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TOWARD A UNIFIED THEORY OF RISK, RESILIENCE AND SUSTAINABILITY SCIENCE WITH APPLICATIONS FOR EDUCATION AND GOVERNANCE

BY
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AALBORG UNIVERSITY
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TOWARD A UNIFIED THEORY OF RISK, RESILIENCE AND SUSTAINABILITY SCIENCE WITH APPLICATIONS FOR EDUCATION AND GOVERNANCE

by

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ENGLISH SUMMARY

The research of this thesis addresses the development of a logical basis, scientific principles, methods, and metrics across the knowledge domain of risk, to contribute to the foundation of a uniform and coherent basis for research, education and governance. A vast body of academic literature on risk has accumulated over the past several decades with little coordination and consensus among the individual contributing disciplines on what constitutes basic concepts relevant to the scope of phenomena a risk science may address or how these concepts may be represented in a coherent system of relations Increased inter-connectivity among social, ecological and engineered systems and the resulting systemic risks associated with geo-physical and anthropological hazards have rendered best practice risk management an inadequate decision support tool for risk governance at local and global scales.

While academic research in the area of resilience and sustainability has increased significantly since the 1990s, a unified theoretical and operational basis for the joint assessment of risk, resilience and sustainability is in the initial stage of development. There are presently no educational programs that holistically, from a systems perspective, combine the study of theories and methods appropriate for the identification, assessment, management, and governance of systemic risks. The complex coordination of multiple stakeholders falls short of addressing global policy preferences as formulated in the Sustainability Development Goals. National and supra-national demands for integrated, all-hazard, risk-informed and evidence-based risk management that takes explicit consideration of sustainability and resilience are not met.

The present thesis aims to contribute to the foundation of a unified risk, resilience and sustainability science, which in synergy with education practice, may provide the basis for informed preferences, decisions and actions in pursuit of sustainable well-being.

To this end, using the logic of matter-form-function design, the thesis:

- Identifies causal factors responsible for disparities between knowledge and action in the context of governance of systemic risks;
- Identifies a unifying theoretical basis for risk, resilience and sustainability science based on the concept of ‘information’, which decouples the theoretical basis from prevailing practices of decision-making based on stated (political) preferences;

- Identifies relevant concepts to form a basis for a domain ontology for the integrated science of risk, resilience and sustainability in accordance with Bayesian reasoning and empirical embodied cognition research;
- Formulates educational requirements targeted to fix the pitfalls in knowledge acquisition, knowledge creation and the practical use of knowledge in context;
- Provides a logical structure for the conceptual knowledge of an integrated risk, resilience and sustainability science in terms of a domain ontology that functions on two planes: formal and semantic. The formal plane, with logical basis in Bayesian non-informative priors, allows concepts to be considered free of prior disciplinary value settings. The semantic plane allows a context-driven weighing of relevant concepts, or contextual trans-disciplinarity;
- Provides a blueprint for education as a dynamic template of context-driven planning for educational activities along multiple learning pathways (from degree program to project level); and
- Provides example applications for two contexts: (i) inquiry problem based learning activity in which a linear correlation between social cohesion and disaster recovery is investigated and (ii) the application of the information-theoretic logic underlying the ontology for supporting decisions related to urban resilience.

DANSK RESUME

Forskningen i denne afhandling omhandler udviklingen af et logisk grundlag, videnskabelige principper, metoder og metrikker på tværs af videnområdet risiko, med det formål at bidrage til etableringen af et ensartet og sammenhængende grundlag for forskning, uddannelse og styring. Over de sidste årtier er der akkumuleret en meget betydelig mængde akademisk litteratur og viden omkring emnet risiko, med ringe koordinering og manglende konsensus blandt de enkelte bidragsdiscipliner om, hvad der udgør grundlæggende koncepter, der er relevante for anvendelsesområdet, som en risikovidenskab kan tage fat på, og hvordan disse koncepter kan repræsenteres i et sammenhængende system af relationer. Øget sammenkobling mellem sociale, økologiske og tekniske systemer og de deraf følgende systemiske risici forbundet med geofysiske og antropologiske farer har gjort bedste praksis for risikostyringen til en utilstrækkeligt beslutningsgrundlag for risikostyring på lokalt og globalt plan.

Mens den akademiske forskning inden for resiliens og bæredygtighed er øget betydeligt siden 1990'erne, er et samlet teoretisk og operationelt grundlag for en fælles vurdering af risiko, resiliens og bæredygtighed stadig i sin vorden. Der er i øjeblikket ingen uddannelsesprogrammer, der holistisk, fra et systemperspektiv, kombinere studiet af teorier og metoder, der er egnede til identifikation, vurdering, ledelse og styring af systemiske risici. Den komplekse koordinering af interessenter udgør en barriere for at adressere de globale politiske præferencer som disse er formuleret i Verdensmålene for bæredygtig udvikling, af de Forenede Nationer. Nationale og supranationale krav om integreret, holistisk, risikobaseret og evidensbaseret risikostyring, der eksplicit tager hensyn til bæredygtighed og modstandsdygtighed, opfyldes ikke.

Formålet med denne afhandling er at bidrage til udviklingen af et grundlag for en fælles risiko-, resiliens- og bæredygtighedsvidenskab, som i synergi med uddannelsespraksis kan danne grundlag for informerede præferencer for beslutninger og tiltag i bestræbelserne på at opnå bæredygtig velfærd.

