude towards stakeholder participation in major risk management, regardless of the type of stakeholders. The results of the present study are consistent with previous studies concerning managing contaminated sites, in which most of the stakeholders were convinced useful or essential to hold discussions and negotiations with the financial owners during the decision-making process(Stezar, Ozunu et al. 2014). In policy terms, this may indicate that increased engagement of stakeholders in major risk management is likely to gain wide support. Furthermore, this observation is important for improving the risk management process because the same issues can be emphasized when promoting stakeholder involvement regardless of the type of stakeholders.

Despite many supporting the direction, the result suggests an uneven distribution of power and responsibilities among stakeholders in major risk management. Most respondents acknowledged that more weight or influence should be assigned to the potentially directly affected socially or politically organized groups, such as high-risk industries, government organizations, and regulatory bodies, and emergency responders. By contrast, the individuals (i.e., potentially directly affected public), observing public (i.e., media, academic institutions), and the third parties (i.e., insurance companies, consultancy agencies, and NGOs) were considered to need a relatively smaller weight in major risk management. This raises an issue regarding which stakeholders should be involved, and their involvement levels should be determined on a case-by-case basis. In risk management terms, this adds another level of complexity to the IRERDM process which needs to be explicitly considered in the stakeholder analysis step.

Most survey respondents showed risk aversion toward major risks regardless of stakeholder categories. Based on the agreement level with the risk attitude statements, some common features could be drawn. First, factors including risk information transparency, lack of trust in industry and experts, and uncertainty of consequences, all contribute to conservative attitudes under major risks. These can be seen from responses to statements 1, 4, 5, 6, and 7. Second, risk compensation does not decrease concern about major risks (statement 2). This is consistent with the prospect theory that people fear large losses more than they value potential benefits (Kahneman and Tversky 2013). According to the rational decision-making theory, any risk can be acceptable given enough compensating benefit (Fischhoff 2015). However, stakeholders may reject rational analysis, given the potential loss is huge.

In the present study, the main motivators of respondents to be involved in major risk management were mitigating risks and improve decision making to protect their own interests. Moreover, the results indicate that there is a strong demand for accountable and transparent decision-making. However, the majority of participants may prefer to be a passive audience rather than to actively engage, for instance directly expressing their concerns and needs. Collaboration and trust-building was given the lower priority (Lynn 1990).

Out of the 90 respondents, public interest was placed at the forefront of priorities. Out of them, the main principles in the participatory process were protecting public health and safety. This is consistent with a previous study concerning the value of safety, in which the value of health is the most recurred value (Yang, Chen et al. 2022). Economic benefits are ranked after long-term impacts and sustainability as well as environmental impacts. This aligns with a previous study on eliciting stakeholders' opinions regarding the types of data that should be collected during the risk assessment stage (Wentholt, Rowe et al. 2009). While the principles regarding social governance, such as maintaining public trust, social and ethical justice, transparency, received less attention from stakeholders.

In this study, the budget was identified as the primary potential barrier to decision-making by the respondents. The budget is closely tied to safety investments, such as technology adoption, safety training, and emergency preparedness, all of which indirectly influence the overall safety level. Knowledge gaps in risk management were considered to be another major challenge in risk management. Risk assessment is a vital component of risk management, and decision-making must be informed by its results. The lack of information and expertise can lead to inefficiency in decision-making. Organizational and political factors, as well as public and pressure group reactions, ranked last in terms of constraints on decision-making.

Translating such results into practical suggestions, the implications of the IRERDM approach should have a clear scope of objectives which they can relate to. It is essential to explicitly highlight the interests of each stakeholder group. Additionally, the aims and scope of the process should be made publicly clear, specifying what stakeholders are expected to do, how the outcomes will be utilized, and by whom. Furthermore, the entire risk management process should be explicitly documented to improve participatory experiences more transparent. Stakeholders should be informed what is the actual physical impacts and probabilities of risk events to improve awareness. To improve effective communication, the moderator should facilitate structured discussion to ensure that everyone's opinion is considered. When recruiting stakeholders, voluntariness should be emphasized, along with measures to minimize participation burdens, such as potential conflicts with personal and family commitments and time constraints. Translating scientific and technical information into accessible and relevant information will further produce more meaningful stakeholder engagement.

It was notable that most of the emotional risk factors in the IRERDM model were considered important to most of the stakeholders. Thus, there was a certain support for the idea of including other aspects than probabilities and physical impacts in risk calculation and prioritization.

Furthermore, the results showed that there was no clear dominant emotional risk factor preferred by the respondents. This indicated that the full range of emotional risk factors included in this study should be considered when developing socially acceptable risk management plans. Potential conflicts may arise if those emotional considerations are not part of the risk management process. Beyond the listed factors, respondents also highlighted the following factors (see Table 4.3) corresponding with the "uncertainty" and "management" dimensions in the IRERDM model (Xu, Reniers et al. 2025).

In the last section of the survey, respondents were requested to voluntarily provide some comments and suggestions on the questionnaire. The respondents' demographic profile and their qualitative responses are listed in Table 4.7, regarding contextual relevance, response options, and gaps between experts and laypersons.

Table 4.7 Respondents' comments and suggestions.

Respondent's statement	Demographic		
	Gender	Region	Stakeholder
(1) I hope to face more specific questions, such as what type of risk is it, how it affects me and how it relates to me. Assuming the chemical plant problem in the question card, I actually don't know whether there is a chemical plant in my city (if there is, it may be far away from the activity area). When it leaks, do we face explosions, water pollution, land pollution or other risks? How do we perceive it	Male	East and Central Asia	Public
(2) The concept of major risk is too broad. If the questionnaire is placed in a certain scenario, it may be more effective.	Male	East and Central Asia	Representatives, investors, and shareholders of high-risk sectors
(3) The current selection limit for multiple responses is a bit restrictive.	Male	East and Central Asia	Employees of high-risk sectors

(4)	The risk characterization process, as defined by the 1996 US National Research Council on Understanding Risk, is an important consideration. The industry still does a poor job of bringing experts and laypersons - data and perceptions - together to deliberate over tolerable risk decisions.	Male	North America	Consultancy agencies

A recurring theme among both the public and the scientific community is the need for more specific and contextually relevant questions. The questionnaire primarily uses fire and explosion risks in chemical plants as an example; however, some respondents may not be familiar with such incidents. The absence of concrete real-world contexts may influence participants' responses. Furthermore, a respondent reported that the response limit for multiple-choice questions is too restrictive, potentially preventing participants from fully expressing their views. At last, a consultant stakeholder emphasized that considering public opinion in risk management is highly important and noted that the industry has not yet given it sufficient attention.

Taken together, the results imply that there is a societal preference for increased resource allocation to involve stakeholders and incorporate ethical and societal considerations into major risk management.

4.4.2 Stakeholder differences and methodological limitations

One key observation from the present study was that, for most issues, there were no statistically significant differences in the choices made by different stakeholder groups. However, a few issues showed notable differences among certain stakeholder groups, such as perceived responsibility of stakeholders, decision-making constraints, perceived importance of trust in risk management. A previous study relating to stakeholders' risk perceptions in the construction industry indicate that the roles and experience of stakeholders significantly affected their risk perceptions in many cases (Al Nahyan, Hawas et al. 2021). The reasons for the present results can be several. First, as limitation, selection bias may have occurred due to non-probabilistic sampling. It may be difficult to generalize the results to larger populations. Second, another explanation may be our sample mainly consisting of experts from academic or research institutes and employees from the high-risk industry. The P value is highly affected by the sample size (Silva and Guarnieri 2014), and the number of participants from several categories, including employers of high-risk sectors, NGOs, media, and insurance companies, was fewer than five. Hence, the small sample size may not produce the desired statistical results. Third, as some of the feedback suggested, due to the questionnaire lacking a detailed description of major risks, respondents may feel disconnected from the risk scenario because it is abstract to them and not directly related to their life. General risk questions may not be effective to increase emotional engagement and awareness.

The objective of this research was to provide first insights into a relatively under-researched area. Given the lack of significant differences identified through the statistical test, future research could employ alternative analytical approaches. Qualitative research methodologies that using open-ended questions, such as interviews, focus groups (Van Kleef, Frewer et al. 2006), could provide richer data than a questionnaire survey produces. Moreover, Delphi techniques (Wentholt, Rowe et al. 2009) with open-ended questions can offer insights into the question of "why" people engage in particular actions or behaviors. This emphasizes the importance of a scenario-based questionnaire that incorporates specific examples of risks, which could make it easier for respondents to relate the risk to their personal experience.

4.4.3 Potential conflicts and challenges in integrated rational and emotional risk management

The results suggest there are no significant differences between the majority of views, such as decision-making styles, perception of emotional risk factors, and variant stakeholders. Moreover, the majority of interviewees tend to adopt a moderate approach when handling conflicts in major risk decision-making. The predominance of mild conflict resolution strategies suggests a general preference for maintaining stakeholder cooperation in major risk management. Most respondents are willing to compromise, given that their own interests are protected. However, there was not always a complete agreement between stakeholders. The potential for conflict is still present.

First, protecting stakeholder groups' interest is ranked in the top two as motivators of participating major risk management. Thus, stakes conflict may be one of the crucial conflicts in decision-making, especially when people who hold very strong attitudes are likely to resist change. Second, there may be disputes regarding who holds greater influence and power in decision-making. Third, stakeholders' opinions on risk reduction strategies are more divided. Over three-fifths of respondents support the "zero-risk" policy (Statement 3), which emphasizes minimizing the adverse impacts of major risks regardless of their low likelihood or the resources required to reduce them. However, it is also important to note that one-fifth of respondents believe that major risks should not be minimized at all costs. In major risk management terms, different types of stakeholders may bring different perspectives and understandings to risk management. This implies that more communication between stakeholders may have a positive impact on risk management.

Meanwhile, the results revealed certain aspects of challenges for promoting the IRERDM method. First, stakeholders with different risk attitudes display different risk acceptability. Extreme risk aversion may lead to inefficiency when they advocate precautionary principles that prescribe highly uncertain actions with great potential risk. They may reject cooperation even when there would be substantial compensation. Second, in addition to the impact of the inherent complexity and uncertainty of major risks on decision-making, external factors such as funding and timing are also key influences on the decision-making process. This implies that there is a need for increased resources (time, money) to involve stakeholders to reconcile public interest and major risk management. Third, the results suggest people may be more inclined to be an audience rather than a collaborator in the participation process, which could make communication more challenging. However, poor communication is better than silence (Fischhoff 2015).

4.5 Conclusions

Laypeople often query or ignore the major risk assessment of scientists. It has been suggested that the formal major risk management process may be extended by introducing emotional considerations to a broader group of stakeholders. Based on the IRERDM model developed in chapter 3, this study elicited views from stakeholders in the attitudes, perceived importance of emotional risk factors and participatory risk management. The key conclusions are as follows. The survey indicates that an integrated rational and emotional risk management method will likely gain support from stakeholders. The results further suggest that there is weak relationship between the roles and experience of stakeholders with the views and risk decision-making styles, perceptions of emotional and ethical risk factors, and the know-how of conflicts solving. The consensus in major risk management is to protect interests and public health. Furthermore, there is strong public demand for transparency and accountability in risk management decisions. However, stakeholders may have different preferences regarding the level of participation. Some may prefer to be informed or consulted, whereas others may wish to participate actively in the decision-making process. Lastly, the survey respondents in general acknowledge the importance of emotional and ethical risk factors in risk management.

To conclude, based on the respondents' answers and suggestions, it would be helpful to involve stakeholders and their emotional and ethical risk considerations in managing major risks.

Chapter 5 Validating the Integrated Rational and Emotional Risk Decision-Making (IRERDM) Approach

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This chapter is modified based on the paper: Xu, Y., Reniers, G., & Yang, M. Validating the Integrated Rational and Emotional Risk Management (IRERM) approach by using a Role-Playing Game. (submitted). Journal of Safety Research.

The survey study conducted in chapter 4 established general profiles of different stakeholder groups in relation to risk decision-making. Building on this study, this chapter presents an experiment using a Role-Playing Game (RPG) as a research tool to further validate the feasibility of the Integrated Rational and Emotional Risk Decision-Making (IRERDM) approach. In this study, consecutive steps of the role-playing game are designed to model the decision-making process for a safety investment problem related to industrial major risk. Within the RPG, participants are assigned with individual roles and engage in a risk ranking and decision-making process that reflects real-world scientific information. The findings from chapter 4 are used as a reference to construct stakeholder profiles for the RPG experiment. After the game, participants' perceptions and comments on the participatory process were collected and analyzed. The results suggest that through engagement activities, stakeholders can express, learn, and adapt their needs, as well as enhance their understanding and acceptance of risk decisions. Finally, drawing on the findings from our research, we demonstrate that RPG is a promising tool for conducting participatory research on major accident management, and that the IRERDM approach has considerable potential for improving stakeholders' acceptance of risk decisions.

