Contributions to enhanced climate change risk research using contemporary risk science

By

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The process of doing a PhD often shares many similarities with a physical journey. It begins with anticipation and excitement, marking the start of a significant undertaking towards academic and personal growth. Like travelers preparing for a journey, we, as PhD students, meticulously plan our research and academic pursuits. Along the way, we encounter challenges, setbacks, and uncertainties that test our resilience and determination. However, with the guidance of our mentors and peers, we navigate through uncharted academic territory, achieving milestones and making discoveries. Each hurdle overcome and milestone achieved brings us closer to our ultimate destination: completing our doctoral thesis and attaining our degree. Throughout the PhD journey, we reflect on our progress, refine our ideas, and experience personal growth, culminating in the fulfilment of our academic aspirations.

The successful completion of this thesis owes much to the invaluable support of several exceptional individuals. At the forefront, I am profoundly grateful to my main supervisor, Professor Terje Aven, and my co-supervisor, Professor Roger Flage, for their guidance and encouragement throughout this journey. Their wealth of experience and expertise in the field provided a solid foundation for the thesis work and inspired confidence in tackling challenging research questions.

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sounding board, and a source of inspiration at every step of the journey. Your expertise and insights have not only strengthened the academic rigor of my work but have also broadened my understanding of the field. Your willingness to share your knowledge and experience has been instrumental in overcoming various challenges and hurdles along the way. You were readily available to offer support, answer questions, and provide clarity on complex concepts, contributing significantly to the quality and depth of the thesis. Moreover, your encouragement has been a constant source of motivation, especially during moments of doubt or difficulty. Your belief in my abilities has instilled confidence and resilience, empowering me to persevere through the inevitable ups and downs of the research process.

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Summary

The overall goal of this thesis is to enhance climate change risk research and the understanding of climate change risk by integrating the latest insights from risk science. This involves comparing contemporary risk science knowledge with current frameworks, tools, and initiatives tackling climate-related risks. Each paper aims to generate Type A knowledge (applied risk analysis) within the context of climate change and smart city lighthouse projects. The emphasis lies in tackling fundamental issues concerning risk management, governance, and policy within these domains. The thesis consists of an introductory part (Part I) and six papers (Part II).

The papers in this thesis aim to contribute to the understanding of climate risk by examining various initiatives, perspectives, and approaches. They highlight the fact that effective management and communication of climate change risk hinge significantly on how the risk is conceptualized and articulated. However, the substantial uncertainties associated with climate change pose significant challenges in understanding, assessing, and managing climate risk. Criticism has been directed towards current perspectives and approaches in climate risk studies for their lack of scientific rigor, leading to misrepresentations and mischaracterization of climate change risks and uncertainties. Strengthening the risk science basis is therefore crucial to improve the current state of climate risk research. Each paper in this thesis offers insights, guidance, and suggestions for enhancements based on contemporary risk science knowledge.

- Papers II and VI thoroughly explore fundamental risk issues, providing insights and perspectives from risk science, and propose fundamental principles, methods, and strategies for risk management to improve how we address the challenges posed by climate change.

- Papers III and V relate to the topic of climate risk disclosures in business and society, and give insights based on current risk science knowledge to improve existing climate risk disclosure frameworks.
- Papers I and IV present a risk management framework, using more comprehensive approaches from the field of risk science to improve risk management in complex systems and examine its application to smart city lighthouse projects.

In more detail, Paper I provides a comprehensive review of all existing 17 smart city lighthouse projects (from 2015 to 2020), assessing their current risk management approaches and identifying their associated challenges. Challenges identified include organizational complexity, governance limitations due to inadequate structures, information security risks, and resilience oversight. The paper suggests expanding risk management strategies beyond conventional standards by incorporating collaborative governance and a risk-resilience-based approach. This integration aims to improve risk management practices, enhance governance and decision-making processes, and strengthen the resilience of smart city systems. Additionally, the paper explores how resilience-based approaches can complement traditional risk management activities to enhance overall risk mitigation efforts.

Paper II aims to propose fundamental principles of risk management, highlighted by risk science knowledge. It also challenges the selection of principles in traditional risk management standards, like ISO 31000 (2018). The paper argues that other principles are more fundamental and important and should be added in guidelines and standards on how to implement risk management in organizations. First and foremost, a basic principle should be that risk management is based on current risk science knowledge, related to concepts, principles, approaches, methods, and models. From this overriding principle, the paper points to a set of more specific principles, which covers both generic management principles and more specific risk management and risk science knowledge principles. The paper not only identifies the principles that merit

emphasis but also presents a rationale for structuring thinking in alignment with these principles.

Paper III provides a brief review of current works on climate risk disclosures, focusing on TCFD (2017) recommendations and the guidance document of Norway's Climate Risk Commission (NOU 2018). Furthermore, the paper presents the fundamental principles we consider should define and support climate-related risk disclosures. Some of these principles are based on contemporary risk science knowledge, particularly the principles presented in Paper II, whereas others are more generic criteria for proper disclosures, for example such as those highlighted by reporting standards and frameworks reviewed in the paper. The paper also offers guidance for businesses on formulating climate-related disclosures, integrating the disclosure recommendations with the fundamental principles. It advocates moving away from conventional approaches like scenario-based descriptions and standard risk matrices for assessing climate risk. Instead, it suggests alternatives grounded in risk science knowledge, emphasizing supporting knowledge and knowledge strength, critical assumptions, and resilience.

Paper IV explores the practical application of the theoretical analysis from Paper I, focusing on the real-life smart city project, Positive CityxChange. The study aims to validate the theoretical findings and recommendations by examining the implementation challenges and benefits within the context of this project. The chosen case study aligns with the research discussed in Paper I, allowing for insights into current risk management approaches and challenges in similar projects. The Positive CityxChange project offers practical insights into the necessity of transitioning from traditional project management to a more holistic approach that emphasizes collaboration, resilience, and adaptability. While the case study provides valuable insights, successful implementation of the framework requires tailored approaches and continuous monitoring to address the unique needs of each smart city project. The Positive CityxChange project serves as a valuable reference for other projects facing similar challenges.

Paper V provides some additional perspectives on climate risk disclosures for businesses and the public sector, advocating for a systemic approach to address the broader socio-economic implications of climate-related risks. It argues that the current focus on individual entities and sectors is insufficient to tackle the systemic effects of climate change. The paper emphasizes the need for wider adoption of climate risk disclosures, including in the public sector, to address the financial system's vulnerability to climate change. It suggests that relying solely on voluntary, single-entity disclosures is inadequate. The paper proposes the imperative for government and public sector climate risk disclosures, and presents a holistic framework that considers social, environmental, and public welfare dimensions alongside financial aspects. Finally, the paper discusses the implications of climate risk disclosures that extend beyond individual entities to encompass organizations, industries, regions, and society.