Til opnåelse af dette tager afhandlingen brug af logikken i stof-form-funktion design:

- Identificerer årsagsfaktorer, der er ansvarlige for forskellene mellem viden og handling i forbindelse med styring af systemiske risici;

- Identificerer et samlet teoretisk grundlag for videnskab om risiko, resiliens og bæredygtighed baseret på begrebet 'information', som afkobler det teoretiske grundlag fra den nuværende praksis for beslutningstagning baseret på erklærede (politiske) præferencer;
- Identificerer relevante begreber til etablering af et grundlag for en domæneontologi for den integrerede videnskab om risiko, modstandsdygtighed og bæredygtighed i overensstemmelse med det Bayesianske rationale og empirisk forskning i kropslejret tænkning;
- Formulerer uddannelseskrav, der er målrettet til at løse faldgruber i viden indsamling, viden skabelse, og praktisk anvendelse af viden i kontekst;
- Tilvejebringer en logisk struktur til den konceptuelle viden om en integreret videnskab om risiko, resiliens og bæredygtighed i form af en domæneontologi, der fungerer på to planer: formel og semantisk. Det formelle plan, med logisk grundlag i Bayesianske ikke-informative prior's, tillader koncepter at betragtes som værende fri for værditildelinger disse eventuelt har haft i tidligere anvendelser. Det semantiske plan tillader en kontekstdrevet afvejning af relevante koncepter og sikrer dermed en kontekstuel tværdisciplinaritet;
- Tilvejebringer et blue-print for uddannelse som en dynamisk skabelon til kontekststyret planlægning af uddannelsesaktiviteter ad flere læringsveje (fra uddannelse til projektniveau); og
- Giver eksempler på applikationer i to sammenhænge: (i) undersøgelses- og problembaseret læringsaktivitet, hvor en lineær korrelation mellem social kohæsion og succes i genetablering efter katastrofer undersøges, og (ii) anvendelse af den informationsteoretiske logik, der ligger til grund for ontologien til støtte for beslutninger relateret til urban resiliens.

PREFACE

The initial spark for the systematic and systemic consideration of risk governance as a problem for information management was ignited in conversation with Professor Michael H. Faber during the course of my master studies in Natural Hazards Management at the Swiss Federal Institute of Technology (ETH Zürich). The master of disaster, as it was colloquially referred to by the students of the first 2009-2011 cohort, was one of the first – if not the first – program to offer postgraduate education in the area of disaster risk, not as a specialization within an established discipline, but as an inter-disciplinary academic subject in its own right. Envisaged and designed by Michael H. Faber, the program was a blend of applied statistics and probability theory, natural and social sciences, and applied civil engineering. The program's ambition was to create holistic analytic capability in support of decisions related to the management and governance of natural hazards at local, national and supra-national scales.

It is impossible to overestimate Michael H. Faber's intellectual and motivational impact on the course of my explorative learning and wayfinding. This course merged our paths northwards, where in 2014, the Global Decision Support Initiative (GDSI) was established at the Danish Technical University (DTU), based on Michael's vision for a common scientific and operational framework for global decision support that integrates risk and sustainability considerations, and an inter-disciplinary academic environment that can support research, advisory and educational activities. My own contribution to the GDSI enterprise was an initial comprehensive situation assessment of the risk and sustainability related research, advisory and educational activities of the six contributing DTU departments (Civil Engineering, Transport, Management, Food, Environment, and Compute), together with a horizon scanning of the trends driving research and policy. A subsequent vision was outlined for the development of a master level program in risk and sustainability informed decision support, based on the generic scientific framework the GDSI was set up to develop.

The idealistic vision of the GDSI project stumbled upon the hard reality of academic and institutional unpreparedness for the realization of the ambitious objectives. But the unfortunate circumstances of the GDSI's arrested development presented a novel opportunity to pursue the original objectives of Michael's vision through a joint research assistant – PhD position at Aalborg University. Aalborg University had, in fact, just established a master level program in Risk and Safety Management in 2014 in joint collaboration with the University of Southern Denmark. The then-Director of the Department of Civil Engineering and my present PhD co-supervisor, Peter Frigaard, saw potential in evolving the program in accordance with the vision for education the GDSI was unable to realize, and I was given the intellectual freedom to pursue this vision in the Socratic way of “following the argument where it leads”…

The intellectual transformation that this enabling environment afforded was further enhanced by a deeply satisfying emotional transformation of exchanging urban life with a life of a novice land dweller and small scale food gardener. Nothing has contributed more to my appreciation of the concept of de-growth as a qualitatively different type of growth. Similarly, my experience of landscape as something one observes and contemplates has been transformed to an interactive experience, in which perception, contemplation and activity have merged in what Ingold (2011) has poetically named a ‘taskscape’. The model for education presented in this thesis is thus not only engendered in the mind but also embodied in this taskscape.

Academically, my explorative path of how to integrate risk, resilience and sustainability into one holistic framework starts from the ideal of classical Greek education as a synthesis of words (knowledge) and action. During my undergraduate studies in ancient Greek language, history and philosophy, I was fascinated by the highly developed embodied cognition of the ancient Greek civilization, in particular by memory and cognition in Homer, the tragedians and the philosophers of the classical period. This influence can be seen in the theoretical discussion of the ontology as well as in the formulation of the education requirements of the blueprint.

The four years between my undergraduate and first graduate studies I spent teaching English as a foreign language point back to a life-long passion for language and love for linguistics. They also point forward to the explicit consideration of image schemas as identified in the research tradition of embodied cognitive linguistics (Johnson 1990 and Lakoff and Johnson 1999) as viable structural elements for mapping the landscape of concepts in the ontology. Language takes many forms in the present thesis. Natural, symbolic and visual language aspects all contribute to the formulation of a basis for a shared language across conceptual traditions – philosophical, cultural and behavioral.