5.1 Introduction

5.1.1 Background

Major risks, also termed as Type II risks (Meyer and Reniers 2022), are characterized with high uncertainties and huge consequences. Risk management is a systematic way to use scientific tools and expertise to calculate risks and guide decisions on how measures dealing with risk should be allocated (Xu, Reniers et al. 2025). Stakeholders who may be affected by risk and by risk management decisions are key in risk decision-making. In addition to improving the technical understanding of risk and logical soundness of risk assessments, in recent years, a number of risk management studies have stressed the importance of considering stakeholders' perceived acceptability of risk decisions, and the sensitivity to moral and ethical concerns (MacGregor and Slovic 1986, Renn 2015, Xu, Reniers et al. 2025). Meanwhile, stakeholders around the world are increasingly concerned about rare events (Rumore, Schenk et al. 2016). However, the traditional risk management approach often relies on rational risk judgements and tend to overlook the heterogeneity of stakeholders, thereby oversimplifying the complexity of emotional and ethical interests and concerns. Therefore, reconciling the gap between scientific risk assessment and laypeople's risk judgements, and incorporating their perceived acceptability of risk decisions, is regarded as one of the central challenges for responsible risk management (Sjöberg 1999, Xu, Reniers et al. 2025).

To enable a paradigm shift in risk management, from a purely technical focus towards a more holistic approach that incorporates societal and ethical dimensions, methods are needed to support integrating individual interests and concerns with rational calculations. In recent decades, many approaches have been proposed to address those challenges. Among these approaches, a widely recognized method is the direct involvement of stakeholders in risk management, fostering collaborative decision-making (Xu, Reniers et al. 2024). The participation encompasses not only the high-level influential stakeholders, but also those located at the local level that can affect or who are likely to be affected by the effects of risk events and their outcome (Begg 2018). The key value of stakeholder participation is that it allows their concerns and priorities to be communicated and incorporated in the risk management process through dialogs and deliberations, ultimately shaping and influencing decision making. Furthermore, collective decision-making can increase the public acceptance, of both risk management models and the resulting decisions (Haapasaari, Mäntyniemi et al. 2013). Moreover, stakeholders and the wide public with different sociopolitical backgrounds, as well as varying degrees of exposure to risk can lead to divergent perceptions and attitudes toward risk problems. How to take emotional and ethical considerations into risk management? How to solve the conflicts between stakeholders in the risk management process?

Despite the recognition of increased stakeholders' participation in risk management, there is a lack of a systematic approach to effectively involve stakeholders in the risk management process. To address this gap, chapter 3 proposed the Integrated Rational and Emotional Risk Decision-Making (IRERDM) method to systematically integrate stakeholders' values, concerns, and knowledge into the risk management process. The IRERDM approach involves 6 steps: (1) defining the risk problem; (2) stakeholder analysis; (3) risk description; (4) risk calculation; (5) risk prioritization; and (6) risk treatment. Traditional risk management models have assumed that risk communication follows from decision making. In the IRERDM approach, stakeholders are involved from the risk description and risk analysis step, collaborating with risk analysts to jointly work on the risk description, participate in risk ranking, and ultimately reach consensus on the final risk decision.

To make responsible use of the IRERDM approach, it is essential to rigorously assess the feasibility of the method and verify whether it may indeed lead to improvement of risk decision-making. Therefore, we aim to conduct a validation study of the proposed IRERDM approach.

5.1.2 Rationale of role-playing game

In this study, we used a Role-Playing Game (RPG) method to test the theoretical IRERDM model, to assess its applicability and validity. RPG is one type of serious games that is not designed solely for entertainment purposes, but as a tool to understand conflict situation and help stakeholders to come up with solutions (Redpath, Keane et al. 2018, Visscher 2024). RPG creates a simplified problem-based "real world" situation and focuses on the interaction between players or players and game designers within a specific story-based framework (Madani, Pierce et al. 2017, Winardy and Septiana 2023). RPG generally involves carefully planned sessions. During RPG exercises, players assume roles of power position, such as decision makers or managers, and receive confidential role-specific instructions with information relevant to their assigned character. Participants then assume their assigned roles, follow the game rules, and interact with other players based on their characters' perspectives. At last, there is a debriefing session in which the whole group of participants are encouraged to reflect upon the game process and to connect to their real-world scenarios. The idea behind RPG is to stimulate reality but using a simplified setting in which participants can foster dialogue and make decisions based on collective knowledge and values, explore a range of possible solutions and build trust among stakeholders (Rumore, Schenk et al. 2016).

Currently, RPG is used for many purposes, such as conflict resolution, communication and education, increasing dialog (Madani, Pierce et al. 2017), etc. RPG is a powerful tool and is applied in many fields, such as transport planning (Ignaccolo, Inturri et al. 2017), land management (Washington-Ottombre, Pijanowski et al. 2010), and food safety management (Celio, Andriatsitohaina et al. 2019), to mimic real decision-making situations and tackle public-policy challenges. Particularly, RPG is flexible to frame a multi-agent system involving multi-stakeholder negotiations and help people achieve a shared understanding of a conflict decision problem. Many RPGs are primarily conducted with university students, particularly undergraduates and graduates, as the main participants. For example, Bots and Hermans (Bots and Hermans 2003) applied RPG to solve a fictitious problem with the aim to increase the polymer production capacity. The RPG was played by master students enrolled in the safety, health, and the environmental programme. involved five groups of stakeholders: the polymer engineering company, chlorine gas production company, railroad company, the state government, and the citizens. The role players needed to negotiate and make decisions from three generic scenarios. Dahdouh-Guebas et al. (Dahdouh-Guebas, Mafaziya Nijamdeen et al. 2022) developed Mangal Play, an RPG designed as an experiential learning method to simulate stakeholder interactions within a hypothetical mangrove forest social-ecological system. The game engaged participants in adopting 20 roles across sectors such as government, fishery, agriculture, forestry, and more.

Real stakeholder participation is difficult as such an approach demands more realistic scenarios (Bots and Hermans 2003). Moreover, in major risk management decisions, it normally involves a large group of stakeholders. Inviting real stakeholders can be expensive and time-consuming due to their agendas. Recognizing the potential of RPG in simulating a real stakeholder participation decision-making process, we aimed to design the RPG method to the context of major risk management. Moreover, risk management can be regarded as a risk-informed decision-making process (Talarico and Reniers 2016), the use of RPG may also be applicable in this domain. Additionally, since the IRERDM model is a novel approach, RPG serves as a suitable method to experientially introduce participants to this new risk management framework and to prepare real stakeholders for future participatory risk management decisions.

5.1.3 Aim and structure of this study

This study focuses on transferring the IRERDM method into an RPG exercise to analyze the deliberations on possible solutions to the problem of safety investment in a hypothetical ammonia production company in the Netherlands. In addition to investigating how the participants hierarchize and make decisions across different major risk scenarios, we also explored the dynamics of multi-stakeholder interaction in major risk decision making. The specific objectives of this research are: (1) first, we aim to explore the potential of a role-playing game as an engagement tool for tackling the major risk decision problem; (2) second, we intend to investigate the validity of the IRERDM approach – which integrates stakeholders' emotional and ethical considerations into risk management – in enhancing the acceptability of risk decision-making.

The remainder of the paper is structured as follows. Section 2 outlines the sequential steps of the role-playing game participation procedure. The results are discussed in Section 3. At last, Section 4 concludes the paper by summarizing the main findings and conclusions for future study.

5.2 Research methodology

In this section, a participatory experiment on major risk decision-making is introduced, which was conducted with PhD students with academic backgrounds in safety science and economics through a role-playing game.

5.2.1 Participants

The participants were recruited by an online invitation letter targeting academic professionals (i.e., PhD students, postdoctoral researchers, and professors) at Delft University of Technology (TU Delft) in March 2025. In the invitation letter (Appendix B1), potential participants were informed about the purpose of study, the duration and formats of the game session, and the game was briefly introduced. They were also told that the role-playing game was entirely voluntary, and all responses will remain anonymous.

Previous studies indicate that participants with backgrounds similar to the roles they assigned roles may produce better results (Maskrey, Mount et al. 2022). Due to constraints in time and resources, the participants' background could not be tailored to be aligned closely with the professional profiles of the real stakeholders. As a result, many participants had backgrounds in safety engineering, which may have influenced their prior assumptions and judgments during the activity. However, the objective of this study was not to focus on predicting the results of risk decisions, but on their engagement in the process and their dialogs. Thus, the inclusion of participants' perception bias was considered acceptable. In total, 9 participants became involved in the role-playing exercises according to the availability of those who registered. Eight were male and one was female. The participants were mainly PhD students. To encourage a more realistic engagement, each participant was asked to assume a role within a risk management committee prior to the RPG. This allows participants to choose roles that as good as possible resonated with their own expertise or experience.

Until they arrived at the meeting place, the participants had no specific information about either the content or the procedure of the session. Before the session began, an opening statement was delivered outlining the aim and procedure of the study, and the tasks to be performed during the game through a slide presentation. After the opening statement, all participants signed a consent form and followed the protocols approved by the scientific ethics committee of the Delft University of Technology (TU Delft).

5.2.2 Implementation of the role-playing game

The risk management role-playing game was conducted mainly based on the initial IRERDM method with slight modifications. While the original model required stakeholders to select emotional indices to evaluate risks based on expressed preferences, this study simplifies the process by allowing stakeholders to make intuitive judgments directly. The aim was to bridge the gap between rational risk analysis and stakeholders' emotional risk judgments. The game was conducted in the Netherlands and the whole session was structured into four sequential steps: (1) role profiling, (2) individual assessment and prioritization, (3) negotiation and decision making, and (4) reflection and data analysis. Figure 5.1 summarizes the procedures applied to conduct the role-playing game.

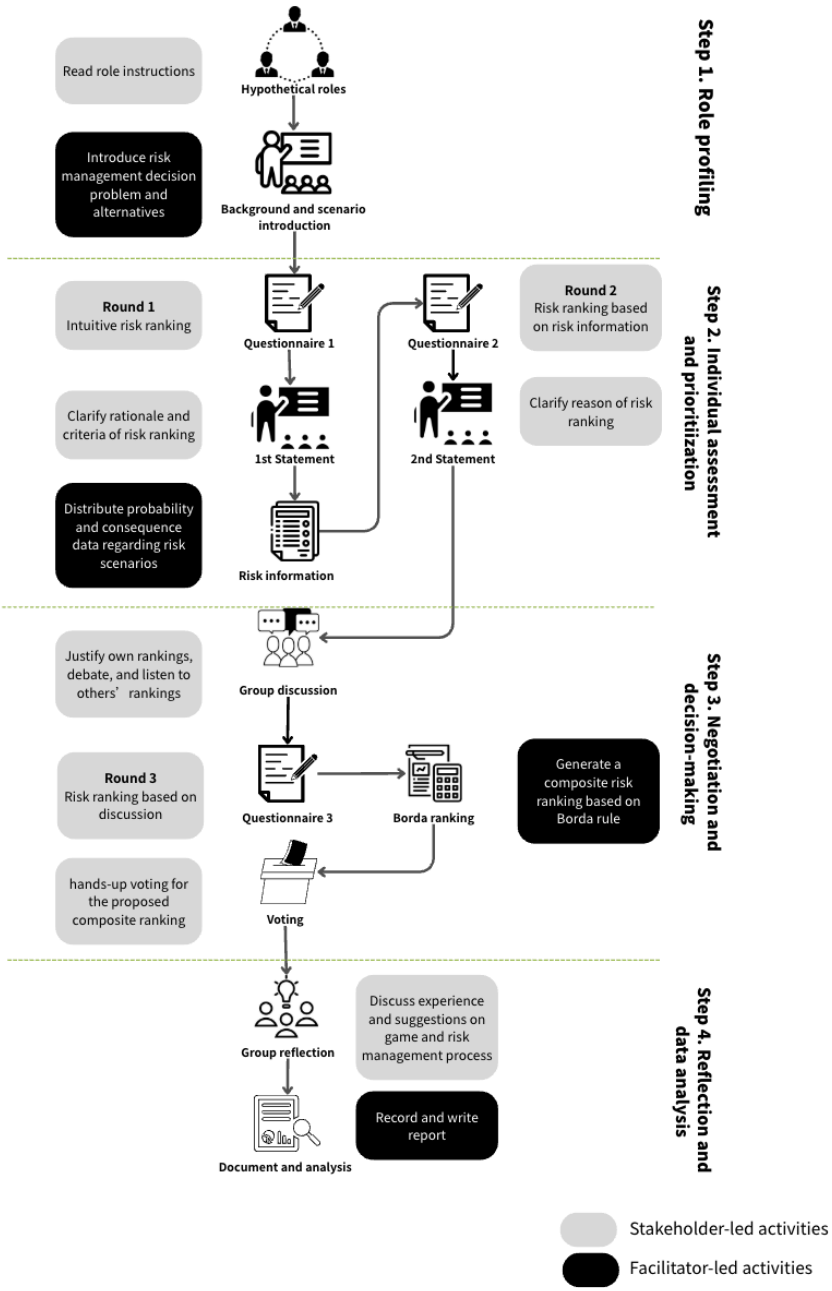

Figure 5.1 Consecutive steps of the role-playing game.