Finally, Paper VI offers a risk science perspective on climate change research, emphasizing three central themes: the utilization of probability models, the implementation of the precautionary principle, and the significance of risk and resilience. The paper sheds light on significant challenges and considerations within these domains, particularly focusing on the comprehension, articulation, and management of uncertainties. By showcasing how contemporary risk science tools, principles, and methodologies can support climate change research, the paper illustrates the potential for enhancing our understanding of climate change risks. It emphasizes the importance of effectively conceptualizing and characterizing climate change risk, as well as accurately representing and addressing associated uncertainties, using insights from risk science.

Contents

List of papers

Paper I

Karatzoudi, K., & Aven, T. (2022). Application of Collaborative Governance and Integrated Risk-Resilience-Based Policies to Improve the Risk Management of Smart City Lighthouse Projects. *Proceedings of the 32nd European Safety and Reliability Conference (ESREL 2022). Research Publishing Services 2022*. ISBN 978-981-18-5183-4. pp.1573-1580. DOI: 10.3850/978-981-18-5183-4_R27-01-086-cd

Paper II

Aven, T., Seif Askari, A., & Karatzoudi, K. (2022). What are the core principles of risk management? *Proceedings of the 32nd European Safety and Reliability Conference (ESREL 2022). Research Publishing Services.* ISBN 978-981-18-5183-4. pp.1471-1478. DOI: 10.3850/978-981-18-5183-4_R25-03-039-cd

Paper III

Karatzoudi, K., & Aven, T. (2024). Principles and guidance on climate risk disclosure for businesses. *International Journal of Business Continuity and Risk Management (IJBCRM), Vol. 14, No.1, pp.14-29.* ISSN 1758-2164. DOI: 10.1504/IJBCRM.2024.10057467

Paper IV

Karatzoudi, K., & Aven, T. (2023). A case study to demonstrate the applicability of a risk management framework based on collaborative governance and integrated risk-resilience strategies for smart city lighthouse projects. *Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023). Research Publishing Services.*

ISBN 978-981-18-8071-1. pp.1885-1. DOI: 10.3850/978-981-18-8071-1_P263-c

Paper V

Karatzoudi, K., Denham, T., & Aven, T. (2024). Perspectives on climate risk disclosures for businesses and public sector. Submitted for review to *Climatic Change Journal*.

Paper VI

Aven, T., Glette-Iversen, I., & Karatzoudi, K. (2024). A risk science perspective on some fundamental issues in climate change research. To be submitted.

Part I

1 Introduction

1.1 Background

In recent years, climate change has received considerable attention in the literature and in society in general, and there has been a particular focus on examining how to mitigate climate change risks. For the last two decades, the focus of climate policy has been almost exclusively on how to achieve the goal of mitigation of climate change particularly, with governments in different countries implementing various strategies and policies to meet climate change risks. The principal international authority assessing climate risk and facilitating this effort is the Intergovernmental Panel on Climate Change (IPCC). The IPCC has devoted its work and competence to articulating a common characterization of climate risk and uncertainties, and its aim is to inform governments about the existing scientific knowledge on climate change issues (Aven and Renn 2015). The communication of this work can be considered successful, as most governments are trying to align their decisions with the main conclusions drawn by the IPCC.

However, climate change is inherently characterized by substantial uncertainties, giving rise to numerous challenges, many of which have direct implications for climate risk considerations. The focus in this thesis is the challenges related to climate change risk and, in particular, fundamental issues concerning risk understanding, risk assessment, and risk handling. Considerable work has been conducted on these topics (e.g., IPCC, Task Force on Climate-related Financial Disclosures (TCFD)), but issues remain that need further developments and research. Examples include the use of probabilities to represent and express variation and uncertainties, principles, strategies, and policies to meet the risk and uncertainties, including resilience management, as will be further discussed in the thesis.

Introduction

The concepts of risk, uncertainty, vulnerability, and resilience play a pivotal role in describing and conveying climate change research.

These very concepts are also at the heart of risk science, encompassing facets like comprehending risk, assessing it, characterizing it, understanding how it is perceived, communicating it, and effectively managing and governing it. Risk science offers a framework to guide climate change research and enhance it with respect to climate risks. It aids in structuring the conceptualization and characterization of climate change-related risks, expressing and addressing uncertainties, facilitating the communication of climate change risks, delving into the perceptual aspects associated with climate change, and formulating strategies and policies for the management of climate change risks (Aven 2020). Through the use of contemporary risk science knowledge, there is a potential to further enhance climate change research.

Presently, there is a broad consensus on the significance of comprehending climate risk and recognizing climate change as a potential threat to financial stability. A central approach for mitigating the financial system's vulnerabilities to the repercussions of climate change is the disclosure of climate-related risks, a tool that is progressively gaining significance for organizations to manage their exposure to the impacts of climate change.

Various voluntary disclosure frameworks have offered direction to companies for reporting their climate-related disclosures, with the Task Force on Climate-related Financial Disclosures (TCFD) to be considered the “first step towards an internationally accepted standard in climate-related financial disclosure” (CDSB 2022, SASB 2016, B20 Taskforce 2017). The TCFD presented a document (TCFD 2017) to guide companies in how to report and consider climate-related risks in their strategy, as well as how these risks should be identified, assessed, managed, and communicated to the public. The document has been extensively referred to in the literature and has strongly influenced the

way companies conduct climate-related financial disclosures. However, the TCFD approach has been criticized for being concerned with the processes that should be carried out without explaining how to identify and actually assess climate risks beyond reference to the use of scenario analysis. Additionally, the TCFD work explains the rationale for key features of the guidance recommendations but is not detailed and does not use generic and current risk science knowledge (NOU 2018).

Capturing the complex and systemic nature of climate-related risks requires taking a step back and considering the fundamental principles that contemporary risk science knowledge offers to define and support such climate risk disclosures. The use of contemporary risk science should be a prerequisite for companies to deliver high quality disclosures. In addition, climate risk disclosures should extend beyond private interests and adopt a broader perspective that serves the public good, to provide a complete understanding of climate risk. In more detail, there is the need to adopt a systems approach to climate risk disclosure, recognizing the systemic implications of climate-related risks and their potential transmission to the broader socio-economic system and thus for wider adoption of climate risk disclosures, including in the public sector and society.

Beyond the financial and broader socio-economic impacts of climate change, a recent initiative has emerged to address the physical and transitional challenges presented by climate change—smart city lighthouse projects (Energy Cities 2022). These projects serve as a unique European innovation mechanism for the large-scale deployment and replication of smart city and energy solutions, aligning with the European Union's mission to establish 100 climate-neutral cities by 2030. Nevertheless, the cross-country and multi-disciplinary nature of these projects not only fosters innovation but also introduces complexity. Managing risk stands as a vital approach to navigate this complexity and address the diverse array of risks inherent in smart city lighthouse projects.