Additional four years of mixed academic and professional involvement in the realm of international relations, security and intelligence, were what brought me to the first direct consideration of the concept of risk. Thus strategic military design and intelligence techniques as well as consideration of concepts such as warning, surprise, preparedness, orientation, and deception but also trust and legitimacy made their way into the world of the proposed ontology and blueprint.

An equally widespread representation is given to the knowledge tradition of disaster risk management, the physical and social processes that interact in producing harmful consequences and benefits as a result of natural hazards, anthropological hazards, land use practices, resource exploitation, etc., which takes us back to the beginning of the Preface and the fountain of inspiration for the present research.

I would not describe the learning path this PhD has taken as pro-gressive or cumulative. My strategy has been to move deeper backwards while covering as wide a periphery as possible, not in the pursuit of new knowledge but in the pursuit of redefining knowledge boundaries by stripping off as much as possible the accumulated layers of assumed a-priori beliefs.

In detailing the circumstances of how this work has come to be, one question has persistently required clarification to myself and to others, namely the meta question of what kind of thing the research of the present thesis is. Ontologically speaking, this question is about classification rules – on which shelf of the library of human knowledge does this thesis belong? This question I would like to invite the reader to consider as he/she reads along the pages of this thesis through the words of the Spanish philosopher José Ortega y Gasset, who defined the ultimate ontological reality as 'life':

"I am me and my circumstance."

Meditations on the Quixote, 1914

In the lifeworld, "I am me and my circumstances" applies equally to a corroded concrete beam, a white Arctic fox in winter, humanity in the Holocene.

In the lifeworld, the reader has complete freedom to choose which shelf best fits the pragmatic arrangement of his or her library.

Regardless the choice of shelf, my hope for the outcome of this PhD project is not measurable in the duration of its shelf life, but in the duration of its life in practical use, off the shelf. I hope that you, reader, proceed, and encounter something of difference that makes a difference in your circumstances.

ACKNOWLEDGEMENTS

First of all, I want to thank my supervisors – Dorina Gnaur and Peter Bak Frigaard – for making this PhD project possible and for the tireless dedication and support in the process from start to end.

The project was further partly enabled by funding from the EU Erasmus + project Knowledge for Resilient Society (K-FORCE), for which I am deeply grateful. Particularly, the project Director – Mirjana Laban was instrumental in contributing to a working environment that fostered knowledge sharing across disciplinary and cultural boundaries and welcomed my participation in a manner that was open, warm, convivial, academically and professionally rewarding.

I would like to thank my co-authors and collaborators Michael H. Faber, Jianjun Qin, Mille Skovgaard Hansen, Sebastian Tølbøll Glavind, and José Guadalupe Rangel Ramirez for their collective contribution to the papers included in this thesis and for the many hours of intellectually stimulating discussions.

I was fortune to be included in the research group of Michael H. Faber – Risk, Resilience and Sustainability in the Built Environment, which provided the best conditions for team-work: engagement, trust, transparency, and curiosity. Thank you to my research group colleagues Michael H. Faber, Jianjun Qin, José Guadalupe Rangel Ramirez, Juan Gonzalo Sepúlveda Astudillo, Sebastian Tølbøll Glavind, Henning Brüske, Min Liu, Wei-hing Zhang, Yue Guan, Kashif Ali, and Akinyemi Olugbenga Akinsanya.

I am much obliged to the assessment committee of the thesis – Katherine Richardson, Garry Peterson and Olav Geil for their constructive comments in strengthening the presentation of my ideas. Without them, this would have been a much less satisfactory result.

I am humbly grateful to the Editors-in-Chief of the journal Civil Engineering and Environmental Systems – Mark W. Milke and Paul W. Jowitt for granting my co-authors and me the inaugural best paper award of their journal for 2019.

It would be impossible to name all the teachers and mentors who have influenced the philosophical approaches followed in this PhD study. Along with the society of dead poets, philosophers and scientists listed in the bibliography, I would like to thank the teachers of the two best PhD courses I attended at Aalborg University: Ole B. Jensen for his inspirational Indeterminate Mobilities course and Peter Axel Nielsen and Erik Stolterman for their thought-provoking Elements of Interaction and Interactivity course.

In the course of this PhD, I had the opportunity to teach and mentor three cohorts of master students in the Aalborg University master program Risk and Safety Management. For me these activities have been the most rewarding aspect of academic life. I would like to thank all the student fellow travellers with whom I shared in the process of learning.

I am deeply grateful to the various support functions my family so unconditionally provided. Thank you to my parents-in-law for being fantastic grandparents when my absence was required as well as the positive attitude and pragmatic grounding, for which you are my role models. Thank you to my mother for putting up, with love, with the total sum of my rationalities and irrationalities – who knows which of these is worse? Thank you to my father for your loving endurance in proofreading vast numbers of pages with cloggy prose and your trusted guidance in matters of not only syntax and style but also quality of content. Thank you to my animal companions – Valdemar cat, Zuma dog and the cohort of chickens who provided hours of playful amusement and just the right mixture of deontological and utilitarian love.

Most of all, thank you Michael and Jasper – you are my safe operating space and define my system boundaries. With my heart-mind, I love you.

Øster Hornum

30 September 2020

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CHAPTER 1. INTRODUCTION

1.1. CHALLENGES TO GLOBAL GOVERNANCE OF INTER-CONNECTED SYSTEMS

"We know what should be done but we fail to do it."