The session was facilitated by the main researcher of this study. First, each participant was asked to assume a role within a risk management committee. Second, participants were individually tasked with the responsibility of prioritizing and agreeing upon a set of risk scenarios. In the subsequent step, participants engage in deliberations aimed at achieving consensus and arrive at a collective decision. Finally, participants were encouraged to discuss their experience and reflections upon the sessions. The game was structured with time limits, and took in total 2 hours. The detailed procedure of the sessions is explained in the following context.

5.2.2.1 Role profiling

First, the participants were asked to imagine that they were members of a risk management committee in the Netherlands. Nine possible roles, including policymaker from ministry, inspector from ministry, mayor, firefighter, CEO, safety manager, and employee of an ammonia production company, NGO officer, and local resident, were attributed to the players. Each of them representing one of a group of stakeholders.

Based on the RPG design principles (Armstrong 2001), the participants were asked to read the role instructions before receiving the background and decision scenario information. A previous survey from the previous chapter was conducted to identify common stakeholder profiles in major risk management, focusing on their attitudes and views in the decision-making process. Based on the results of the questionnaire and the author's experiences, the profile of the nine types of stakeholders has been built and transformed into role scripts, as can be found in Table B1 in the Appendix B. These instructions reflect the key interests and responsibilities of the stakeholder groups represented in major risk scenarios. Subsequently, the background information was presented as follows: "The government and the ammonia production company have reached a consensus to invest a fixed budget in chemical plant safety over the next five years to prevent high-risk events. Ammonia is a colorless gas with a strong odor. Inhalation can cause chemical burns to the eyes, skin, severe lung damage, and even death at higher concentrations. Ammonia leaks can also harm the environment, affecting air quality, soil, water, and vegetation. To this end, the chemical plant has convened stakeholders to form a risk management committee to discuss the priorities of safety investments. As requested, you and the other stakeholders are invited to attend the risk management meeting".

Once this scenario was set, the participants were presented with five decision alternatives, each representing a distinct risk scenario. The five risk scenarios shared the same potential outcome but differed in their underlying causes.

A. Major ammonia leak due to a bomb (terrorist attack)

B. Major ammonia leak due to a cyber-attack (terrorist attack)

C. Major ammonia leak due to a flood (natural hazard)

D. Major ammonia leak due to an external explosion (in neighboring chemical plant)

E. Major ammonia leak due to equipment failure (human/technical)

Each participant was tasked with determining the priority order for safety investment across the five risk scenarios and ultimately reaching a consensus in the prioritization of scenarios. All participants were required to behave as their assigned stakeholder role would in real-life situations, and these instructions were consistently reinforced by the facilitator throughout the session.

5.2.2.2 Individual assessment and prioritization

Following the role profiling and the scenario briefing, the dynamics of the role-paying game began. This step involves two rounds of risk ranking, and the tasks were completed in a format of a questionnaire. The participants were asked to prioritize those risk scenarios through a hierarchical structuring scale from 1-5; with 1=highest priority, and 5=lowest priority. In this step, each participant was asked to individually write down a rank ordering of the decision alternatives. After all participants completed the questionnaire, the participants took turns sharing their rankings and the rationale behind them in an open discussion format. The dialog built around the perceptions constituted the sociologically relevant data. The guided questions were:

- Why did you rank a certain risk with higher/lower priority?
- What criteria did you consider when ranking the risks?

Questionnaire 1: Intuitive risk ranking. The first round of risk ranking task aims to collect the participants' emotional criteria of risk prioritization. Participants were asked to intuitively rank the five decision alternatives (risk scenarios) according to their priority for investing in safety measures, while considering the responsibility and interests of their roles. Players were expected to make their choices on their own experiences; therefore, no information was provided regarding the potential likelihood or consequences of the different options.

Questionnaire 2: Risk ranking based on risk analysis results. The second round of risk ranking is similar with the first risk ranking. However, this step is designed to observe the influence of scientific information on stakeholders' risk judgement. Before the second round of risk ranking, participants received information cards outlining the probabilities and consequences associated with each risk scenario. This scientific information was developed based on expertise and informed judgment. To help participants better understand the information, consequence data was predefined into five descriptive categories, with applicable outcomes marked for each risk scenario (as shown in Table B2 and B3 in Appendix B). Probability data was presented using a linguistic scale (i.e., very low, low, medium). Moreover, to facilitate comparing rational risk ranking results with participant's risk rankings, the consequences were set uniformly as "10 fatalities or more" across all five risk scenarios. Therefore, the rational risk ranking was solely determined by the differences in probability. We explained to the participants that the information had been assessed by risk experts. Upon receiving the scientific risk information, participants were instructed to re-rank the five risk scenarios. They had the option to either keep their original ranking or change it based on the new information.

5.2.2.3 Negotiation and decision-making

The main aim of this step was to reach an agreement on the ranking of the relevant risk scenarios within the risk management committee members.

At the beginning, there is an unstructured negotiation phase allowing participants to engage in an open debate. During this phase, players were expected to justify their prioritization of risks, convince their fellow committee members, and listen to the proposals of the other members. The participants were informed that if they cannot reach a consensus in the negotiation stage, the researcher (facilitator) will propose a composite ranking that reflects the group's overall preferences, and participants will then be asked to vote on the proposed ranking. Voting is a common method in collective decisions (Tideman 2017). Normally, when it comes to group voting, the individual preferred rankings must be aggregated into a unique collective ranking to best reflect the general preference of the group (Le Pira, Inturri et al. 2015). The Borda score is mainly used in voting problems but has also been applied in risk management contexts (Goerlandt and Reniers 2017). With the "Borda rule", the highest ranked risk event receives a Borda score (n-1), with n the number of risk events. The lowest-ranked risk event receives Borda score zero. Finally, the Borda scores are added across stakeholders and a corresponding ranking produced. In this study, we applied the Borda method to generate a collective ranking and assigned equal importance to each stakeholder's ranking.

Questionnaire 3: Risk ranking based on debating. The third round of risk ranking came after the negotiation phase. The ranking task remained the same with the previous two rounds of risk ranking, however, participants needed to integrate the information and discussions from the previous rounds into their final judgment. Once participants completed the third round of risk ranking, a ranking was derived using the Borda method.

Agreement of participants about Borda-driven ranking after debate. Following this, the final decision was made through hands up voting method. While anonymous voting is often recommended to reduce social pressure in risk decision-making context (Postmes and Lea 2000), hands up voting was considered more appropriate in this role-playing game by making participants' risk perception more explicit, thereby supporting collective communication and learning during the decision-making process. Participants can choose "agree", "disagree", or "neither agree nor disagree". To determine the agreement level, only "agree" and "disagree" responses were considered. Based on a majority decision rule, a 70% level of agreement has commonly been suggested to define consensus in the Delphi method (Hohmann, Cote et al. 2018, Kondratev and Nesterov 2020). In this experiment, a 75% threshold was adopted to represent a consensus agreement. If over 75% of these counted responses were "agree," the proposed ranking was accepted and subsequently documented and implemented. If the level of agreement was below 75%, the game concluded without reaching consensus, and the decision was considered unsuccessful.

5.2.2.4 Reflection and data analysis

After the game sessions, group debriefings were conducted. Participants were encouraged to reflect from two aspects: the dynamics of the role-playing game and the mechanism of the risk management approach. The triggering questions were: (1) What feedback can be provided to improve the role-playing game in terms of its attractiveness and challenges? (2) What are your reflections on stakeholder involvement in major risk management, including its benefits and drawbacks?

The data of role-playing game consisted of two aspects. The first was the quantitative data derived from the three rounds of risk ranking. These data have been imported into Excel sheet for further comparative analysis. The second involved qualitative data from group interactions, specifically the discussion transcripts. All the discussions were audio-recorded and transcribed before being analyzed using thematic analysis. The transcriptions were anonymized and collated with the audio files by the research team. Thematic analysis is a commonly used qualitative data analysis method, and is used for identifying, interpreting of "themes" using descriptive categories (Braun and Clarke 2024). As in every qualitative analysis method, thematic analysis tends to be influenced by the researchers' perspectives (Joffe 2011). To make valid inferences and coding from transcripts, the credibility of the findings was checked by dialogue between the co-researchers of this study (Boso, Garrido et al. 2024). Quotes from participants are included to exemplify the results.

5.3 Results

5.3.1 Questionnaire and voting results

The three rounds of rankings by the nine participants are presented in Table B4-B6 in Appendix B. To examine the variations in overall risk rankings across different stages, the risk rankings provided by the three stakeholder groups were aggregated into a final ranking through the application of the Borda algorithm. Meanwhile, the rational risk rankings are also presented in Table 1 for comparison with the emotional risk rankings.

Table 5.1 Comparison of Borda-driven ranking and rational risk ranking.

Risk scenario	**1st risk ranking**	**2nd risk ranking**	**3rd risk ranking (of the Borda method application)**	**Rational risk ranking**
Major ammonia leak due to bomb	4	5	4/5	5
Major ammonia leak due to cyber-attack	3	4	3	3
Major ammonia leak due to flood	5	2	2	2
Major ammonia leak due to external explosion	2	3	4/5	4
Major ammonia leak due to equipment failure	1	1	1	1

As observed in Table 1, with the provision of scientific risk information and subsequent discussions, the overall emotional risk rankings 1st and 2nd risk rankings showed a progressive convergence toward the rational risk ranking. Moreover, it is worth noting that the scenario of a major ammonia leak caused by equipment failure was consistently ranked as the most important across the three rounds of risk ranking. The final ranking following discussion closely aligned with the rational risk ranking. The only divergence was that a major ammonia leak caused by bomb and by external explosion received an identical joint rank of 4/5. People's minds were changed via the consensus building.

When the three rounds of risk ranking by stakeholders is compared, there are some remarkable differences. In the first round of intuitive risk ranking, the scenario of a major ammonia leak due to equipment failure was ranked as the highest risk by the majority of participants, including the inspector, firefighter, industry CEO, safety manager, industry employee, NGO representative, and local resident. In contrast, both the policy maker and the mayor prioritized a major ammonia leak caused by a bomb (terrorist attack) as the most severe scenario.

In the second round of risk ranking, participants were provided with additional information about the risk events. As a result, the majority (8 out of 9 participants) revised their initial rankings, with the industry employee being the only exception. Notably, both the policy maker and the mayor shifted their top-ranked scenario from a major ammonia leak caused by a bomb (terrorist attack) to one caused by a flood (nature-related).

In the third round of risk ranking, most participants maintained their previous rankings, with the exception of the inspector, who made further changes.

Based on the third round of risk ranking results, an integrated risk ranking by considering the collective preference of stakeholders was derived based on Borda rule. After presenting this ranking to the participants, their hands up voting result is presented in Figure 5.2.

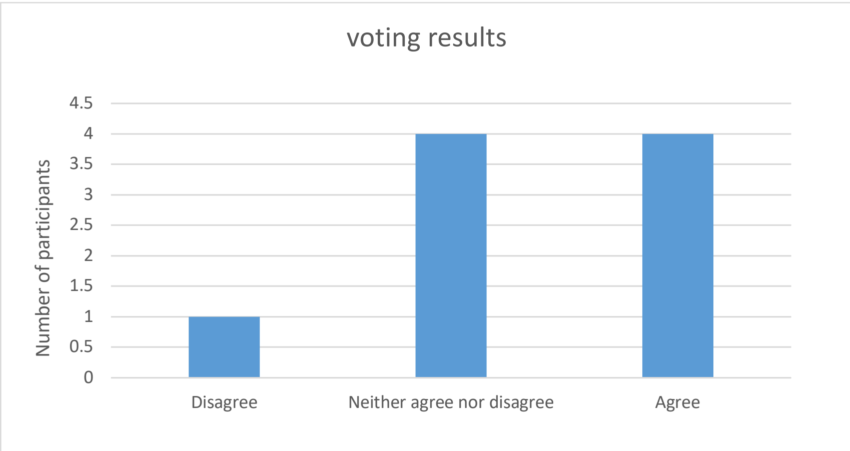

Figure 5.2 Hands-up voting results toward Borda-driven risk ranking.