However, these projects have shown a short-sighted attitude towards the use of risk management, as their strategy relied solely on the use of traditional risk management that seem to have neither served the complexity nor met the diverse types of risks that have occurred (SCIS 2017). Thus, there is a potential for improved risk management, for example by including the use of integrated risk-resilience strategies that contemporary risk science offers, which give weight to uncertainty, resilience, and vulnerability. In climate change research, there is a significant focus on the resilience concept, due to inherently large uncertainties, and recently we have seen calls for a shift from risk to resilience (UNISDR 2015, Aven 2019b). Research shows that risk and resilience can be fully integrated (Logan et al. 2022), with resilience being an essential aspect of risk handling.

The potential to advance climate change risk research through using contemporary risk science is grounded in the dynamic, systemic, and evolving nature of climate change. The core idea here is the necessity of being well-prepared to address surprising and unforeseen events and scenarios resulting from climate change. Traditional risk assessment and management tools, which primarily concentrate on known events and scenarios, have notable limitations when dealing with substantial uncertainties. While these tools continue to be widely used, contemporary insights from the field of risk science have expanded the scope of risk assessment and management, offering more comprehensive frameworks and approaches (SRA 2017b, Renn 2008, Aven and Thekdi 2022).

1.2 Research objectives

The thesis' main objective is to contribute to enhanced climate change risk research by using current risk science knowledge. This is achieved by contrasting contemporary risk science knowledge with existing

climate-related risk frameworks, tools, and initiatives, the aim being to contribute to strengthening the climate risk research. This thesis focuses particularly on the following three areas:

- Fundamental risk issues in relation to climate change research
- Climate risk disclosures in business and society
- Application to smart city lighthouse projects

1.3 Scientific approach

The Norwegian Research Council (NRC) has undertaken substantial efforts to explore dimensions of research quality, with a focus on the concept's intricacies (NRC 2000). Defining research quality is not straightforward, but there seems to be a common perception that the concept is particularly associated with the following aspects of research:

- Originality: Tied to the novelty and innovative application of theory and methodology
- Solidity: Involves robust substantiation of claims, honest argumentation, and transparent data presentation
- Relevance: Correlated with academic development or practical and societal applicability

In more detail, originality involves advancing existing theory, synthesizing knowledge innovatively, and contributing to groundbreaking discoveries. Solid research is distinguished by high data quality, recognized scientific methods, proper citations, coherence, a critical stance, and clear presentation. Academic relevance is tied to cumulativity and generalizability, with cumulative contributions filling gaps and setting the stage for future investigations. Generalizability is linked to research of broad significance, revealing fundamental principles or introducing new tools. Relevance in practical or societal

terms varies, based on affected sectors, user groups, and time limit. In applied research, utility is paramount, defining quality by tangible practical results and emphasizing real-world impact.

Throughout the present work, the aim is to align with the principles and criteria of scientific quality as proposed by the Norwegian Research Council (NRC 2000). The work covered by this thesis is composed of a series of published papers (Part II), accompanied by an introductory section framing these papers into a broader context (Part I). The papers in Part II constitute the primary scientific contribution of this thesis. The work covered in this thesis has been conducted as part of an integrated process, with the following activities playing a significant role:

- Reviewing literature in specific fields relevant to the presented objectives.
- Analyzing documents and conducting searches for literature related to specific cases involving climate risk disclosure frameworks and related works.
- Searching databases for documents and reports related to cases concerning the application of smart city lighthouse projects.
- Engaging in brainstorming sessions, having guidance from, and participating in discussions with, supervisors.
- Engaging in discussions, correspondence, and collaboration with researchers in similar and related disciplines.
- Iterative processes in paper writing, involving drafting, revising, and continuous improvement based on comments and feedback.
- Publishing papers in conference proceedings and peer-reviewed journals.
- Presenting papers and research at international conferences, with subsequent discussions, feedback, and questions.

The outcomes of these processes and activities yield research with diverse characteristics. Research can be categorized in multiple ways, often differentiating between descriptive and analytical categories, such

as applied versus fundamental, quantitative versus qualitative, and conceptual versus empirical (Kothari 2004). As with most research work in practice, the work presented in this thesis aligns with various aspects of this classification. First, the research falls under the analytical category, as it uses and analyzes facts and information to make a critical evaluation. It is of conceptual character and qualitative but also has an empirical dimension, as conceptual ideas, principles, methods, and frameworks have been applied to real-life case studies and examples. It generates what Aven (2020) referred to as type A knowledge (applied risk analysis and risk science), as it is related to a specific application—climate change research and smart cities. The present work seeks to enhance this research by comparing this A type of analysis and science with the B type of risk analysis and science knowledge (generic risk analysis) on issues linked to management, governance, and policy.

Also, this work can be viewed as conceptual risk research (as discussed in Aven 2018 and Aven 2020), covering concepts, principles, approaches, methods, and models for understanding, assessing, communicating, and handling risk. Reasoning and argumentation are the key instruments. This type of research work builds on elements such as identification, revision, delineation, summarization, differentiation, integration, advocating, and refuting (MacInnis 2011, Aven 2018). In more detail, the following examples illustrate these elements for the present study:

- Identification: To identify key challenges related to climate change risk, particularly fundamental issues concerning risk understanding, risk assessment, and risk handling.
- Revision: To change or adjust interpretations by using contemporary risk science knowledge.
- Delineation: To focus the study on fundamental risk issues related to climate risks and the use of contemporary risk science knowledge to improve existing frameworks of climate risk

disclosures and initiatives aiming to deal with climate change risks.

- Summarization: To state crucial issues and points concerning the understanding and use of climate risk disclosures for businesses and the public sector.
- Differentiation: To distinguish between alternative definitions, interpretations, and perspectives on topics related to climate risk.
- Integration: To build and combine scientific contributions addressing diverse topics relevant to the understanding of climate risk and the use of existing tools to deal with it.
- Advocating: To argue for the rationality of using current risk science knowledge to enhance climate risk research.
- Refuting: To challenge and improve the current methods and frameworks for understanding, assessing, and communicating climate risk disclosures in businesses and society, as well as the effectiveness of current risk management approaches in smart city lighthouse projects.

1.4 Thesis structure

The thesis is structured in two parts. Part I presents and motivates the research areas and questions. It consolidates and connects the work undertaken within the thesis but also situates it within a broader context. Part I, therefore, offers a condensed overview and contextual backdrop for Part II of the thesis. In particular, Section 1 describes the background, the objectives for the thesis work, the scientific approach and scientific contribution. Section 2 provides an overview of the main findings and the scientific contributions of this research. Subsequently, Section 3 outlines ideas and recommendations for potential areas, directions,

future work, and research. These insights primarily draw upon the scientific contributions presented in the thesis papers.

Part II comprises a compilation of six distinct papers that constitute the scientific contributions presented in the thesis. Four of these papers have already been published: three in the peer-reviewed proceedings of the European Safety and Reliability Conference (ESREL) and the fourth in the peer-reviewed journal, *International Journal of Business Continuity and Risk Management*. The fifth paper is submitted to peer-reviewed journal, *Climatic Change*, and the sixth paper is ready for submission to peer-reviewed journals.