Michael H. Faber, (2011). On the governance of global catastrophic risks

Over the last century, risk has increasingly gained importance as a means for governance in the face of uncertainty and is presently utilized in largely any context of societal activities whether related to public governance, industry or research. In its ubiquity of application, risk can be seen as a multi-dimensional life science that spills over disciplinary boundaries, application sectors, spatial and temporal scales, and public-private demarcations.

As illustrated in Figure 1 applications of risk encompass a vast number of industrial activities in society together with governance and management of health, finance, environment and natural resources. Risk is also an integral part of academic research and is applied keenly within the natural, technical social and human sciences As highlighted in Nielsen and Faber (2020, Part I), however, significant disparities among the best practices of applying risk may be observed. This concerns largely all aspect of risk informed decision making, such as the basic conceptualization of risk, perception of risk, modeling of preferences, representation of knowledge, modeling of systems, risk metrics, modeling of consequences, risk acceptance criteria, risk communication and risk analysis tools. As demonstrated by Soares (2010) a major reason for this is that even though a theoretical foundation of risk informed decision support is readily available[1], its utilizations and interpretations have taken diverging courses within different application areas and research domains. In this manner application area and research domain "silo developments" have defined what can be understood as the present best practices on risk informed decision making and have also strongly influenced the academic developments within the related sciences.

This might at first glance appear not to be a major problem, in the sense that it could indeed be relevant that each application area and research domain

[1] Through the seminal works of Raiffa and Schlaifer (1961) on Bayesian decision analysis together with the axioms of utility theory by von Neumann and Morgenstern (1944).

benefit from the concept of risk in whichever manner is best suited for their purposes. However, in the broader context of governance, where in principle all systems subject to governance are dynamically connected, and consequences of decisions evolve across temporal and geographical scales, with no notion and respect of application area and research domain boundaries, the present best practices in fact are a barrier for consistent ranking of governance decision alternatives.

To illustrate this point a basic sketch of the silo like developments in the domain of risk is provided in Fig. 1

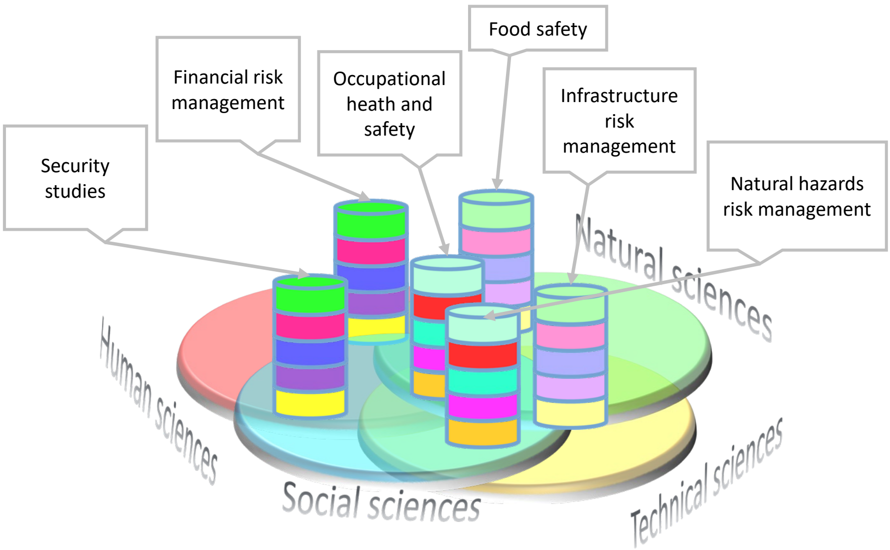

Fig. 1 Illustration of the silo oriented developments of risk sciences – driven by specific contexts.

In Fig. 1 the lower level bases showing the different sciences represent the conceptual basis for risk-informed decision making developed over time within the sciences. Surely significant parts of those are overlapping, but there are significant differences and incompatibilities as well. The individual silos are represented with different layers but with similar colors. These layers aim to illustrated the various components of importance for risk modeling and risk informed decision making, such as representation of preferences, conception of knowledge, modeling of systems, choice of metrics, modeling of consequences, representation of perception, rationale for assessing tradeoffs, communication, risk acceptance, risk modeling techniques and tools. The similar colors in the different silos indicated that in principle these components may be identified within all silos but in different forms.

The lack of homogeneity results in a lack of shared language not only among experts, but also decision makers and stakeholders. Moreover, consistent aggregation and governance of risks are not possible. In the past, utilizations of risk as a means of navigation in optimizing economic efficiency, production reliability and safety, was not thought to pose a significant problem; however, as societies at national and global scale strive for increased welfare, and at the same time are challenged by climate change, diminishing renewable resources and population growth, this situation is changing, see also Faber (2011).

The largest contemporary challenge for humanity is to balance growth (population and development) and consumption in order to ensure the continuity of "a safe operating space", which in Rockström et al. (2009) and Steffen et al. (2015) Planetary Boundaries framework refers to the bio-physical conditions defining the Holocene. This challenge, global and local at once, presents an opportunity to unify the fragmented knowledge domain of risk into a systems framework for modeling the complex, non-linear interactions among the constituent hazard, bio-physical, engineered, ecological, and social sub-systems that together define the boundary conditions for a global management and governance of risks.

In this respect, the main epistemic challenge is to formulate a theoretical framework for risk science, which (i) synthesizes the individual disciplinary and sectoral perspectives on risk into a coherent methodical structure for decision support, and (ii) integrates risk, resilience and sustainability considerations into a holistic systems approach that facilitates the assessment and ranking of options in a consistent manner in accordance with preferences, uncertainties and the best available knowledge.