Obviously, Figure 5.2 shows that the large majority of participants could agree with or be neutral to the proposed ranking. Thus, the proposed risk ranking was adopted as the final decision. This suggests the approach was successful.

5.3.2 Deliberations

This section discusses the thematic analysis results of participation dialogs and discussions. Since this is an exploratory study, it does not intend to find causal relationships from its findings. At the most general level, we characterize the deliberations into five dominant themes corresponding to the different phase of the risk management role playing game: (1) emotional criteria for setting priorities; (2) scientific information and its implications for risk ranking; (3) conflict points in decision making; (4) reasoning behind decision-making; and (5) reflection on risk management and role-playing game.

5.3.2.1 Emotional criteria for setting priorities

When stating the criteria and reasons why give certain alternatives a higher or lower ranking, one recurring theme identified from participants' discussions is the "perceived likelihood". Many participants rated the major ammonia leak due to human error as the first place because they perceived it has higher likelihood of happening compared to other risk scenarios.

Another recurrent theme is stakeholder responsibility and liability. Several participants evaluated the risks partially based on who would be held accountable if such events occurred, especially under circumstances where they believed they have responsibility and ability to deal with the risks themselves. According to the causation of risk events, the five decision alternatives can be divided into external attack, internal failure, and nature related risks. Human-related risks and particularly risks that are preventable through precautionary behaviour are regarded as more blameworthy. For example, in the given context, equipment failure was considered to be partly the ammonia company's responsibility. The CEO and safety manager participants expressed greater concern for a major risk scenario due to equipment failure. Moreover, for some stakeholders, such as the fire-fighter and mayor, that were not directly affected by the outcome of risks, they put more focus on externally imposed harm when the consequences affected others. For instance, a major ammonia leak caused by an external explosion in neighbouring chemical plant primarily considered the responsibility of the neighbouring company. Thus, for the fire-fighter and mayor, a major ammonia leak caused by an external explosion was perceived as less acceptable than internal equipment failures.

A few participants also mentioned other factors, such as societal impacts, manageability of risk, knowledge of risk by the exposed population, immediacy of effect, and scientific knowledge of risk in influencing the priorities of safety investment decisions. For instance, the mayor participant stated that external threats such as physical and cyber-attacks may arise fear around the public and receiving great attention in the society. Moreover, whereas the majority of participants identified the risk of ammonia leak due to equipment failure as the highest priority, the mayor participant placed it fourth. He argued that individuals working in high-risk environments typically have certain understanding or awareness of such potential consequences. Similarly, a major ammonia leak due to an external explosion was considered more severe by the mayor participant. This is because he believed that the staff of the ammonia company, general public, who might be affected by such an event, often lacks sufficient understanding of chemical plant operations. In addition, the mayor participant places greater importance on immediate impacts over long-term effects, as is illustrated by his view on a major ammonia leak caused by flood.

The inspector player argued that although likelihood is one important criterion, the capability to control or mitigate the risks is also significant. For example, risk originating from onsite operations, such as physical terrorist attack, is generally more controllable through managerial measures compared to cyber-attacks. Given the same likelihood of occurrence, he believed the investment priority should be given to risk scenarios that are more easily manageable. Furthermore, the inspector player argued that the consequence of major ammonia leak caused by flooding may be catastrophic, but the occurrence of flooding is relatively predictable. A major risk event is perceived as less severe when there is a high level of knowledge about its likelihood and potential consequences.

5.3.2.2 Scientific information and its implications for risk ranking

Following the second round of risk information-based ranking, participants were prompted to reflect on and discuss the rationale behind any modifications to their first-round rankings.

A subset of participants, such as the fire-fighter, the local resident, the safety manager, and the inspector participants, initially mainly focused on perceived likelihood and liability to judge risk priorities. Upon receiving additional scientific information, they revised their intuitive rankings to reflect more rational or more evidence-based risk assessments.

Furthermore, the notion of potential economic, environmental, and societal impacts triggered new considerations among some participants, which had been overlooked during the initial round of intuitive risk ranking. For instance, the CEO participant put the major risk due to flooding higher after realizing its potential environmental damages related to the company's operations and market performance. The inspector player adjusted the ranking of a major ammonia leak caused by a cyberattack upon reconsidering the trade-offs between cost and the effectiveness of various safety investment strategies.

Notably, the NGO player was the only one to suggest that scientific information can be biased. On one hand, he believed the societal impacts provided are calculated mainly based on money, however, the incommensurable effects such as loss of lives are not considered. On the other hand, there are uncertainties regarding the impacts of risk assessment, and it is hard to exactly measure the impacts. He indicated that the consequence data should be interpreted with caution, and it is unwise to rank risk priorities fully based on the rational risk analysis results. As a result, he updated the risk priorities in the second round by incorporating probability information into his considerations.

For both mayor and policy maker participants, they put more importance concerning the consequence information rather than on probability data. For them, probability is a binary state: the event either happens or it doesn't, with no consideration for level of uncertainties. Hence, if a risk has a possibility of happening, then it will happen in the long run. In that way, they showed a deterministic viewpoint. Therefore, adjustments were made to the first-round intuitive risk rankings by taking the magnitude of the consequence into account.

5.3.2.3 Conflicting points in decision-making

Following the individual ranking exercises, a group discussion was facilitated to exchange ideas of stakeholder priorities. After a discussion about the different priority rankings submitted by participants, five key themes emerged as focal points of debate.

The policymaker participant suggested there should be a distinction between short-term and long-term safety investment strategies. Most participants think it is more urgent to prevent risks with a higher likelihood of occurring. As an exception, the policymaker player emphasized that greater importance should be attached to risks with very low probability but potentially long-term impacts, such as major ammonia leak due to physical attack. On one hand, he argued that although the probabilities of occurrence of these risk scenarios are very low, they could increase in the long run. On the other hand, if such risks were to occur, their potential secondary impacts, such as public distrust toward government and the company, could hinder long-term stakeholder cooperation.

Some players brought up the significance of reduction potential of risks. For example, the inspector participant put less priority on reducing the risk of major ammonia leak due to a bomb. He perceived the existing security measures such as restricted access and physical barriers should already be in place, and further investments in protection would not be cost-effective, as the additional benefits would be marginal compared to the resources required. Similarly, the local resident player mentioned the limited capacity of an individual institution to prevent a terrorist attack, and he believed such risk due to external threats are beyond the scope of a single chemical company.

Another point of debate was the perceived credibility of scientific data used to justify risk rankings. The NGO participant indicated that some participants are not aware of the uncertainty of scientific data. He stated that scientific information, and particularly the consequence analysis, can only reflect part of the outcomes of risk events. For example, the incommensurable effects, such as lives of trees, are not included in the scientific risk analysis.

In the debating process, the mayor participant proposed the distinction between individual and collective values. In contrast to most other stakeholders in the risk management committee, he gave more weights to risks that pose threats to broader groups rather than those impacting single institutions. For instance, protecting the safety of the company is the utmost value of the company employees and employers. However, the impacts resulted from flooding and physical terrorist attack can be more widespread and long-lasting, with the potential to affect neighbouring communities and future generations.

In addition, the policymaker participant noted that the source of the budget was a key factor influencing his risk ranking ordering. He explained that if the majority of the budget came from the company, he would be more inclined to align with the company's preferences.

5.3.2.4 Reasoning behind decision-making

After voting towards the proposed risk ranking based on Borda rule, participants were asked to state the rationale behind their decisions. Their reasons included similarity to personal priorities, transparency and fairness of the decision-making process, and perception of the will of the public.

Participants generally showed a higher level of acceptance toward the final decision when it closely aligned with their own rankings. For instance, the CEO participant chose to remain neutral, because he felt the final ranking was partly aligned with his interest but contained with a conflicting point. The policymaker participant disagreed with the outcome of the decision, as the scenario involving a major ammonia leak due to equipment failure – which he considered to be the lowest importance – was ultimately ranked as the priority.

Besides the differences between individual and collective ranking, the NGO participant indicated that transparency was another criterion influencing his decision-making preference. Specifically, he emphasized that it is unclear how the composite score was calculated, i.e., the underlying mathematical calculations were not communicated to participants. Moreover, the simple averaging was perceived as inappropriate account for different opinions of individual stakeholder perspectives.

Furthermore, the mayor participant reported the role of public pressure on influencing his decision-making. He explained that balancing the tension between policy strategies and managing public opinion was a constant challenge during decision making.

5.3.2.5 Reflection on risk management and role-playing game

After the decision-making session, the facilitator stopped the role play and asked participants to discuss their experience and feelings throughout the game process. All the players thought that the role play was very fun and practical, acknowledged the importance of involving stakeholders in major risk management. Some of them also provide some feedback concentrated on the risk management process and the insights derived from the game exercise, which are discussed below.

Several participants discussed the necessity to assign weights to different types of stakeholders in decision making. Participants generally agreed that equalizing stakeholder rankings to produce a composite prioritization was a biased way of interpretating the groups' opinion. One participant proposed power-interest analysis is essential in decision making context to capture the asymmetry in power and interests. Regarding the how to determine stakeholders' influence in risk management, participants held different opinions. The policymaker participant perceived that people with higher power should be assigned higher weights. By contrast, the NGO participant argued that greater weight should be assigned to stakeholders who are simultaneously highly affected by the outcomes (i.e., high stakes) and have limited decision-making power. For example, residents living near by ammonia production plant may be directly exposed to risks of major ammonia leak, but they do not have access or influence on the budget.

During the reflection, the NGO participant raised concerns about the appropriateness of communicating and sharing the risk information with stakeholder in real decision-making context. He explained that the public was perceived to be more emotional, less rational, and less knowledgeable about major risk events compared to experts. As a result, providing detailed information might amplify emotional reactions and increase public anxiety or fear.

Participants discussed the challenges they came across in their task completing and negotiation process and potential ways of improvement in the game format. Generally, the feedback reflects a desire for more realistic and complex game settings, as well as the inclusion of more information in the risk management RPG. For example, one participant emphasized that the absence of specific details about the physical setting, i.e., the distance between the ammonia plant and the nearby residential areas, made it difficult to rank risks. In terms of consequence information, participants preferred to see impacts tailored to each stakeholder's interests rather than general outcomes. The policymaker participant noted that some unexpected events, such as public protests, lobbing are common in real-word risk management scenarios. Including these elements in game design can significantly influence game results. One participant reported a lack of clarity regarding the interests of other stakeholders throughout the process and made it challenging for them to evaluate the situation effectively. In addition to the demand for more detailed information and a more realistic RPG design, the NGO participant felt that a neutral facilitator could help guide the negotiation process and foster consensus.

5.4 Discussion

The scientific literature increasingly calls for more ethical and societal considerations to be incorporated in major risk management (Ball and Boehmer-Christiansen 2007). One of the possible strategies of improvement of current major risk management is to involve stakeholders. This study applied the role-playing game method to engage a group of participants to rank different alternative risk scenarios. Applying this technique, we endeavoured to focus attention on the mechanisms of the deliberation process to investigate the practicability of the IRERDM approach. In addition, we tried to discover the motivation of participants in addressing their prioritization of major risk events.

The results demonstrate the capability of using a role-playing game to promote dialogue and understanding among various stakeholders in the major risk management context posed. An important part is that participants were able to adapt to and internalize the roles they were assigned. As one participant marked: "*I was amazed how quickly I transformed into a political figure*". Although the risk ranking task was considered to be abstract and difficult given very simplified scenarios and information, the participants were able to rank priorities of decision alternatives, sharing their rationale and criteria, and have discussions based on their own experiences while staying in their roles. Through individual assessment and dialogs, participants tried to reach an agreement on how to deal with the safety investment problem. Thus, although they have varying opinions regarding the safety investment priorities, through collective dialogs, most of the participants placed particular emphasis on major ammonia leak due to equipment failure. In the group voting process, all but one participant agreed with the final ranking.