2 Research areas and findings

This section outlines the main scientific contributions of the papers presented in Part II of the thesis. The main objective is to contribute to the understanding of climate change risks by integrating the latest insights from risk science. This entails juxtaposing contemporary risk science knowledge with existing frameworks, tools, and initiatives addressing climate-related risks. All the papers seek to contribute to the creation of Type A knowledge (applied risk analysis) within a specific context—namely, climate change and smart city lighthouse projects. The focus is on addressing fundamental issues related to risk management, governance, and policy in these domains. More specifically, the six papers of the thesis relate to the topics shown in Figure 1.

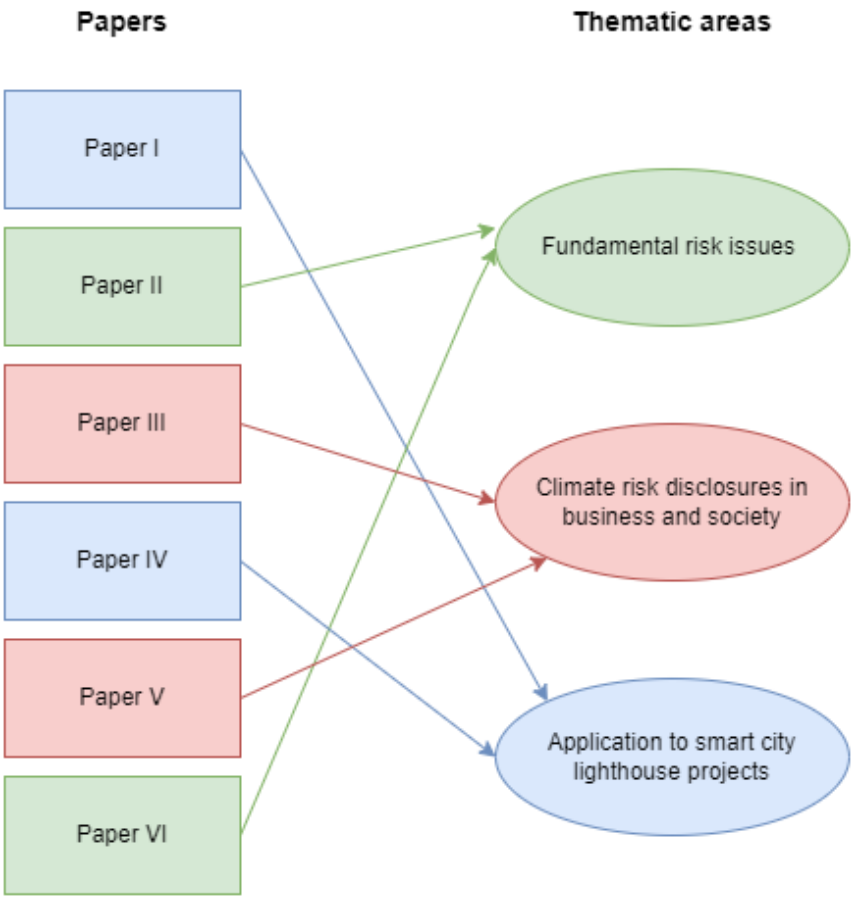

***Figure 1*: Thematic areas of the papers**

As shown in Figure 1, Papers II and VI address fundamental risk science issues, concerning risk understanding, assessment, and handling under large uncertainties. Papers III and V relate to the topic of climate risk disclosures in business and society, and give insights based on current risk science knowledge to improve existing climate risk disclosure frameworks. The remaining Papers I and IV present a risk management framework, using more comprehensive approaches from the field of risk science to improve risk management in complex systems and examine its application to smart city lighthouse projects. The specific

contributions of each paper are detailed and discussed in the articles presented in Part II of the thesis. The main contributions of the papers are also illustrated in Figure 2.

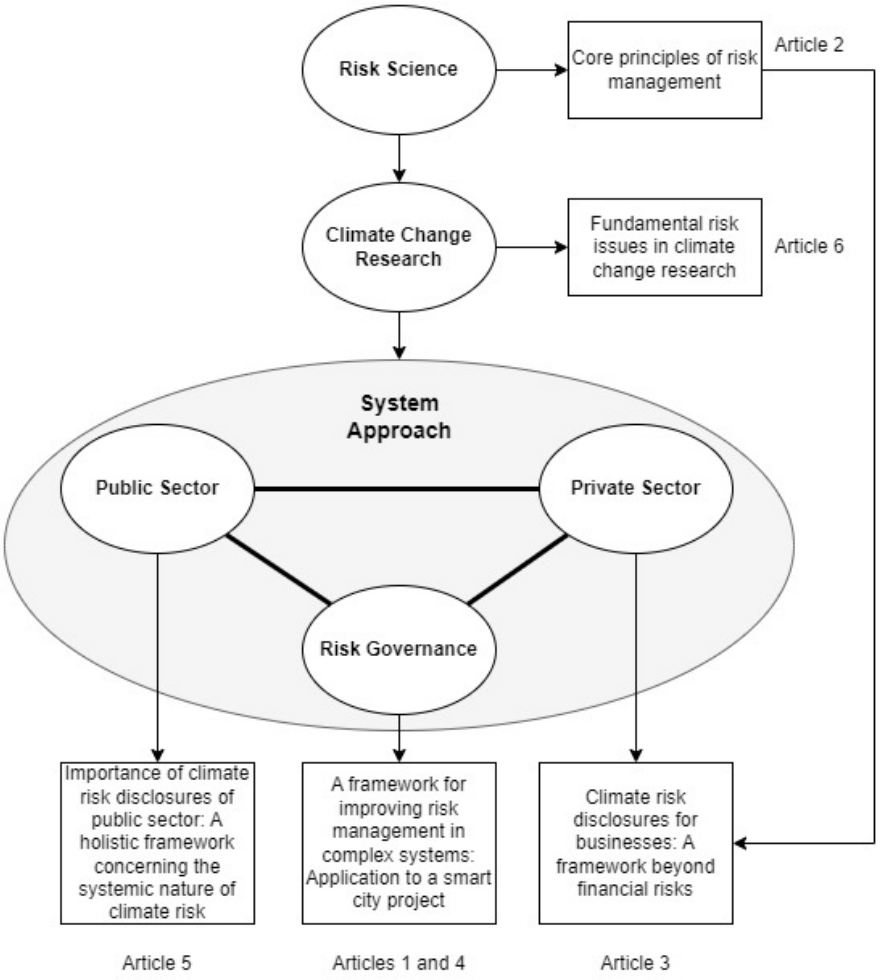

***Figure 2*: Main contribution of the papers**

In the subsequent sections, the papers will be presented according to the topic that they mainly address. Section 2.1 addresses fundamental risk

issues and presents the contributions of Papers II and VI. As shown in Figure 2, Paper II uses current risk science knowledge to identify the core principles of risk management and points the differences to the principles specified in traditional risk management standards. Likewise, Paper VI gives a risk science perspective on fundamental risk issues in climate change research. It also argues that risk science, with its concepts, principles, methods, and models, provides insights, and offers a framework to guide and enhance climate change research.