Parallel to the epistemic challenge is the axiological challenge of turning knowledge into action. This challenge is at the core of developing an adaptive capacity for our being and well-being in the world. The gap between knowing and doing, as in the quote at the beginning of this section, whether expressed as a gap between stated and revealed preferences, descriptive and prescriptive science or intentions and outcomes, fundamentally relates to our perception of reality as external or internal to our thought processes and our deepest a-priori beliefs with regard to free will.

The relation between knowing and doing is a central theme in the classical traditions of both Western and Eastern thinking. The Greeks, who invented tragedy, were keenly aware of, and interested in actions and dispositions (hubris) leading to self-destruction. Similarly, classical Chinese schools of thought emphasized the pragmatic application of epistemology in pursuit of harmonious living. In Greece, education (paideia) was the adaptive mechanism by which individual self-destruction or ruin as a result of lack of knowledge, incorrect knowledge or deception could be avoided. In China, education in the state academies had the function to ensure the collective continuity of social structure threatened by anarchic dissolution of laws and rules both cosmic and human while education in the *daoxue* (learning of the way) schools provided the same functionality at the level of the individual.

For education to continue to fulfill its life-supporting function, it must evolve contextually as an adaptive capacity within an ever changing environment. The greatest challenge for education is to stay relevant while balancing between its function to preserve and its function to create knowledge. For as Nietzsche colorfully warned, an education which is only concerned with the transmission of established knowledge and has no creative power of its own leads onto a path of intellectual decay and vital demise:

> *"In the end, modern man drags an immense amount of indigestible knowledge stones around with him which on occasion rattle around in his belly as the fairy tale has it. This rattling betrays the most distinctive property of this modern man: the remarkable opposition of an inside to which no outside and an outside to which no inside corresponds, an opposition unknown to ancient peoples."* (Nietzsche, F. *On the Advantages and Disadvantages of History for Life,* 1900/1980)

It is evident that epistemic and axiological challenges are mutually dependent and that problems of risk, resilience and sustainability governance cannot be solved in isolation from problems of education. Governance and education must form a synergy through inquiry problem based learning that rests on the philosophical foundations of general systems theory, Bayesean reasoning and pragmatic consequentialism. General systems theory provides the basis for a process view of reality, which facilitates the representation of the inter-linking information flows (feedback) between systems components. Bayesean reasoning provides the theoretical and empirical basis not only for updating a-priori beliefs but also weighing the relevance among multiple priors. Pragmatic consequentialism allows preferences, objectives and decision alternatives to be weighed and ranked in a consistent and transparent way with respect to the outcomes of actions – and this in turn serves the ultimate goal of achieving informed preferences for actions of governance.

In the collection of papers that make up this thesis, epistemic and axiological challenges to the sustainable development of human civilization are explored for the purpose of defining a scientific paradigm through which they can be optimally addressed. As such the overarching motivation for the research undertaken is to contribute to the foundation of a unified theory of risk, resilience and sustainability that may provide the basis for informed preferences, decisions and actions in pursuit of sustainable well-being.

1.2. OBJECTIVES OF THE THESIS AND RESEARCH QUESTIONS

The principal objective of this PhD project is to establish the theoretical and methodological basis for an integrated risk, resilience and sustainability science that provides the logical basis of an education for governance.

A science is to be understood as a structure for the organization of knowledge, with the following essential characteristics:

(i) a set of decision problems to be addressed,

(ii) a set of concepts that describe and explain phenomena relevant to the scope of (i);

(iii) a topology of the relations contained in (ii)

There are ubiquitous references in the scientific and gray literature over the past several decades to an emerging risk or emerging sustainability, or emerging resilience science. Indeed these knowledge domains have grown significantly in that period (see Nielsen and Faber 2019) in terms of research output, and some efforts have been made to formulate a theoretical and methodological basis for a sustainability science (e.g., Kates et al. 2001) or a risk analysis science (e.g., Aven 2018). Research integrating risk, resilience and sustainability into a common scientific and operational framework is, in comparison, at the vanguard in the state-of-the art (see e.g., Faber 2018). The integration of these three knowledge traditions into a unified discipline with a common set of concepts, common methodological basis for causal reasoning and a common set of problems that can be addressed through contextually driven trans-disciplinarity is the intended outcome of the present PhD study.

The research questions pursued to this end are:

Q1. What are the trends and challenges driving research in the knowledge domain of risk?

Q2. To what extent are resilience and sustainability considerations integrated in the knowledge domain of risk?

Q3. What are the benefits to decision-makers and stakeholders at different scales of integrating risk, resilience and sustainability considerations into a common scientific and operational framework?

Q4. Are trends and challenges driving research in the knowledge domain reflected in educational practice?

Q5. What are the generic theoretical underpinnings (concepts and methods) of risk analysis that are applicable to different kinds of hazards, academic disciplines, and application areas?

Q6. What classification methods can be used to develop a domain ontology?

Q7. What logical criteria should be used for including/excluding a concept and relating concepts topologically?

Q8. What design methods can be used to develop a blueprint for the design and planning of educational offers, for which the domain ontology provides the structuring principle such that research and education may evolve concurrently and relative to the challenges posed in a given decision context?

Q9. What design principles, methods and tools can be used for the visualization of the ontology and the blueprint in order to most effectively communicate the logic of the design to stakeholders and users?

In the papers included in this thesis, the challenge of providing a knowledge structure based on the principles of unity in multiplicity and a shared language among disciplines and cultures is thus taken up by establishing:

(i) Rules for classification of hazards that are logically consistent with the principle of unity in multiplicity;

(ii) Rules for classification of concepts that enable a flat but structured domain ontology;

(iii) A domain ontology of concepts for an integrated science of risk, resilience and sustainability generic of application area; and

(iv) A blueprint for the design and planning of educational activities in support of governance of inter-connected systems.