The RPG exercise has proven valuable of the IRERDM approach. The narratives of participants unveiled that emotional criteria are an essential part in judging risk priorities. Considerations, such as perceived likelihood, stakeholder responsibility and liability, societal impacts, knowledge of risk by the exposed population, and other factors are raised by participants. This aligns well with the previous studies (Litai 1980, Slovic, Fischhoff et al. 1986, Xu, Reniers et al. 2025). Moreover, the risk ranking survey pointed out the fact that participants acting roles with different socio-political background can have different opinions regarding major risk ranking. Involving stakeholders into the risk management process contributes to foster understanding among stakeholders of various viewpoints. Furthermore, the results indicate that participants were able to have adaptive reflections by integrating their emotional judgement with rational risk analysis. During this process, they have different ways of processing the scientific data and their own intuitive judgments rather than simply multiplying probability and consequences. For example, some place more emphasis on the number of fatalities, while others assign more weight to probability of occurrence than to consequences.

Furthermore, the IRERDM approach enhances the acceptability of risk-related decisions. At the initial stage, stakeholders received no information about the risk events, reflecting real-world conditions in which most people have limited prior knowledge of risks. Across the three rounds, stakeholders' risk rankings gradually converged toward the rational ranking. This trend indicates that increased understanding of risk events contributes to greater acceptance of rational risk calculations. Differences in stakeholders' opinions can be reconciled through dialogue and interaction. From an ethical perspective, participatory engagement allows underlying considerations to be made transparent and visible to all participants.

The study also shows that the IRERDM approach has the potential to improve major risk management, particularly on developing collective problem-solving skills and generating new management ideas. For example, group discussions not only helped to reach agreement but also promoted debate and reflection on how to prioritize and what strategies are the best to protect the collective interests. Therefore, during the negotiation phase, participants proposed new options not initially contemplated by the research team, such as long-term and short-term strategy, individual *vs* collective value, budget allocating. In terms of risk management, this suggests that participants are not only capable of influencing decisions but also of providing possible useful insight in risk management. In addition to understanding how other stakeholders think, participants were able to examine different possible outcomes in strategic scenarios. The discussion can be leveraged to eventually change the risk management framework, such as reframing the risk problem, the decision goals, and refining risk assessment. For instance, the long-term and shot-term strategy can lead to revisit the first step “define risk problem”. Rather than framing it as a singular prioritization issue, the decision problem and decision goals can be reframed – e.g., differentiating long-term and short-term investment priorities. As a result, the IRERDM approach can serve as an iterative tool for incorporating diverse stakeholder perspectives into the feedback loop.

5.5 Conclusions

In this study, we developed a step-by-step description of a role-playing game process in risk ranking and provide tools to execute a role-playing game in a major risk management setting. The role-playing game process has been refined on the basis of the original IRERDM method to integrate role-playing throughout the entire process. The results of this study show that role-playing can be a valuable tool for gathering information from stakeholders and to introduce their emotional and ethical considerations in participatory major risk management and may be considered a tool to help justifying the major risk prioritization and ranking. In addition, the involvement of stakeholders is demonstrated to be useful in improving insights in risk problems through collective skills.

PART III CONCLUSION

Chapter 6 Conclusions, Recommendations, and Future Research

This study develops an Integrated Rational and Emotional Risk Decision-Making (IRERDM) approach, which provides a structured method for integrating stakeholders' emotional and ethical concerns into a rational risk assessment and prioritization model. The approach can be used to aid risk-informed decision-making in the chemical industry, and it also has the potential to be applied more broadly across all private and public organizations. The main conclusions and the answers to research questions are illustrated in Section 6.1. The research limitations and future research issues are discussed in Section 6.2.

6.1 Conclusions and recommendations

The scientific study of risk first emerged within mathematics in the mid-17th century. It was not until the end of the 19th century, particularly following the second Industrial Revolution, that an increasing number of disciplines began to engage in the study of risk. The earlier concept of risk is strongly influenced by mathematics and economics, strengthening risk is quantifiable by "probability" and "utilities". With the development of increasingly complex systems, risk assessment and risk management have gradually evolved into established disciplines. Consequently, contemporary risk management approaches are largely grounded in technical and rational principles. With the development of society, a growing number of social scientists have entered the risk domain, introducing new research topics (such as risk perception, risk communication) and perspectives (such as ethical and societal aspects) on the concept of risk.

Risk definitions and risk assessment methods are inevitably influenced by their disciplinary background. In chapter 2, risk definitions were categorised into four groups according to disciplinary characteristics: economics and decision science, engineering and science, social science, and philosophy. The risk assessment methods were divided into four categories: Quantitative Risk Assessment (QRA), Multi-Citeria Decision Making (MCDA), psychometric risk paradigms, and ad-hoc approaches that are tailored to specific cases or situations. Each method has its advantage and limitations.

Integrated risk management approaches that can integrate technical needs and societal concerns are needed; accordingly, in chapter 3, this thesis develops an Integrated Rational and Emotional Risk Management (IRERDM) approach building on conventional risk management frameworks. The IRERDM approach systematically involves stakeholders and takes into account their considerations in the entire risk decision-making process. It consists of six main steps: define risk problem, stakeholder analysis, risk description, risk calculation, risk prioritization, and risk treatment. Through adding an additional step "stakeholder analysis", relevant stakeholders concerning major risk management can be identified and can prepare for the following participatory activities. The additional risk description step allows stakeholders to interpret their concerns to determine what to be analysed in risk assessment. Meanwhile, the risk prioritization step is designed for resolving the conflicts between scientific risk analysis and laypeople's risk judgments. Both rational risk ranking and emotional risk ranking are provided to stakeholders, triggering discussion and negotiation among stakeholders to ultimately finish with a final accepted risk ranking.

Applying the IRERDM method with a hypothetical case in an ammonia site selection problem theoretically illustrates that considering emotional and ethical factors can lead to a ranking that differs from one based solely on rational criteria.

In chapter 4, the response of a survey on stakeholders' attitudes and perspectives toward the IRERDM approach shows that direct participation of stakeholders in risk management is likely to gain support from the stakeholders. Budget and lack of time are the main constraints of participating in risk management. It is helpful to explicitly highlight the interests of each stakeholder group and make the process transparently documented throughout the process. Most participants considered emotional and ethical concerns to be important in risk management.

In chapter 5, the RPG provided a practical setting to test the applicability of the proposed model in simulated decision-making scenarios. The findings suggest that integrating emotional and moral factors, as well as stakeholder profiling, helped participants better understand diverse perspectives, facilitated communication, and promoted mutual respect. Most importantly, it enhanced participants' acceptance of the final risk decisions, even when those decisions did not fully align with their initial preferences. Applying the RPG demonstrates the capability of the IRERDM approach proposed in chapter 3. On one hand, participants can understand the situation clearly in participating in risk management. On the other hand, the IRERDM approach enhanced the transparency and acceptability of risk decisions.

Risk management is a specialized discipline to provide decision-makers with a scientific method to create the desired alternatives. The aim of risk management approach is to help the organizations to make good decisions to achieve their goals. There is a large variety of risk management models in scientific literature in different domains such as management, safety, finance, decision science, and economics. Risk management paradigm is flexible and should be constantly re-examined to meet developing societal demand. Current risk management paradigm is mainly based on a purely rational model of risk assessment of probability and consequences, and such approaches often overlook various stakeholders' goals in risk management process.

In response to the new requirements, this thesis proposes a potential way of refining current risk management paradigm to capture diverse societal and ethical concerns of stakeholders. The feasibility and effectiveness of this adapted paradigm are examined through empirical and experimental studies. The new paradigm is proposed as an improvement on the many current risk management models combining integrative stakeholder participation theory and hybrid rational and emotional decision-making theory. The refined approach retains the current rational risk management models while incorporating emotional factors; thus, it is called Integrated Rational and Emotional Risk Decision-Making (IRERDM) approach. First, by including a step "stakeholder analysis" in the formal decision process, it allows stakeholders to be directly involved throughout the risk management cycle, thereby transparency and ethical accountability can be strengthened. Second, in addition to a scientific(/rational) risk ranking, the refined risk paradigm provides an additional emotional risk ranking that derives from risk perceptions by stakeholders. This improvement helps stakeholders express their concerns and understand others. Finally, the approach is designed to incorporating social and emotional concerns that allows stakeholders to enhance the acceptability of ultimate risk decision while achieving a desired goal in risk management process.

6.2 Recommendations for future work

In this section, we present two general directions for future work on methods of risk decision-making. The first direction should be focused on further improvement of the current approach. Secondly, the opportunities for practical implication are discussed.

6.2.1 Need further improvement of the Integrated Rational and Emotional Risk Decision-Making (IRERDM) approach

This thesis provides an initial step-by-step risk decision-making approach for integrating stakeholders' concerns and needs with rational risk analysis and decision-making. However, the concrete techniques or tools to be employed at each step remain to be examined in greater detail in future research. Moreover, future studies could employ qualitative methods, such as focus groups, to gather more comprehensive feedback from risk decision-making experts and practitioners on the proposed approach. Subsequent work on improving the IRERDM approach should focus on refining and operationalizing the procedure.

The developed IRERDM approach was tested through a role-playing game. Role-playing game, like every serious game, is a simplification of reality, with a limited level of information and cannot capture the full complexities of the real-world (Parker, Cornforth et al. 2016). Future designs incorporating more sophisticated elements—such as sudden events, as suggested by participants—could enhance engagement. Ideally, such games should be played by actual stakeholders, or at least by participants closely matching the stakeholders they represent in terms of background, attitudes, and objectives. Participants in the role-playing game predominantly had safety engineering backgrounds, meaning that cognitive biases likely influenced their decisions. A potential next step would be validation with real stakeholders. The results show that participants primarily prioritized likelihood and stakeholder responsibility when assessing risk, while giving comparatively less attention to other factors. Role-playing games are an exercise to initiate social dialogue in an organized way, but they cannot result in final decision-making (Boso, Garrido et al. 2024). Researchers intending to use or adapt this risk management RPG should allocate sufficient resources to customize the exercises and carefully select participants to yield more informative insights for policy development.

Stakeholder participation in risk management can improve procedural and informational justice of risk decision making (Begg 2018). However, the integration of stakeholder analysis into prioritization and risk decision-making inevitably shifts the process toward science-policy interface[8] (Van den Hove 2007, Gluckman 2016), generating new theoretical normative challenges. These include uncertainties and limits of scientific knowledge, power distribution among stakeholders, and translating scientific knowledge into policy-relevant terms. For example, an important question arising from participants' statements was how to assign appropriate weights to the perspectives of different stakeholders in decision-making. In risk management, power-interest analysis and its application are important issues in the stakeholder analysis stage (Kim 2024). For example, Hosseini and Brenner (Hosseini and Brenner 1992) utilized the analytic hierarchy process (AHP) approach to derive pairwise comparison matrices for defining stakeholder weights, assigning higher weights to those with greater influence and interest. However, alternative approaches may prioritize stakeholders with lower influence but high stakes. This raises normative questions about whether power should be distributed based on equity or equality, and how the quality of deliberation can be assessed. Besides, stakeholders may hold diverse or conflicting viewpoints regarding emotional concerns and risk priorities. In the role-playing game, voting was used as an illustrative means of aggregating different stakeholder views and facilitating a collective decision. Future research could further examine how divergent stakeholder perspectives can be represented and accommodated in risk decision-making. While resolving these questions is beyond the primary scope of this thesis, the overarching aim of IRERDM is to promote more ethical and responsible risk management, making these topics worthy of future exploration.

Furthermore, in real-world settings, stakeholders vary in knowledge, education, and experience. Some may have received scientific risk assessment and/or management training, while others may have only a layperson's understanding. Effective communication of risk information is therefore essential to ensure meaningful engagement across stakeholders (Gregory and Keeney 2017).

[8] Here, "science-policy interface" refers to interactions between knowledge production and decision-making.

Questions remain regarding the most effective formats for conveying scientific risk results—qualitative (verbal), quantitative (numerical or verbal), or graphical—to avoid misconceptions or intuitive errors that could influence decision-making. More careful planning of risk communication strategies is necessary in future implementations.

6.2.2 Need for validation and implementation in other fields

The IRERDM approach was developed based on the ISO 31000: 2018 risk management framework. In this thesis, the approach was tested in a simulated scenario targeted on major industrial risks. Future work should further examine the feasibility of this approach in real-world settings, for instance, by engaging real stakeholders and testing the approach under authentic decision-making conditions. Furthermore, comparison studies could be conducted to examine its effectiveness in enhancing stakeholders' acceptance of risk decisions. In addition, the case study in this thesis is limited to the chemical industry. Future work could apply the IRERDM approach to other sectors beyond chemical plants to further test and validate its applicability. Continuous application in diverse contexts will also help identify new challenges and will support the ongoing improvement of the approach.

Appendix A Questionnaire Survey Materials

Appendix A1. survey sample

Survey Consent Form

You are being invited to participate in a research study titled ***Integrated rational and stakeholder-based risk management***. This study is carried out by PhD researcher Yuanyuan Xu. The data will be used for academic research. Please read the following information carefully before deciding whether or not to participate.