Section 2.2 considers climate risk disclosures in business and society and presents the contributions of Papers III and V. Paper III uses the core principles of risk management identified in Paper II to provide a framework and specific guidance to businesses on how to formulate climate risk disclosures and can be viewed as providing a risk science foundation for the TCFD framework (2017) and related guidance document (NOU 2018). Paper V highlights the imperative to embrace a systemic approach to climate risk disclosure, acknowledging the interconnected nature of climate-related risks and their potential impact on the broader socio-economic system. It underscores the necessity for a more extensive adoption of climate risk disclosures, including the public sector and society at large and presents a framework aligned with public sector priorities.

Finally, the contributions of Papers I and IV are presented in Section 2.3, which discusses the improvement of risk management strategies in complex systems, through a suggested framework, as well as insights gained by its application to smart city lighthouse projects.

Each section starts with a concise introduction to the addressed topic, providing a brief overview before delving into more detailed discussions on specific issues and presenting the findings outlined in the papers.

2.1 Fundamental risk science issues

As discussed in section 1.1, the considerable uncertainties related to climate change cause many challenges, particularly concerning the understanding, assessment, and management of climate risks. While substantial work has been undertaken by different sectors to meet the climate change risk (e.g., IPCC, TCFD), there are issues that necessitate further exploration and research. Notable examples include the representation of uncertainties through probabilities and the development of principles, strategies, and policies to effectively navigate and address the complexities of climate risks. Effective communication and management of climate change risk hinge significantly on how the risk is conceptualized and articulated. Existing perspectives and approaches in this regard have been criticized for their insufficient scientific rigor, resulting in a less-than-optimal presentation of climate change risks and uncertainties. Strengthening the risk science basis is essential for enhancing the current situation in the climate change risk research field (Aven 2020). Contemporary risk science offers a framework to guide climate change research and enhance it with respect to climate risks. Risk science knowledge can play a significant role in the management and governance of climate change, given that risk is a central aspect of this phenomenon, as the consequences of climate change are severe and surrounded by uncertainties.

In more detail, utilizing risk science can enhance climate change management and governance by offering knowledge and guidance on various aspects, such as conceptualizing and understanding climate risk, providing a foundational understanding of the challenges at hand. It also involves characterizing climate risk, delving into the specific nature and implications of the risks involved. Furthermore, it helps in representing and expressing uncertainties associated with climate change, acknowledging the complexity and unpredictability of the phenomenon.

Effective communication of climate change risk is another key aspect addressed, ensuring that information is conveyed accurately and comprehensibly to relevant stakeholders. Beyond this, it also explores the perceptional aspects related to climate change, considering diverse perspectives and attitudes towards the issue. It contributes to the management and governance of climate change risk, offering strategies and policies to navigate and mitigate the challenges posed. Finally, it assists in formulating strategies and policies tailored to address the specific nuances of climate change risk, providing a structured and informed foundation for decision-making in this domain (Aven 2020).

Paper II and Paper VI delve into these fundamental risk issues, offering risk science insights and perspectives and proposing fundamental risk management principles, methods, and strategies to enhance the approach to climate change challenges.

More specifically, the main aim of Paper II is to propose the core principles of risk management, highlighted by risk science knowledge. It also challenges the selection of principles in traditional risk management standards, like ISO 31000 (2018). For organizations to develop their risk management practices, they require guiding principles that serve as the underpinning to determine which ideas and perspectives to embrace. Paper II offers direction in this regard by not only identifying the principles that merit emphasis but also presenting a rationale for structuring thinking in alignment with these principles. Here "principle" denotes a foundational belief or guiding perspective. Once the core principles are identified, organizations will be guided on the basic pillars—the foundation—of risk management that are relevant to all types of applications.

2.1.1 An alternative set of risk management principles

Paper II centers the discussion on an alternative set of risk management principles, placing a strong emphasis on aligning risk management with current risk science knowledge. The primary principle (P1) underscores the need for organizations to build their risk management on the latest scientific insights, encompassing concepts, principles, approaches, methods, and models. While acknowledging the practical utility of standards, the paper urges caution in blindly accepting them, emphasizing the potential gap between standards and contemporary scientific knowledge (Aven and Ylönen 2019).

The second principle (P2) directs the focus of risk management towards potential undesirable events and their consequences. This principle highlights the essential purpose of risk management: addressing and mitigating potential damage and loss. While risk management should consider a broad spectrum of consequences, its primary objective remains the avoidance or reduction of undesirable outcomes.

To structure the knowledge on risk management, the paper distinguishes between guidance based on generic management knowledge and more specific risk management and risk science knowledge. Generic management principles, such as those outlined in ISO 31000 (2018), are discussed, but the paper acknowledges the need to go beyond these and consider additional principles related to effectiveness, efficiency, knowledge management, and ethical conduct. In addition, other principles are also considered, focusing on organizational capacity, leadership, and knowledge sharing, as discussed in Paté-Cornell and Cox (2014).

Another proposed principle introduces the concept of building a risk culture based on risk science (Aven and Ylönen 2020), extending the principle's scope to encompass the related concepts of safety, security,

and resilience. This principle emphasizes the importance of incorporating diverse scientific sources and their practices into risk management principles, reinforcing the idea that risk management principles should not be restricted to a single standard.

The paper then introduces principles based on more specific risk management and risk science knowledge. Drawing on guidance from the Society for Risk Analysis (SRA 2017b) and various formulations found in the literature (Aven et al. 2022), several key principles are highlighted. These principles cover fundamental aspects, including the distinction between the concept and measurement of risk, the balance between knowledge and values in determining risk levels, the cautionary/precautionary principle in the face of uncertainties, judgment of risks to protect values, rejection of unnecessary risks, the role of management review and judgments in decision-making, and the alignment of responsibility with control.

The highlighted principles collectively form a comprehensive framework for guiding risk management decisions, considering both uncertainties and value-based aspects. While acknowledging the inherent subjectivity in such decisions, the paper aims to provide theoretical insights and practical guidance for risk management. The paper concludes by emphasizing the importance of incorporating the selected principles into real-life organizations' risk management practices. It recognizes the gap between principles and practical implementation, suggesting that quality checks at various stages are crucial for ensuring effective risk management decisions. Useful guidance in this respect is provided by SRA (2019).