1.3. THESIS OUTLINE

Table 1 provides an overview of the organization of the present thesis. It shows how each chapter is related to stages in the research process as well as the main outputs from each chapter with respect to the entire research design. In the rest of Section 1.3 the contribution of each chapter to the thesis is elaborated.

Chapter 1 is an introduction to the problem context. It discusses the epistemic and axiological challenges and their inter-relations for the knowledge tradition of risk, together with the motivation for integrating risk, resilience and sustainability into a unified science. Because this motivation entails bringing about epistemic and behavioral changes in addressing governance challenges, a pragmatic research design philosophy is chosen that seeks a synergy between research and education, knowledge and practice through the radical constructivist approach of inquiry problem based learning. In this manner, the research objectives and research questions are introduced relative to the problem, to which the undertaken research seeks to provide a solution.

Chapter 2 provides an overview of the research design. This includes a description of the research philosophy, research approach, methodological choice, research strategy, time horizon, and data.

Chapter 3 is the first of the seven papers that make up this thesis. The paper is a large-scale bibliometric literature review of the state-of-the-art in risk, resilience and sustainability between 1990 and 2017. This study has three functions within the overall PhD project.

Table 1 Logical organization of the thesis.

Stage in research process	Thesis chapter	Research output
Problem Definition	Chapter 1 Introduction	Problem-context description as a set of challenges an integrated risk, resilience and sustainability science can address
Methodological approach	Chapter 2 Research design	Action plan for research process
Data collection & analysis	Chapter 3 Paper 1 Nielsen, L. and Faber, M.H. (2019) *Impacts of sustainability and resilience research on risk governance, management and education*	Situation assessment state-of-the-art research: - Bibliometric analysis of volume, disciplinary composition, geographic, institutional and author distribution of research over 30 year period - Identification of set of misfits stemming from research best practice (to be used in model building Ch. 5) - Identification of set of possible concepts that describe and explain phenomena related to the scope of problem-context (described in Ch. 1)
Analysis	Chapter 4 Paper 2 Nielsen, L. Tølbøll, G.S., Qin, J., Faber, M.H. (2019) *Faith and fakes – dealing with critical information in decision analysis*	Situation assessment best practice in decision making: - Identification of causal factors driving misfit between knowing and doing (i.e. between science and decision-making) - Identification of a conceptual framework for unification of disparities causing the knowing-doing misfit
Synthesis	Chapter 5 Triad of papers 3-5 Nielsen, L. and Faber, M.H. (submitted 2020) *Toward an information-theoretic ontology of risk, resilience and sustainability and a blueprint for education (Part I – III)*	Model building: - Part I : Definition of model boundaries based on problem context (Ch. 1) and situation assessments (Ch. 3, Ch. 4, Annex) - Part II: Establishment of a flat domain ontology of concepts for an integrated risk, resilience and sustainability science - Part III: Establishment of a blueprint for education design as a dynamic template of contextually evolving misfits, requirements and best available knowledge (concepts)
Example application	Chapter 6 Paper 6 Nielsen, L., Hansen, M., Qin, J., Faber, M.F. (2018) *Flood risk and indicators of social cohesion in the Western Balkans*	Partial model testing (proof of concept one of multiple model functions): - Hypothetical example of how the blueprint for education developed in Ch. 5 can be applied at the project level of inquiry problem based learning
Example application	Chapter 7 Faber, M.H., Qin, J. and Nielsen, L. (2019) *Objectives and metrics in decision support for urban resilience*	Partial model testing (proof of concept model logic): - Hypothetical example of how the logic of the entire model developed in Ch. 5 can be applied in the context of governance for urban resilience
Analysis	Chapter 8 Results and Discussion	Answers to research questions
Synthesis	Chapter 9 Conclusion and Outlook	Expected impacts of research and future work

First, it provides a longitudinal situation assessment of the state of research in the three knowledge traditions of risk, resilience and sustainability and the extent to which they are presently integrated. This includes a historical timeline of the evolution of research in terms of volume; distribution of disciplinary composition; and distributions of the geographic origin, academic institutions, and authors producing the research. Based on this bibliometric data, an analysis of the trends driving research as well as an analysis of the impacts for governance, management and education is presented following a qualitative hermeneutic method.

The second function of the bibliometric study is to provide insight into the causal processes responsible for the gap between knowing and doing, with a focus on ineffective best practices in research. Central among these are practices stemming from:

(i) Context-dependent representations of physical phenomena such as the practice of classifying hazards by their source of origin (this is elaborated in Chapter 4);

(ii) Lack of homogeneity among disciplinary contributions to the general body of knowledge on risk, characterized by multiple competing definitions of concepts (including instances of polysemy and homonymy) and arbitrary, unsystematic use of methods and metrics; and (iii) Separation of risk, resilience and sustainability knowledge domains into their individual disciplinary traditions, of which they have emerged as sub-disciplines in terms of theories and methods.

Based on these causal considerations, a set of misfits stemming from inadequate research practices is identified. The same causal considerations are observed to apply to the domain of education (see e.g., Nielsen, L. 2020) and are used as the basis for developing a set of misfits stemming from inadequate education practices. The effects of these two pairs of misfits represent a gap between research and education, which in turn has indirect consequences for the effectiveness of governance practices. The misfit pairs thus play a central role in identifying educational requirements upon which a blueprint for education is designed and presented in Chapter 5, Part III.