Purpose of the study

Major risks (e.g., natural disasters, industrial major accidents, global pandemics, terrorist attacks, etc.), though infrequent, are increasingly impacting people and communities. However, traditional risk management norms are primarily focused on the rational analysis of risks, often overlooking public concerns and emotional factors. This can lead to gaps and distrust between the public and risk management practices. This study aims to integrate public's concerns and emotional thinking into formal risk management. We hope to extract some common features from various stakeholders regarding those aspects. Your feedback is crucial in helping us better understand your perspective

Procedures

You will complete an online survey that will take approximately 5-10 minutes with 25 close-ended questions and 2 open-ended questions. It includes questions about:

1. Demographic information of the respondent (gender, geographical area, your area(s) of expertise, and professional/personal experience related to risk management)
2. Attitude towards stakeholder involvement in risk management
3. Risk attitude
4. Factors influencing risk-based decision-making (objectives, principles, constraints)
5. Socio-psychological factors
6. Interactions between stakeholders (conflicts)
7. Respondent comments and recommendations

Confidentiality

As with any online activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. We will minimize any risks by ensuring that the survey is completely anonymous; no IP addresses or other personal data will be collected. The data will be securely stored on TU Delft servers, and any identifying information will be removed to ensure confidentiality. Anonymized data may be made available as open data for future research, but no personally identifiable information will be shared. Your participation in this study is entirely voluntary and you can withdraw at any time.

You are free to omit any questions. If you wish to have your data removed, please contact us within two weeks of completing the survey, as this will not be possible after that period due to the anonymisation process.

Risk and Benefits

The potential of psychological stress and discomfort is minimal, and you may skip uncomfortable questions. In appreciation of your time and input, you will receive a summary of the survey results once the study is completed.

For any questions or concerns, you can contact Yuanyuan Xu at Y.Xu-8@tudelft.nl, the responsible researcher for this study.

By checking the "I agree" box below, you are consenting to participate in the study.

- I agree

Page Break

Q1 | Demographic information

1. What is your gender?

- Male
- Female
- Non-binary / third gender
- Prefer not to say

Q2 | Demographic information

2. Which geographic area are you currently reside in?

- East and Central Asia (e.g., China, Japan, Uzbekistan)
- South and Southeast Asia (e.g., India, Indonesia, Singapore)
- West Asia/Middle East (e.g., Iran, Isreal, Saudi Arabia)
- Eastern Europe (e.g., Hungary, Poland, Russia)
- Western Europe (e.g., Greece, Sweden, United Kingdom)
- North Africa (e.g., Egypt, Morocco, Sudan)
- Sub-Saharan Africa (e.g., Kenya, Nigeria, South Africa)
- North America (Canada, United States)
- Central America and Caribbean (e.g., Jamaica, Mexico, Panama)
- South America (e.g., Brazil, Chile, Colombia)
- Pacific/Oceania (e.g., Australia, Fiji, Papua New Guinea)
- Prefer not to say

Q3 | Demographic information

3. Which of the following best describes the group you belong to in the context of risk management?

- ○ Employees of high-risk sectors (e.g., oil and gas industry, nuclear power, aviation, maritime, railways, manufacturing, construction, etc.)
- ○ Representatives, investors, and shareholders of high-risk sectors
- ○ Government organizations and regulatory body (National, local or municipal government, regulatory agency, e.g., environmental, health, safety)
- ○ Non-Governmental Organizations (Humanitarian organization, environmental, health, and safety NGOs, local community group, etc.)
- ○ Academic or research institution (e.g., Universities, or college, research institutes)
- ○ Emergency responders (Firefighters, medical emergency responders, police or security services, etc.)
- ○ Insurance company
- ○ Consultancy agencies
- ○ Media
- ○ Public (I do not belong to any of the above organizations)
- ○ Others (please specify)

Page Break

Instructions

Stakeholders are socially organised groups or public that are or will be affected by the outcome of the event or the activity from which the risk originates and/or by the risk management options taken to counter the risk.
(Instructions: please respond to the following questions based on the stakeholder role you selected in Q3. When answering, consider your professional experience and responsibilities, as well as the views, priorities, and concerns that you believe are representative of this stakeholder group, rather than your personal opinions.)

Q4 | Attitude towards stakeholder involvement in risk management

4. From the perspective of your stakeholder role, to what extent do you agree with the following statement?

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
Stakeholder participation is meaningful for the management of major risks	○	○	○	○	○

Q5

5. From the perspective of your stakeholder role, which stakeholder group do you believe should have more influence or weight in the risk management participation process? (select up to 4)

- ☐ Employees of high-risk sectors (e.g., oil and gas industry, nuclear power, aviation, maritime, railways, manufacturing, construction, etc.)
- ☐ Representatives, investors, and shareholders of high-risk sectors
- ☐ Government organizations and regulatory body (National, local or municipal government, regulatory agency, e.g., environmental, health, safety)
- ☐ Non-Governmental Organizations (Humanitarian organization, environmental, health, and safety NGOs, local community group, etc.)
- ☐ Academic or research institution (e.g., Universities, or college, research institutes)
- ☐ Emergency responders (Firefighters, medical emergency responders, police or security services, etc.)
- ☐ Insurance company
- ☐ Consultancy agencies
- ☐ Media
- ☐ Public (People who do not belong to any of the above organizations but could be influenced by a hazardous event)
- ☐ Others (please specify)

Page Break

Q6 | Risk attitude

6. From the perspective of your stakeholder role, to what extent do you agree with the following statement?

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
"I believe that the risk associated with industrial accidents is much higher than what is reported in industry".	○	○	○	○	○

Q7 | Risk attitude

7. From the perspective of your stakeholder role, to what extent do you agree with the following statement?

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
"I am not willing to accept major risks with compensation, such as chemical leakages, gas explosions, or large-scale industrial accidents, even if the proposed benefits or compensations are substantial".	○	○	○	○	○

Q8 | Risk attitude

8. From the perspective of your stakeholder role, to what extent do you agree with the following statement?

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
"The adverse impacts of major risks (e.g., loss of lives due to chemical plant explosions) should be minimised at all costs (e.g., time, money), even if the likelihood of their occurrence is minimal".	○	○	○	○	○

Q9 | Risk attitude

9. From the perspective of your stakeholder role, to what extent do you agree with the following statement?

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
"I believe the long-term consequences of chemical plant accident scenarios can still be largely ignored by current science ".	○	○	○	○	○

Q10 | Risk attitude

10. From the perspective of your stakeholder role, to what extent do you agree with the following statement?

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
"Even when a chemical industrial company meets all safety standards, I still feel concerned about potential consequences of an adverse event".	○	○	○	○	○

Q11

11. From the perspective of your stakeholder role, to what extent do you agree with the following statement?

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
"I still pose a negative attitude towards an undesired event with high consequences, even when an expert tells me that the likelihood is low".	○	○	○	○	○

Q12

12. From the perspective of your stakeholder group, to what extent do you agree with the following statement?

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
"In situations when not all major risks are fully understood, I believe it is possible to stop operations until further assessments can be made".	○	○	○	○	○

Q13 *

13. From the perspective of your stakeholder role, what would you identify as your main objective in participating in risk management? (select up to 4)

- ☐ Mitigating risks
- ☐ Improve decision-making
- ☐ Protecting my stakeholder group's interests (i.e., minimising harm, ensure safe work environment, etc.)
- ☐ Express concerns and needs
- ☐ Ensure standards and regulatory requirements are met
- ☐ Facilitating collaboration among different stakeholders
- ☐ Timely communication
- ☐ Ensure transparency and accountability in risk decisions
- ☐ Obtain more information about risk events
- ☐ Building trust with other stakeholders
- ☐ Advocating equity and fairness
- ☐ Others (please specify)

Q14 | Factors influencing decision making *

14. From the perspective of your stakeholder role, what principles do you primarily follow when participating in risk management decision-making? (select up to 4)

- ☐ Protecting public health and safety
- ☐ Reducing environmental impacts
- ☐ Maximising economic benefits
- ☐ Long-term impacts and sustainability
- ☐ Scientific objectivity
- ☐ Compliance with law or regulations
- ☐ Maintaining public trust and reputation
- ☐ Risk management and mitigation
- ☐ Social and ethical justice (i.e., equity, fairness)
- ☐ Public communication and transparency
- ☐ Others (please specify)

Q15 | Factors influencing decision making *

15. From the perspective of your stakeholder role, what factors do you believe limit your decision-making ability the most? (select up to 4)
In the context of risk management, you often face various challenges that can affect your ability to make effective decisions. These challenges may arise from internal and external pressures, information availability, time limitations, and other factors that can complicate the decision-making process.

- ☐ Financial and fiscal capacities
- ☐ Time constraints
- ☐ Administrative efficiency
- ☐ The legal and normative requirements
- ☐ Uncertainty of risks
- ☐ Lack of data/infomation
- ☐ Public and pressure group reaction
- ☐ Internal organizational policies
- ☐ Political acceptability
- ☐ lack of experience or expertise
- ☐ Others (please specify)

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Note: Currently, risk is defined as a combination of risk scenario, uncertainty, consequences, and knowledge. However, there is growing recognition that socio-psychological factors (e.g., fear, equity, voluntariness) play a crucial role in shaping risk management decisions and strategies, significantly influencing how stakeholders perceive and accept risks.
From the perspective of your stakeholder role, please rate the importance of these factors in affecting risk acceptance.

Q16 | Risk perception *

16. **From the perspective of your stakeholder role, to what extent do you believe the following factor is important in risk management?**

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
emotional responses (fear, anxiety, etc.)	○	○	○	○	○

Q17 | Risk perception

17. From the perspective of your stakeholder role, to what extent do you believe the following factor is important in risk management?

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
previous experience with similar risks	○	○	○	○	○

Q18 | Risk perception

18. From the perspective of your stakeholder role, to what extent do you believe the following factor is important in risk management?

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
the causation of risk (i.e., intentionally or non-intentionally)	○	○	○	○	○

Q19 | Risk perception

19. From the perspective of your stakeholder role, to what extent do you believe the following factor is important in risk management?

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
potential reward from the risk (e.g., enhanced quality of life, economic growth, employment)	○	○	○	○	○

Q20 | Risk perception

20. From the perspective of your stakeholder role, to what extent do you believe the following factor is important in risk management?

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
trust towards government, experts, and companies	○	○	○	○	○

Q21 | Risk perception

21. **From the perspective of your stakeholder role, to what extent do you believe the following factor is important in risk management?**

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
social impact (e.g., psychological stress, social stability)	○	○	○	○	○

Q22 | Risk perception

22. **From the perspective of your stakeholder role, to what extent do you believe the following factor is important in risk management?**

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
fair distribution of risks	○	○	○	○	○

Q23 | Risk perception

23. **From the perspective of your stakeholder role, to what extent do you believe the following factor is important in risk management?**

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
voluntariness of exposure to hazards	○	○	○	○	○

Q24 | Risk perception

24. **From the perspective of your stakeholder role, to what extent do you believe the following factor is important in risk management?**

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
the ability of the company/government to prevent or mitigate the accidents	○	○	○	○	○

Appendix A2. Supplementary Data

1. **Meaningfulness of stakeholder participation in risk management**

From the perspective of your stakeholder role to what extent do you agree with the following statement?

Emotion	EHS	RIS	GOV	NGO	RES	EMR	INS	CON	MED	PUB
Not at all important	2	0	2	0	2	0	1	0	1	1
Somewhat important	0	0	0	0	0	0	0	0	0	0
Important	1	0	0	0	2	0	1	0	1	0
Very important	4	0	6	1	17	1	0	0	2	2
Extremely important	12	2	3	0	17	2	0	3	1	2
Total	19	2	12	1	38	3	2	3	5	5

2. **Risk attitude**

To what extent do you agree with the following statement?

2.1"I believe that the risk associated with industrial accidents is much higher than what is reported in industry."

Stakeholder type	**Strongly disagree**	**Somewhat disagree**	**Neither agree nor diagree**	**Somewhat agree**	**Strongly agree**	**Total**
EHS	0	0	3	8	8	19
RIS	0	0	0	1	1	2
GOV	0	0	2	6	4	12
NGO	0	0	1	0	0	1
RES	0	1	7	18	12	38
EMR	0	0	1	0	2	3
INS	0	1	0	1	0	2

CON	0	0	0	3	0	3
MED	0	1	1	3	0	5
PUB	0	0	1	2	2	5
Total	0	3	16	42	29	90

2.2 "I am not willing to accept major risks with compensation, such as chemical leakages, gas explosions, or large-scale industrial accidents, even if the proposed benefits or compensations are substantial."