2.1.2 Fundamental risk issues in climate risk research

Research areas and findings

As discussed in section 2.1.1, one of the principles selected to be particularly crucial is the principle that underlines the significance of addressing uncertainties and that managing risk inherently involves managing uncertainties. Paper VI investigates some specific challenges in relation to the guidance that risk science provides to climate change research, addressing uncertainties and the associated handling. These challenges encompass issues such as using models, especially probability models to represent uncertainties, utilizing probabilities as a means of expressing these uncertainties, and formulating strategies and policies to address them, including the implementation of resilience management.

Scientific studies on climate change use probabilistic modeling, particularly focusing on the concept of fat-tailed distributions (Nordhaus 2011, Weitzman 2011, Taleb et al. 2014, Hwang et al. 2016). Climate change literature (e.g., Hwang et al. 2016) often categorizes fat tails in terms of the distribution of parameters like climate sensitivity, future temperature change, and economic impacts of climate change. The paper questions the practice of referring to fat-tailed probability distributions in climate change settings due to large uncertainties, high complexity, and continuous changes in the studied phenomenon of climate change. Frequentist probabilities and probability models are difficult to justify.

In contrast to frequentist probabilities, subjective probabilities express uncertainties and the assessor's belief levels based on supporting knowledge. While not inherently uncertain, the strength of the knowledge behind subjective probabilities can vary. In situations with significant uncertainties, the associated probability distributions may lack robust knowledge support, raising questions about their relevance in such contexts. The use of imprecise probabilities does not resolve the challenge of articulating the strength of knowledge either, as the interval might objectively represent available knowledge but provides no insight into its strength. Notably, in the context of the IPCC (Intergovernmental

Panel on Climate Change), the emphasis is on confidence, reflecting the strength of knowledge, but there is no explicit linkage to probability.

The paper emphasizes that probabilities alone have limited value in cases of large uncertainties, stressing the need to always relate probabilities to the supporting knowledge, the strength of this knowledge, and potential surprises in risk assessments. It also refers to frameworks that current risk science provides which link probability, its supporting knowledge, and the knowledge strength (Aven 2019a).

Furthermore, the paper explores the understanding and application of the precautionary principle in the climate change context. The criteria for invoking the precautionary principle emphasize that it is applied when facing threats with serious consequences and these consequences are subject to scientific uncertainties. However, some authors, such as Taleb et al. (2014), argue that the principle should only be invoked in extreme situations involving systemic ruin and irreversible harm. The paper questions this restriction, arguing that limiting the precautionary principle to ruinous and global problems is unfortunate and excludes many relevant situations.

The precautionary principle, as defined by the Society for Risk Analysis (SRA), aims to provide protection in the face of serious threats with scientific uncertainties, irrespective of the scale of the problem. The paper questions the dichotomy presented by some authors (e.g., Taleb et al. 2014), which separates the precautionary principle from risk management. Taleb et al. (2014) restrict risk management to known probabilities. Following risk science knowledge, risk management encompasses all types of situations, including those with weakly founded probabilities and varying magnitudes of gains and losses. The paper advocates a broader interpretation of the precautionary principle in line with risk science knowledge (SRA 2017a, Aven 2023), making it relevant whenever the consequences are severe and scientific

uncertainties are present, irrespective of the scale, scope, or context of the risk problem. Moreover, rather than being positioned in contrast to risk management, the precautionary principle is part of risk management. Based on this reasoning, the principle's application not only involves scientific considerations but also concerns values and priorities.

Finally, the paper highlights the growing emphasis on resilience in climate change research, with a call for a shift from a risk-centric to a comprehensive risk and resilience approach (UNISDR 2015, Aven 2019b). Resilience, defined as the ability of a system to recover after stress or disturbance, is deemed crucial in addressing surprising events resulting from climate change. The integration of risk and resilience is emphasized, with resilience considered a key aspect of risk handling.

2.2 Climate risk disclosures in business and society

In the rapidly evolving landscape of contemporary business and finance, there is a resounding consensus among stakeholders about the critical importance of understanding climate risk. The pervasive recognition of climate change as a potent threat to global financial stability has prompted organizations to proactively engage in strategies aimed at mitigating vulnerabilities. Among these strategies, the disclosure of climate-related risks has emerged as a powerful tool, steadily gaining significance across diverse industries.

A cornerstone of the financial system’s approach to climate risk is its advocating for climate risk disclosure by companies, through the recommendations of the Task Force on Climate-Related Financial Disclosures (TCFD). The TCFD introduced a comprehensive guideline (TCFD 2017) designed to assist companies in reporting and addressing

climate-related risks within their strategy and communicating these risks to the public. However, the TCFD's methodology focuses extensively on outlining procedures without providing clear guidance on the actual identification and assessment of climate risks. In addition, the TCFD emphasizes private benefits and considerations, which raises questions about its suitability to address the systemic and networked nature of climate risk, since climate risk disclosures for governments and the public sector are not included in its current approach.

Paper III and Paper VI bridge these gaps by i) considering the fundamental principles that contemporary risk science knowledge offers to define and support such climate risk disclosures and to provide a risk science foundation for the TCFD framework (2017) and ii) exploring climate risk disclosures as a comprehensive system that goes beyond individual interests, advocating a broader perspective that benefits the public good. This entails emphasizing the crucial role of governments and the public sector's involvement in climate risk disclosures to ensure a complete understanding of climate risk.

In more detail, Paper III provides a brief review of current works on climate risk disclosures, focusing on TCFD (2017) recommendations and the guidance document of Norway's Climate Risk Commission (NOU 2018). The review highlights both similarities and differences between the two works, emphasizing the suggested extension of NOU (2018) to make the recommendations more general and relevant for all types of risks that a company faces because of climate change. The changes relate to both main theme headings and content, to obtain a better match between each theme heading and its content.

Furthermore, the paper presents the fundamental principles we consider should define and support climate-related risk disclosures. Some of these principles are based on contemporary risk science knowledge, particularly principles presented in Paper II, whereas others are more

generic criteria for proper disclosures, for example such as those highlighted by TCFD (2017), NOU (2018), and other reporting standards and frameworks reviewed in the paper. For example, we consider principle P1 (also discussed in section 2.1.1 and Paper II) to be a basic principle that organizations should build their climate risk disclosures on. The organizations should use contemporary scientific risk science knowledge to deliver high-quality disclosures.

The paper also provides some specific guidance to businesses on how to formulate climate-related disclosures. This guidance relates to the thematic areas inspired by NOU (2018) and presents a figure that integrates the disclosure recommendations under each thematic area with the fundamental principles that organizations should build their climate risk disclosures on. Businesses are encouraged to use this figure and guidance when planning and presenting climate change disclosures.

Finally, the paper advocates a departure from conventional approaches, such as scenario-based descriptions and standard risk matrices when assessing climate risk. The emphasis is on moving away from adherence to standards and toward a more critical evaluation of existing risk assessment and management practices, particularly questioning the scientific basis of standards like ISO 31000 (2018), as discussed by Aven and Ylönen (2019).