Finally, the third function of the bibliometric study is to identify a set of potential concepts that are of mutual interest to the knowledge traditions of risk, resilience and sustainability because they are used to describe and explain phenomena that concerns a common set of decision problems. This is first done on the basis of statistical cluster analysis of a corpus of 0.5 million scientific publications resulting in network visualizations of terms (concepts) and links. Terms have a label and a circle, whose size indicates the number a term occurs in a title or abstract. The strength of a link between two terms expresses the number of times the terms occur together. But while the clustering method offers a transparent basis for identifying concept alternatives for a domain ontology, it is insufficient in itself as a criterion for deciding the relevance of individual concepts. Indeed, the paper argues that some of the most obvious candidate concepts in terms of the frequency of occurrence and the strength of their co-occurrence are concepts that do not meet the scientific criteria of the planned ontology: generic application and freedom from a-priori value setting (this is discussed in depth in Chapter 5, Part I, Section 3 and in Chapter 5, Part II, Section 4.1). For this reason, the statistical data mining approach is complemented by a qualitative hermeneutic method of data interpretation.

Like Chapter 3, Chapter 4 aims to identify the causal factors responsible for the gap between knowing and doing but in this case through a situation assessment of the logic and principles of present practices in decision-making.

Three practices are identified as central to why and how decisions and actions are presently made such that the gap between knowledge and action continues to widen. A logical scheme then is proposed for how the concept of 'information' and methodological approaches based on information modeling can be instrumental in diminishing the gap.

The first of these practices relates to cognitive biases associated with the perception of hazards as being qualitatively different when they are experienced as intentional or non-intentional. These biases reflect deep a-priori beliefs about the objective or subjective nature of reality, what can be measured quantitatively or qualitatively, what phenomena can be predicted and what remains necessarily unpredictable, what constitutes necessary and sufficient conditions for truth, and what may be counted as evidence. Risk perception and communication are prominent on the lists of misfits for research and education, and are clearly a major challenge to decision-making. Yet research in this area has stalled since the 1990s (Nielsen and Faber 2019) while in education, risk perception is rarely, if ever, part of curricula. Risk communication is addressed only marginally in the context of emergency communication protocols. For this reason, both in the design of the ontology (Chapter 5, Part II) and the education blueprint (Chapter 5, Part III), much effort has been expended on minimizing misfits related to perception and communication.

The second practice that widens and deepens the gap between knowledge and action in practice relates to the classification of hazards by their source of origin. This practice is the cause for classifying hazards into natural or anthropological, and further into accidental or intentional. Based on this practice, disciplinary specializations have multiplied to address a Pandora's box of hazards from earthquakes to oil spills to space debris to cyber attacks, etc. contributing to the general body of knowledge on risk by adding to the plethora of multiple technical definitions for single concepts, debating the validity of their endorsed methods, and waging disciplinary-cultural wars on what metrics should legitimately be used to measure phenomena. Furthermore, this practice leads to partiality (both in the sense of bias and incompletion) in risk assessment, which leaks inefficiency and inefficacy in the subsequent stages of risk management, governance and regulation.

A new hazard classification is proposed in Chapter 4, which classifies hazards into five information types based on the common sets of characteristics associated with their consequences. This classification enables the modeling of hazards and risks such that system boundaries are defined according to the context, i.e. the extent in space and time of the sum total of direct and indirect consequences, to the best of available knowledge. Further affordances of this classification scheme include the potential for replacing the single sector approach to governance with a multi-hazard and all-hazard approach (discussed in Chapter 5, Part I, Sections 2.2.1 and 4); and replacing the disciplinary approach within research and education with contextual trans-disciplinarity such that the appropriate mixture of disciplinary subject matter and methodology is determined on the basis of each problem (context) (discussed in Chapter 5, Part III, Section 4).

Finally, the third practice splitting knowledge and action in practice relates to the reliance of risk managers on procedural frameworks and guidelines (e.g. ISO procedural frameworks, DRM frameworks), which are not adaptive to context dynamics. In Chapter 4 it is argued that the preference for procedural frameworks should be abandoned in favor of scientific frameworks based on Bayesian reasoning. This is because the latter enable not only the updating of prior to posterior knowledge (evidence based on the degree of belief) but also enable the assessment of the relative importance among possible prior beliefs (i.e. pre-posterior value of information analysis).

It is thus in Chapter 4, where the concept of 'information' is identified as the common denominator for linking risk, resilience and sustainability. A system representation of the information flows between human actors involved in decision processes (stakeholders, decision-makers and risk specialists) and indicators of system states and consequences is established. Based on this, five information conditions are identified that can influence the outcome of decisions. These information conditions form the basis for a novel hazard classification by information type instead of the current practice of classifying hazards by their source of origin.

When anchored in the concept of 'information', an integration of the heretofore separate knowledge traditions of risk, resilience and sustainability into a unified science is logically enabled. What is more, the information basis provides the logical foundation for such science to be truly generic, independent of application area, and free of a-priori value settings. The label 'information theoretic' is used in Chapter 4 and the triad of papers that constitute Chapter 5 as an umbrella term for theories and methods based on Bayesian reasoning, including probabilistic methods, systems theory and its logical basis in process philosophy, affordance theory, embodied cognition theory, and the Chinese Daoist school of philosophy. Together, these provide the logical basis for a domain ontology of concepts of an integrated risk, resilience and sustainability science whose function is to help in-form the preferences, decisions and actions of individuals and collectives (the ontology and its functional affordances are presented and discussed in the triad of papers included in Chapter 5).