Stakeholder type	**Strongly disagree**	**Somewhat disagree**	**Neither agree nor diagree**	**Somewhat agree**	**Strongly agree**	**Total**
EHS	0	0	3	6	10	19
RIS	0	0	0	1	1	2
GOV	0	1	2	1	8	12
NGO	0	0	1	0	0	1
RES	2	2	4	11	19	38
EMR	0	0	0	2	1	3
INS	0	1	0	1	0	2
CON	0	1	0	1	1	3
MED	0	1	0	2	2	5
PUB	0	0	0	2	3	5
Total	2	6	10	27	45	90

2.3 "The adverse impacts of major risks (e.g., loss of lives due to chemical plant explosions) should be minimized at all costs (e.g., time, money), even if the likelihood of their occurrence is minimal."

Stakeholder type	**Strongly disagree**	**Somewhat disagree**	**Neither agree**	**Somewhat agree**	**Strongly agree**	**Total**

			nor diagree			
EHS	2	5	1	3	8	19
RIS	0	0	1	1	0	2
GOV	0	1	1	4	6	12
NGO	0	0	0	0	1	1
RES	2	6	4	12	14	38
EMR	0	0	1	1	1	3
INS	0	0	0	2	0	2
CON	0	1	0	1	1	3
MED	0	1	2	1	1	5
PUB	0	0	2	0	3	5
Total	4	14	12	25	35	90

2.4 "I believe the long-term consequences of chemical plant accident scenarios can still be largely ignored by current science."

Stakeholder type	**Strongly disagree**	**Somewhat disagree**	**Neither agree nor diagree**	**Somewhat agree**	**Strongly agree**	**Total**
EHS	1	0	7	5	6	19
RIS	0	0	1	0	1	2
GOV	3	1	1	2	5	12
NGO	0	1	0	0	0	1
RES	0	5	5	22	6	38
EMR	0	0	1	1	1	3

INS	0	0	1	1	0	2
CON	0	2	0	1	0	3
MED	0	1	2	2	0	5
PUB	1	0	2	1	1	5
Total	5	10	20	35	20	90

2.5 "Even when a chemical industrial company meets all safety standards, I still feel concerned about potential consequences of an adverse event."

Stakeholder type	**Strongly disagree**	**Somewhat disagree**	**Neither agree nor diagree**	**Somewhat agree**	**Strongly agree**	**Total**
EHS	0	0	1	12	6	19
RIS	0	0	0	2	0	2
GOV	0	0	2	6	4	12
NGO	0	0	1	0	0	1
RES	0	1	6	20	11	38
EMR	0	0	1	0	2	3
INS	0	0	0	1	1	2
CON	0	0	0	3	0	3
MED	0	2	1	2	0	5
PUB	0	1	0	3	1	5
Total	0	4	12	49	25	90

2.6 "I still pose a negative attitude towards an undesired event with high consequences, even when an expert tells me that the likelihood is low."

Stakeholder type	**Strongly disagree**	**Somewhat disagree**	**Neither agree nor diagree**	**Somewhat agree**	**Strongly agree**	**Total**
EHS	0	3	6	7	3	19
RIS	0	1	0	0	1	2
GOV	0	1	2	6	3	12
NGO	0	0	0	1	0	1
RES	0	9	9	16	4	38
EMR	0	1	1	1	0	3
INS	0	0	0	1	1	2
CON	0	1	1	1	0	3
MED	0	0	3	2	0	5
PUB	0	0	4	1	0	5
Total	0	16	26	36	12	90

2.7 "In situations when not all major risks are fully understood, I believe it is possible to stop operations until further assessments can be made."

Stakeholder type	**Strongly disagree**	**Somewhat disagree**	**Neither agree nor disagree**	**Somewhat agree**	**Strongly agree**	**Total**
EHS	0	1	3	10	5	19
RIS	0	0	0	2	0	2
GOV	0	2	0	3	7	12
NGO	0	0	0	1	0	1
RES	0	2	8	20	8	38

EMR	0	0	2	0	1	3
INS	0	1	0	1	0	2
CON	0	1	0	2	0	3
MED	0	0	3	2	0	5
PUB	0	0	2	3	0	5
Total	0	7	18	44	21	90

3. Emotional factors

From the perspective of your stakeholder role to what extent do you believe the following factors are important in risk management?

Emotion	EHS	RIS	GOV	NGO	RES	EMR	INS	CON	MED	PUB
Not at all important	1	0	1	0	0	0	0	0	0	0
Somewhat important	3	1	0	1	2	0	1	1	0	0
Important	2	0	3	0	6	1	1	2	1	1
Very important	10	1	7	0	20	2	0	0	4	3
Extremely important	3	0	1	0	10	0	0	0	0	1
Total	19	2	12	1	38	3	2	3	5	5

Experience	EHS	RIS	GOV	NGO	RES	EMR	INS	CON	MED	PUB
Not at all important	0	0	0	0	0	0	0	0	0	0
Somewhat important	2	0	0	0	1	0	0	0	1	0
Important	3	0	2	0	2	0	0	1	1	1
Very important	8	1	10	1	19	2	1	1	3	2

Extremely important	6	1	0	0	16	1	1	1	0	2
Total	19	2	12	1	38	3	2	3	5	5

Causation	EHS	RIS	GOV	NGO	RES	EMR	INS	CON	MED	PUB
Not at all important	1	0	1	0	0	0	0	0	0	0
Somewhat important	2	0	0	0	2	0	0	1	2	0
Important	3	1	2	0	5	1	0	1	0	0
Very important	8	1	4	1	17	1	1	1	3	4
Extremely important	5	0	5	0	14	1	1	0	0	1
Total	19	2	12	1	38	3	2	3	5	5

Reward	EHS	RIS	GOV	NGO	RES	EMR	INS	CON	MED	PUB
Not at all important	2	0	1	0	0	0	0	0	0	0
Somewhat important	0	0	1	0	3	0	0	1	0	2
Important	6	0	3	0	10	0	1	1	3	2
Very important	10	2	6	1	18	2	1	1	2	1
Extremely important	1	0	1	0	7	1	0	0	0	0
Total	19	2	12	1	38	3	2	3	5	5

Trust	EHS	RIS	GOV	NGO	RES	EMR	INS	CON	MED	PUB
Not at all important	1	0	1	0	0	0	0	0	0	0

Somewhat important	1	0	0	0	2	0	1	0	1	1
Important	4	0	1	1	9	0	0	2	1	2
Very important	10	1	2	0	22	1	0	1	2	2
Extremely important	3	1	8	0	5	2	1	0	1	0
Total	19	2	12	1	38	3	2	3	5	5

Social impact	EHS	RIS	GOV	NGO	RES	EMR	INS	CON	MED	PUB
Not at all important	1	0	1	0	0	0	0	0	0	0
Somewhat important	1	0	0	0	1	0	0	0	1	0
Important	3	0	3	1	6	0	1	1	1	1
Very important	12	2	4	0	22	2	1	2	2	4
Extremely important	2	0	4	0	9	1	0	0	1	0
Total	19	2	12	1	38	3	2	3	5	5

Fairness	EHS	RIS	GOV	NGO	RES	EMR	INS	CON	MED	PUB
Not at all important	1	0	1	0	0	0	0	0	0	0
Somewhat important	2	0	1	1	4	0	0	0	0	0
Important	5	1	1	0	10	1	1	1	1	1
Very important	7	1	6	0	18	2	1	2	3	4
Extremely important	4	0	3	0	6	0	0	0	1	0
Total	19	2	12	1	38	3	2	3	5	5

Voluntariness	EHS	RIS	GOV	NGO	RES	EMR	INS	CON	MED	PUB

Not at all important	0	0	2	0	0	0	0	0	0	0
Somewhat important	3	0	1	0	5	0	0	0	0	0
Important	7	2	1	0	10	0	1	3	3	1
Very important	3	0	4	1	16	3	0	0	1	2
Extremely important	6	0	4	0	7	0	1	0	1	2
Total	19	2	12	1	38	3	2	3	5	5

Management	EHS	RIS	GOV	NGO	RES	EMR	INS	CON	MED	PUB
Not at all important	0	0	**0**	0	0	0	0	0	0	0
Somewhat important	0	0	0	0	2	0	0	0	0	0
Important	5	0	1	1	3	0	0	2	1	0
Very important	4	2	4	0	20	2	1	1	3	2
Extremely important	10	0	7	0	13	1	1	0	1	3
Total	19	2	12	1	38	3	2	3	5	5

4. Conflicts solving

From the perspective of your stakeholder role, how you would handle potential conflicts with other stakeholders?

(1) I prioritise collaboration and consensus-building

(2) I try to find compromises while protecting my interests

(3) I focus on achieving my goals,even if conflicts arise

(4) I avoid conflicts and defer to experts to resolve the conflict

(5) I would consider stepping back from decision-making process if the conflict becomes too intense

(6) Others

	EHS	RIS	GOV	NGO	RES	EMR	INS	CON	MED	PUB
(1)	9	1	3	0	13	0	0	1	2	1
(2)	6	0	5	0	11	1	1	1	1	3
(3)	1	0	2	0	6	0	0	1	2	0
(4)	1	0	1	1	6	1	1	0	0	1
(5)	2	1	0	0	1	1	0	0	0	0
(6)	0	0	1	0	1	0	0	0	0	0
Total	19	2	12	1	38	3	2	3	5	5

Table A1. Explanation of emotional risk factors.

Item	**Explanation**
Emotion	emotional responses (fear, anxiety, etc.)
Experience	previous experience with similar risks
Causation	the causation of risk (i.e., intentionally or non-intentionally)
Reward	potential reward from the risk (e.g., enhanced quality of life, economic growth, employment)
Trust	trust towards government, experts, and companies
Social impact	social impact (e.g., psychological stress, social stability)
Fairness	fair distribution of risks
Voluntariness	voluntariness of exposure to hazards
Management	the ability of the company/government to prevent or mitigate the accidents

Appendix B Role-Playing Game Materials

Appendix B1 Invitation letter

Subject: Invitation | Role-Playing Game – Risk Decision making

Dear colleagues,

We are looking for participants to take part in a Role-Playing Game experiment on risk management. This activity will bring together participants, each representing different stakeholders (such as government officers, industry CEOs, NGOs, Public), to collaboratively discuss and make decisions on major risk issues. In this process, you can experience real risk management process and contribute to innovative research in the field of risk management. The research is focused on integrating stakeholders' views and concerns in major risk management process.

Event Details:

- **Who:** We warmly welcome researchers at all career stages, including PhD students, postdoctoral researchers, and professors, to participate in this engaging simulation.
- **Date:** The experiment will take place on working days (Monday till Friday) in April.
- **Location:** The experiment will be held at **the Room-31.C1.060.TPM**
- **Duration:** The role-play game will last approximately 100-120 minutes
- **Participation mode:** In person

Game Overview:

In this simulation, each participant will be assigned a specific stakeholder role and engage in risk ranking and decision discussions based on the background information and principles of their role. The goal of this game is to explore how different stakeholders perceive and prioritize risks, helping us better improve the risk management approach.

If you are interested in participating in this fun role-play game, please find an available timeslot and register through our online schedule: https://doodle.com/group-poll/participate/dy2rppze. Please confirm your attendance by 7th, April.

Please feel free to contact Yuanyuan Xu (Y.Xu-8@tudelft.nl) if you have any questions.

Looking forward to your participation!

Kind regards,

Table B1. Role descriptions for role-playing game.

Stakeholder	Role profile
Policy maker	Policymaker is responsible for ensuring long-term safety and security, as well as environmental and economic sustainability. In face of conflicts, you focus on multi-party cooperation to ensure a balance of interests among government, industry and the public. **Key interest**: Protecting public health and safety environmental protection; sustainable economic development.
Inspector	Your primary responsibility is to ensure the safety and security of industrial operations. Your goal is to protect both the workers' well-being and the surrounding community, ensuring a safe and secure operating environment. **Key interest**: Protecting worker and public safety
Mayor	You are responsible for ensuring the safety and security of industrial operations while addressing local residents' concerns. Your role requires balancing economic development with public safety and environmental protection. Meanwhile, you pay attention to local residents' concerns and ensure transparent communication to avoid social discontent/public reactions caused by safety accidents or pollution problems. **Key interest**: Protecting local population and infrastructure; maintaining public trust and political stability
Fire fighter	Your primary goal is to minimize casualties for potential fire and hazardous material incidents. **Key interest**: Protecting human life; preventing the spread of the hazard
CEO	Your primary responsibility is to balance the company's long-term profitability and operational stability with safety and security. You are particularly inclined to minimize the risk of corporate liability for negligence or harm. **Key interest**: Protecting company reputation, avoiding liability of risk events, avoid operational shutdowns and financial loss
Safety and security manager	Your primary responsibility is to protect the company's safety and security. Your role is to protect both employees and the surrounding community. **Key interest**: Protecting employees; reduce the risk of damage to physical assets

Employee	Your primary concerns are ensuring workplace safety and security, as well as the potential risk of losing job due to hazardous events. **Key interest**: Personal safety and health; stable employment
NGO	The main task of the NGO is responsible for ensuring that the ammonia plant operates with the highest safety standards, minimizing risks to workers and nearby residents, and preventing environmental pollution. **Key interest**: Protecting public health and safety environmental protection
Local resident	You represent the residents living near the ammonia plant. Your primary concerns are safety and security. At the same time, you worry that a major incident could lead to the plant's closure, resulting in job losses. **Key interest**: Personal and family safety, health and environmental protection

Table B2. Consequence information regarding five risk scenarios.