Instead, the paper suggests alternatives grounded in risk science knowledge, giving weight to supporting knowledge and knowledge strength, addressing potential surprises relative to this knowledge, and taking into consideration critical assumptions, as well as introducing specific procedures to identify, for example, unknown knowns. Robustness and resilience also need to be given weight, to meet hazardous situations and other types of events due to climate change, particularly surprising types of events, should they occur.

Research areas and findings

In addition to providing a risk foundation to the TCFD (2017) framework in Paper III, in Paper V we provide some additional perspectives on climate risk disclosures for businesses and the public sector, focusing on a systems approach to climate risk disclosures. This entails recognizing the systemic implications of climate-related risks and their potential transmission to the broader socio-economic system and arguing thus for a wider adoption of climate risk disclosures, including in the public sector.

To elaborate, the paper discusses the notion of systemic risk and how it is related to financial risks, as well as examining the role of climate risk as a systemic risk. Climate risk extends beyond the boundaries of individual entities or sectors and can permeate and disrupt entire systems (Carter et al. 2021). In this context, systemic risks need to be considered when assessing climate risks. These risks involve interconnected relationships, feedback loops, and interactions within and between sectors, which can amplify the overall risk and its potential consequences. Recent studies (Simpson et al. 2021, Carter et al. 2021) shed light on the significance of understanding and addressing these systemic effects. Their research highlights the interplay between climate risks and the vulnerabilities of different sectors, emphasizing the need for comprehensive risk assessment and disclosure practices that account for the systemic nature of these impacts.

The paper argues that the current focus on individual entities and sectors is insufficient in addressing the systemic effects of climate change. Therefore, relying on a fragmented approach of voluntary, single-entity disclosures is inadequate and unlikely to fulfill the TCFD's goal of addressing the financial system's vulnerability to climate change effects. To build on this argument, the paper first provides a review of the existing literature on climate risk disclosures, assessing their benefits and challenges in their implementation.

Furthermore, it presents TCFD's response to systemic risk through their framework recommendations and provides a review of the application of climate risk disclosure recommendations by the private sector. Based on this review, it discusses the gaps and deficiencies of TCFD as an approach to systemic risk. Highlighted concerns include the framework's narrow emphasis on financial implications, challenges in practical application, heavy reliance on disclosures for financial stability, absence of regulatory interventions, discord between climate science and financial modeling, underestimation of climate risks, and the framework's failure to provide explicit guidance on public sector disclosure despite the interconnectedness of climate risks across both sectors.

In response, the paper discusses the imperative for government and public sector climate risk disclosures and the adoption of a broader perspective that serves the public good. It analyzes the challenges and opportunities faced by government organizations when implementing frameworks like the Task Force on Climate-related Financial Disclosures (TCFD) and provides valuable insights into the specific considerations and actions required to integrate climate risk disclosures into public sector practice. It presents a holistic framework that aligns with the public sector's priorities considering social, environmental, and public welfare dimensions alongside the financial aspects of climate-related risks. The suggested framework is built on the recommendations of Norway's Climate Risk Commission for climate risk disclosure at the national level (NOU 2018). In the framework, under the existing themes, new components were added to incorporate a better understanding, addressing the disclosure of climate risks for the public sector in a systemic context. In this light, the framework for public sector risk disclosure presented in the paper is a step towards a thorough system of disclosures.

Finally, the paper discusses the implications of climate risk disclosures that extend beyond individual entities to encompass organizations, industries, regions, and society. A systemic approach to disclosure, inclusive of the public sector, reveals how disclosures by one entity can influence the risk exposure and disclosure practices of others within the system.

2.3 Application to smart city lighthouse projects

In addition to the financial and broader socio-economic consequences of climate change, a recent initiative has surfaced to confront the physical and transitional obstacles brought about by climate change: smart city lighthouse projects. The initiatives entail collaborative efforts across countries and disciplines, bringing together municipalities and diverse stakeholders like industries, citizens, Small and Medium-sized Enterprises (SMEs), researchers, and investors, with the shared goal of shaping cities into smarter and more sustainable environments (European Commission 2020). At its core, the smart city initiative aims to transition cities into climate-neutral hubs by optimizing resource utilization, reducing emissions, and enhancing energy efficiency in buildings. Thus, these endeavors serve as strategic responses to climate change and climate-related risks.

However, the cross-border, multi-disciplinary, and multi-stakeholder nature of these initiatives not only stimulates innovation but also introduces complexity. Effectively managing risk emerges as a crucial strategy to navigate this complexity and mitigate the diverse range of risks inherent in smart city lighthouse projects. Nevertheless, these projects have demonstrated a short-sighted approach to risk management. They have relied primarily on traditional risk management strategies, which have proven inadequate in addressing the complexity

and diverse range of risks encountered (SCIS 2017). Indeed, the occurrence of several high-profile cybersecurity and privacy-related vulnerabilities has questioned the effectiveness of projects' current risk management approach and uncovered the need for its improvement.

More extensively, Paper I presents a review including all 17 existing smart city lighthouse projects (from 2015 to 2020), explaining the current risk management approaches and their challenges. The review revealed that the risk management in most lighthouse projects is in line with common standards, as described in ISO 31000 (2018) and the Open PM2 Project Management Framework, highlighting the identification, analysis, evaluation, and treatment of project risks. Key challenges highlighted include organizational complexity, governance limitations caused by inadequate governance structures, information security risks, and resilience oversight.

The paper further explores the potential benefits of broadening the risk management strategy beyond conventional standards. It examines how integrating elements like collaborative governance and a risk-resilience-based approach could enhance current risk management practices, bolster governance and decision-making processes, and fortify the resilience of smart city systems. It also investigates how such resilience-based approaches can be better integrated into the traditional risk management activities to improve the overall handling of risks and vulnerabilities.

The paper introduces the concept of collaborative governance and presents a model, commonly referred to in the literature and developed by Ansell and Gash (2008), for how to implement collaborative governance. Model variables were used to identify measures such as change of current institutional design and use of facilitative leadership to promote and safeguard an inclusive decision-making process in the projects. A key point of the methodology is to achieve more adaptable

project structures that emphasize stakeholder participation and involvement while addressing organizational complexities.

The work also presents a risk-resilience-based approach to improving the risk management of smart city lighthouse projects. Here, resilience is understood as the ability of the system to sustain or restore its basic functionality following a risk source or an event (hazard, threat) (SRA 2015). As a complex and interdependent system, the smart city system needs to be resilient and able to recover when facing disruptions, disturbances, changes, and surprises due to technological, natural, or man-made events. The paper discusses suggestions for how the resilience thinking can be integrated into the current risk management, to improve the overall handling of disruptions in smart city lighthouse projects. The main objective is to integrate resilience assessments and cross-organizational business continuity plans into traditional project risk-management activities. The initiative highlights the involvement of all project stakeholders in the risk-resilience analysis and management, as a suggestion to build project resilience and ensure continuity in project operations.

The methodology and analysis provided in Paper I is a theoretical conceptual analysis, based on reasoning using knowledge from risk management and risk science literature. Paper IV examines the practical applicability of this theoretical analysis. The aim of the paper is to support and give substance to the theoretical findings and recommendations based on a study of a real-life smart city lighthouse project (Positive CityxChange smart city project). The study investigates the benefits that the suggested framework can bring to the project and the challenges that the project might face when implementing the suggestions.

The case study chosen for analysis in Paper IV aligns with the research discussed in Paper I, meaning that the insights derived from the review

regarding the current risk management approaches and challenges of similar projects are also applicable to this specific project. The paper first provides a brief description of the Positive CityxChange smart city lighthouse project and the project's goals and objectives, as well as its current risk management approaches and their challenges. It then outlines the necessary processes and actions to implement the suggested framework within its existing project management structures. Based on these processes and actions, it discusses the potential benefits that the framework's implementation can bring to the project, some of which may include enhanced stakeholder engagement, improved collaboration and communication, alignment with the needs and concerns of the project stakeholders, integration of resilience strategies, and increased project resilience to potential threats and hazards. However, the implementation of the framework also requires the consideration of certain requirements related to, for example, the development of a collaborative governance structure, the availability of resources, proper planning, and efficient resource allocation.

The case study of the Positive CityxChange lighthouse project has given some valuable insights into the suggested framework's implementation. It underscored the necessity of transitioning to a risk management framework grounded in collaborative governance and integrated risk-resilience strategies. This shift requires departing from the project's current top-down management structure, which does not adequately address the multifaceted challenges inherent in such initiatives involving diverse stakeholders. Instead, the proposed framework advocates inclusive decision-making and stakeholder empowerment to comprehensively address disruptions stemming from various sources.

For instance, the COVID-19 pandemic's impact on the Positive CityxChange project highlights the importance of integrating resilience management and business continuity planning. The traditional risk management approach, while effective in identifying and mitigating

risks, may overlook broader systemic impacts and unanticipated disruptions, leaving the project vulnerable. Furthermore, assessing the resilience of innovative technological solutions poses a significant challenge due to their complexity and rapid evolution, necessitating specialized expertise and resources. While the suggested framework offers valuable insights, its success hinges on tailored implementation and ongoing monitoring to address the unique needs of each smart city project, with the Positive CityxChange case serving as a valuable reference point for others facing similar challenges. Regular evaluation will be essential to ensure the framework's efficacy in achieving its intended objectives.

3 Further work

As discussed in Section 2, the work conducted in relation to this thesis has, as a primary aim, the enhancement of climate change risk research by incorporating latest insights from risk science. This involved comparing contemporary risk science knowledge with current frameworks, tools, and initiatives addressing climate-related risks. This section briefly outlines some of the unexplored ideas and links them to what are perceived as significant avenues for future research. These ideas are mainly based on the scientific contributions of the thesis papers.

Section 2.1 addresses fundamental risk science issues, concerning risk understanding, assessment, and handling under large uncertainties, such as the case of climate change. Paper II and Paper VI thoroughly explored fundamental risk issues, providing insights and perspectives from risk science, and proposed fundamental principles, methods, and strategies for risk management, to improve how we address the challenges posed by climate change. The research reveals that effective management and communication of climate change risk depend heavily on the conceptualization and articulation of the climate risk. Current perspectives and approaches in climate risk studies have faced criticism for lacking scientific rigor, leading to misrepresentations and mischaracterization of climate change risks and uncertainties.

One avenue for future research is to delve deeper into the representation of uncertainties associated with climate change, for example exploring current uncertainty representation methods and comparing the effectiveness of these methods in capturing and communicating different dimensions of uncertainty. One example includes the use of climate-scenario modeling as one prominent tool to deal with large uncertainties related to climate change. Concerns have been raised about the economic

models used in climate scenario modeling within the financial services sector, following TCFD recommendation processes, and that existing climate scenarios may not adequately characterize the risks posed by climate change to our planet and society. These scenarios could be limited in their usefulness, as they fail to effectively assess and communicate the level of risk that we are likely to encounter in the future (Trust et al. 2023).

Section 2.2 examines climate risk disclosures in business and society. Paper III considers the fundamental principles that contemporary risk science knowledge offers to define and support such climate risk disclosures and to provide a risk science foundation for the TCFD framework (2017). It also provides some specific guidance to businesses on how to formulate climate-related disclosures and encourages businesses to use this guidance when planning and presenting climate change disclosures. Further research is warranted to empirically evaluate the efficacy of the suggested framework and schemes in real-world contexts. Conducting practical case studies will allow for a comprehensive assessment of how these recommended approaches perform in different settings and scenarios; it will validate their utility and enhance their applicability in addressing climate risk disclosures effectively.

In Paper V, climate risk disclosures are examined as a holistic system that extends beyond individual interests, advocating for a broader perspective focused on the public good. The paper underscores the importance of government and public sector involvement in climate risk disclosures to ensure a comprehensive understanding of climate risk. The paper also argues that a systemic approach to disclosure, inclusive of the public sector, reveals how disclosures by one entity can influence the risk exposure and disclosure practices of others within the system. This interconnectedness within the system can result in a cascading effect, where the actions and disclosures of one entity may have ripple effects

on the risk perceptions and decisions of others. Understanding the ripple effects of climate risk disclosure in a broader context can shed light on the dynamics of risk propagation and interdependence among various entities. It is of note that these dynamics are implied within the TCFD, as disclosure is seen as an element of investment decisions and interfirm comparisons. Further research is considered imperative to comprehensively explore the intricate relationships and mechanisms through which climate risk disclosures shape risk perceptions, transfer responsibilities, and stimulate further disclosure. It also needs to address criticism of climate risk disclosures, as some critics argue that disclosure efforts may be more for a public display rather than genuine and impactful measures. Such skepticism underscores the importance of ensuring that climate risk disclosure and related initiatives are not just superficial actions but substantive measures with tangible outcomes. Understanding these dynamics will enable us to develop climate risk disclosure frameworks that drive positive systemic changes, encourage entities to proactively manage climate risks, and contribute to a more resilient and sustainable future.

Finally, Section 2.3 considers the improvement of risk management strategies in complex systems, through a suggested framework (Paper I), and insights gained by its application to smart city lighthouse projects (Paper IV). To enhance the understanding of the framework's practical applicability and to refine the methodology, additional case studies of smart city lighthouse projects should be conducted. This includes exploring the feasibility of implementing the framework to other smart city lighthouse projects, studying the challenges faced by different types of smart city projects, and assessing the long-term effectiveness of the framework. Then, there is a need to synthesize the findings across all case studies, to understand the effectiveness of the risk management framework and identify ways in which it can be improved or adapted for different contexts. This can help to ensure that the framework is relevant to and effective for a wide range of smart city lighthouse projects.

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