Risk scenario		Consequence				
		10 fatalities or more	Major environmental damage to the region	Major economic disruption in the Netherlands	Huge societal distrust in Europe	Major economic loss for the company
Major ammonia leak due to	a bomb	✓			✓	✓
	a cyber-attack	✓				✓
	a flood	✓	✓	✓		✓
	an external explosion	✓		✓		✓
	equipment failure	✓			✓	✓

Table B3. Probability information regarding five risk scenarios.

Risk scenario	Major ammonia leak due to				
	a bomb	a cyber-attack	a flood	an external explosion	equipment failure
Probability of occurrence	Very low	Low	Low	Very low	Medium
	$1*10^{-8}$/-$1*10^{-6}$year (Turk 2005)	$1*10^{-6}$-$2*10^{-4}$(Moreno, Reniers et al. 2018)	$2*10^{-6}$-$1*10^{-4}$/year (Jonkman, Kok et al. 2008)	$2.7*10^{-9}$-$1.95*10^{-5}$- (Antonioni, Spadoni et al. 2009)	$1*10^{-6}$-$3*10^{-4}$ (Shafaghi 2008)

Table B4. First round risk ranking data based on intuitive judgement

Stakeholder	Major ammonia leak due to				
	a bomb	a cyber-attack	a flood	an external explosion	equipment failure
Policy maker	1	3	4	2	5
Inspector	5	4	3	2	1
Mayor	1	2	5	3	4
Fire fighter	5	4	3	2	1
Industry (CEO)	2	3	5	4	1
Industry (safety & security manager)	3	2	5	4	1
Industry (employee)	5	4	3	2	1
NGO	5	4	2	3	1
Local resident	5	4	3	2	1

Table B5. Second round risk ranking data based on risk information

Stakeholder	Major ammonia leak due to				
	a bomb	a cyber-attack	a flood	an external explosion	equipment failure
Policy maker	2	4	1	3	5
Inspector	5	4	2	3	1
Mayor	2	5	1	3	4
Fire fighter	5	3	2	4	1
Industry (CEO)	2	3	4	5	1

Industry (safety & security manager)	4	3	2	5	1
Industry (employee)	5	4	3	2	1
NGO	5	3	2	4	1
Local resident	5	4	2	3	1

Table B6. Third round risk ranking data based on negotiation

Stakeholder	Major ammonia leak due to				
	a bomb	a cyber-attack	a flood	an external explosion	equipment failure
Policy maker	2	4	1	3	5
Inspector	4	3	2	5	1
Mayor	2	5	1	3	4
Fire fighter	5	3	2	4	1
Industry (CEO)	2	3	4	5	1
Industry (safety & security manager)	4	3	2	5	1
Industry (employee)	5	4	3	2	1
NGO	5	3	2	4	1
Local resident	5	4	2	3	1

Table B7. Subthemes of emotional criteria for setting priorities.

Subthemes	Illustrative quotes
Perceived likelihood	● "I mostly looked at what I would perceive to be the most likely scenario" (Local resident). ● "Human errors are very common. So definitely leak due to the equipment failure in our plant is the highest priority" (Employee). ● "[…] and I also think that these are things that have the major likelihood to happen […] we are now living in difficult times as well, so it could be, but I believe cyber-attacks are more likely […]" (Fire-fighter). ● "I think cyber-attacks are most happening compared to the bomb. […] I think we are in a country which may be happening of some terrorist attack or less" (Employee). ● "…and the location of the plant. Because it's close to the sea, I rank the flood slightly higher" (NGO).
Stakeholder responsibility and liability	● "Those are the stuff that I have control over, at least that I can have access to and inspect" (Inspector). ● "[…] So terrorist attacks, […] the ministry is responsible for that. Cyberattacks is a core responsibility because it was within planned and the general system of security that is implemented" (Policymaker). ● "Equipment failure is my top priority as it puts direct liability on me […] and flood is the lowest cause, it's a nature -related thing. So, there's no liability to me. […] So, it's a safety, security problem and if I'm

	not putting the right people for security then that's also a liability for me" (CEO). ● "My key role is to protect the workers, and company assets, and also the surrounding." (Safety manager). ● "[…] every plant that is located in the industrial park has a responsibility to abide by safety procedures and if something were to happen these plants are responsible […]" (Fire-fighter). ● "If one chemical plant would explode and affect another one it would just It seemed like they don't get their business in order" (Mayor).
Societal impacts	● "[…] the safety of the citizens concerning the flooding, can they sleep in their house, is there access to food and less so a leak of ammonia. It's a side problem at the time" (Mayor).
Manageability of risks	● "[…] I do think the likelihood outweighs the difficulty for mitigating the effect of it. […], although I do think it's easier to inspect for site security […]" (Inspector).
Knowledge of risk by the exposed population	● "And the reason why I chose equipment failure as four is that I thought, well, I think everybody can understand that working in a high-risk environment also involves taking certain risks." (Mayor). ● "[…] most people don't really know what's happening in chemical plants and stuff what's done there" (Mayor).
Immediacy of effect	● "My most important concern at this moment [..] It's a side problem at the time" (Mayor).
Scientific knowledge of risk	● "Considering the flood, I would consider it a bit higher in the ranking because it is, although it's a

	major event, it has predictable outcomes and you could theoretically, you can predict for it to happen […]" (Inspector).

Table B8. Subthemes of scientific information and its implications for risk ranking.

Subthemes	Illustrative quotes
Updating risk ranking based on new information	• "My job is to protect, saving of people lives, so all of these scenarios and with ten fatalities or more, then I look at the probability of these things happening" (Fire-fighter). • "I'm giving more priority to the flood and less to the external explosion, mostly because the external explosion has a very low chance of occurring […] mainly I just focus on the probability of occurrence" (Local resident). • "I do more concerns on the flood risk, because it also will impact the company, I mean in terms of economics, so I put it higher at this time" (Safety manager). • "The reasoning behind this is because the flooding, for me as an inspector, has the only distinguishable consequence that's relevant for me, relevant for the environment and the people surrounding the plant. And it has a higher occurrence than the external explosion, so it will rank higher" (Inspector).
Emerging considerations	• "Now flood is a higher priority for me, and external explosion is lower. But it is higher because it would also lead to environmental damage, and I don't want my company associated with environmental damage that could be a bad marketing or publicity for me […]" (CEO).

	● "I was considering putting cyberattacks higher because of cost -benefit analysis, but I would think... would make it an effective strategy to reduce risks […] you see the... cost-benefit analysis of investing in these areas" (Inspector).
Trust in expert data	● "I do believe that consequences are generally calculated in a monetary basis, they do not consider the value of life or even the environment for that case. But probabilities are calculated due to data, so it's a bit easier to trust them" (NGO).
Consequence outweigh probability	● "I want to look at which has the most consequences and make sure that it's prevented. […] even though it's a very low probability of the event happening […]" (Mayor). ● "[…] And despite the probability of things being low or very low, very low black swan events, let's say, are likely to happen in the long run. I just updated something based on likelihood of that happening or not" (Policymaker).

Table B9. Subthemes of conflicting points.

Themes	Illustrative quotes
Short-term and long-term strategy	● "What we care is the long term [..] if we are talking about our priorities for the next five years, for what concerns I fully agree with you that the budget is allocated mostly to make the plant as safe as possible […] we have to strike a balance in short-term, long-term division" (Policymaker). ● "I'm just not going to agree with you that the probability or the consequence of a terrorist attack is

	going to increase in the longer time horizon" (Local resident). ● "[…] something will happen in the long run doesn't mean that the others don't happen recurrently till the long run" (NGO). ● "What would happen if that happened? What would be the relationship between you as a resident and us as the government? And say, if in your city a terrorist attack happens, what would be your relationship with institutions supposed to safely save you from that" (Policymaker).
Reduction potential of risks	● "They already have their side fenced off, they have badges to get in and out of the system […] Pragmatically, I do think they've reached the limit of what they can do for their protection without installing anti-aircraft" (Inspector). ● "You can have a terrorist attack at every institution, every company. And preventing that, I think, is not the responsibility of all responsibilities. It's not something that should be addressed at the level of one power plant" (Local resident).
Reliability of scientific data	● "I also do believe that […] you're relying too much on the consequence data because it does say that the impact due to human -related doesn't cause any environmental damage, but I will not trust this data very blindly […] the consequences are very difficult to calculate. How will you calculate life of trees that are destroyed?" (NGO).
Individual vs Collective value	● "[…] I would like to emphasize that it's not we versus you, but we just represent us, so the collective. And that's how we look at these scenarios, for all of us collectively […] to make sure that we think in our

	collective best interest and not in our singular interest" (Mayor).
Source of budget	● "I think it's also to be clarified a bit how, who the sources of this budget are. Whether we are talking about a 50 -50 kind of a budget in terms of the government providing 50 % of this budget and 50 % is provided by the company." (Policy maker).

Table B10. Subthemes of reasoning behind decision-making.

Subthemes	Illustrative quotes
Similarity to personal priorities	● "[…] the final ranking here is very similar with the one that I rank […]" (Fire-fighter). ● "[…] the equipment failure is still the highest priority. So, I wanted to just focus on that part" (Employee). ● "I would be the guy who would put on the liability for not having the security. That's a very big deal and shouldn't be the lowest for me. The first one is fine […] The bomb threat shouldn't be there" (CEO). ● "[…] bomb attack for me it's a two and overall it's five and the last one is equipment failure human related I have a five overall is one […]" (Policymaker).
Transparency and fairness of the decision-making process	● "It's just taking an average purely for the ranking. […] it's already pretty biased. but at the same time, in practical scenarios, such rankings are directly placed as well, and they just show up. So that's why I neither agree nor disagree, because in some practical scenarios, it does happen that they just, yeah, took an average" (NGO).

Perception of the will of the public	● "[…] it was a strategic choice, a stalling question. but at the same time, I invited them to listen to their voice, and they chose me. So, should I listen? […] if you want to make a stupid decision, go ahead […]" (Mayor).

Table B11. Themes of reflection on risk management and role-playing game.

Themes	Illustrative quotes
Need weighting stakeholders' input	● "The power-interest matrix you're just looking at one dimension, which is interest. But then the power is completely excluded from this picture so when you talk about decisions" (Policymaker). ● "[…] I can block every negotiation from happening, that's the reality" (Policymaker) ● "[…] if you want to divide the consequences as well, there are people in this room who will be directly impacted by the consequences […] So you have to weigh the people without power, give them a higher weightage, I guess, equalize the rankings in some other ways" (NGO).
What information should be communicated to the public	● "[…] we cannot even share that information because if we share it this will make. You know general hysteria in the public if I tell you know there was an actual attempt of disrupting a chemical plant close to your house, you'll be like oh why should I live here then?" (NGO).
Perceived difficulties in game design	● "[…] major environmental damage to the region, is the local residents or is the entire region because the flood can carry it all the way […]" ● "[…] I would have indeed liked some more information like as a setting of the game […] maybe a

	local resident can organize a protest because they're very much involved in the community and NGO can facilitate the protest and also raise awareness of the collective problems" (Policymaker). ● "I found difficult is that I didn't really knew the interest of people…There are pieces of them flying around throughout the discussions and agreements or discussions that they were not very clear to me" (Mayor). ● "I also thought that during the, when we started negotiating, if there was a […] neutral mediator that focuses the group on certain areas, it moves the negotiation a bit, could have been faster" (NGO).

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List of Publications

Journal paper

- **Xu, Y***., Reniers, G., & Yang, M. (2025). Integrating Rational and Emotional Risk Management: A Stepwise Approach and Practical Implications. Journal of Safety Science and Resilience (In press). https://doi.org/10.1016/j.jnlssr.2025.02.004.
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