Chapter 5 consists of a triad of papers (Part I – III), which collectively aim to lay the foundations for an integrated risk, resilience and sustainability science. That includes:

(i) formulation of the purpose, scope and target audience for this integrated science (Part I);

(ii) establishment of the logical premises through a domain ontology of concepts generic to the phenomena the individual traditions of risk, resilience and sustainability aim to understand and model (Part II)); and

(iii) development of a model (blueprint for education design) for how (ii) can support a synergy between research and education (inquiry problem based learning) as the instrumental means of achieving the objectives of governance based on informed (rather than stated or revealed) preferences (Part III).

The problem addressed in the triad of papers is formulated as a design problem, for which matter-form-function reasoning elaborated in the architectural design methodology of Alexander (1967) provides a paradigm for best-fit problem solving. As a truly generic paradigm for creative synthesis, it enables an analogy to the process of structural design in civil engineering where function-form-matter logic similarly underlies the construction of any artifact in the built environment. Whether it is applied in the context of biology, ecology, engineering, architecture, philosophy, or art, a key characteristic of this approach is its emphasis on context, which is to be understood as the dynamic interaction of entities in motion.

In the triad of papers included in Chapter 5, matter is information – the immaterial material and the contents of form. In the design of the domain ontology, matter means the set of all concepts possibly relevant to the set of decision problems a unified science of risk, resilience and sustainability may addressed, to the best of knowledge. Form means the structural arrangement of the set of concepts in a domain ontology. In Chapter 5 form is described as a flat hierarchy. What this means is that the concepts are grouped categorically, but no category is more or less significant than another one prior to a formulation of a particular question (decision problem context). To explain how particular concepts acquire meaning or significance only in relation to a context, two planes in the ontology are distinguished: flat and semantic planes. The flat (also referred to as formal) plane is based on the concept of non-informative priors from Bayesian probability theory (Part I, Section 2.2.4). The flat plane of the ontology is presented and discussed in Part II of the triad. The semantic plane is where a concept's relative significance is weighed in relation to the context of education. In interaction with misfits and educational requirements, concepts from the ontology form a dynamic model (blueprint) for education. The semantic plane is the subject of Part III of the triad.

The challenge to make multiple disciplinary traditions inter-operable in a common framework is immense. Its importance cannot be overstated in the context of developing objectives and metrics on which to base strategies for resilient and sustainable governance. Since these objectives and metrics involve many global challenges, they cannot be formulated based exclusively on Western conceptual and cultural (behavioral) traditions. To this end, a shared language for an integrated risk, resilience and sustainability science is instrumental to not only solving the problems that make up the agenda of this science, but also to ensuring that the right questions are asked. A shared language is not a matter of synchronizing glossaries of technical terms among disciplines, or importing - exporting neologisms across speakers of different languages. A shared language in Chapter 5 is discussed in terms of a shared conceptual system.

To address the possibility of a shared language among disciplinary traditions within the Western conceptual system, the research tradition of embodied cognition provides an empirically tested model of image schemas as dynamic structures for categorizing experience (Lakoff and Johnson 1999). Biologically in-formed but undetermined, image schemas interact with the context (sensory, cultural, spatio-temporal) in producing meaning, not in a symbolic sense-reference manner but in action. Image schemas are thus used to unravel the perceptions that in-form the con-ceptions included in the ontology (Chapter 5, Part II, Sections 5-6)

To address the possibility of a shared language among cultural traditions, Chapter 5 goes to some length in trying to find a basis for a shared language between the philosophical-cultural traditions of West and East. The Chinese tradition is selected as it is typically perceived as antithetical to Western thinking. Starting with the introduction of categorical pairs (the Chinese ontological unit) as complements to the individual categories (the Western ontological unit) in the ontology (Part II) to placing side by side in the educational requirements of the blueprint (Part III) the Chinese notion of *daoxue* (learning the way) and the Socratic ideal of “following the argument where it leads”, a rudimentary step has been made toward this non-trivial challenge.

In Chapters 6 and 7 examples are provided for the application of the theoretical contribution of this PhD study to education and to governance.

Chapter 6 includes a paper written collaboratively by students and teachers in the context of an EU Erasmus + project aimed at developing educational designs in the context of disaster risk management and promoting knowledge sharing in a consortium of countries from the Western Balkans, Central Europe and Scandinavia. The specific problem context of the paper is to investigate a possible correlation between social cohesion and disaster recovery, which may form the basis for policy in the geographic region known as the Western Balkans. The results presented in this paper are not of direct relevance to the PhD’s goals and objectives. However, it was considered relevant to include in this thesis as the process of its production served as the basis for the design of one of the multiple adaptive learning pathways described in Chapter 5, Section 5. The same paper provides the basis for the sketch of a repository of digital learning objects in support of adaptive learning navigation described in Chapter 5, Annex A.

Chapter 7 includes a paper to which the author of the present PhD has contributed (in Sections 1-3) to the theoretical basis of a decision framework for the governance of risk, resilience and sustainability based on informed rather than stated or revealed preferences. The paper is considered relevant for the thesis as it provides an example application for how the theory developed in the present thesis can contribute to the applied decision context of urban resilience.

In Chapter 8 results are discussed in relation to the thesis' objectives and research questions. Chapter 9 closes the thesis with a reflection on the thesis contribution to the general body of knowledge on risk, resilience and sustainability and an outlook for future activities.

CHAPTER 2. RESEARCH DESIGN

The research design of the present thesis is structured according to a model developed by Saunders et al. (2015) to facilitate the planning of research activities, including research philosophy, approach and methodologies. In Fig. 2 a visualization of the research design components and choices is provided in accordance with this model.

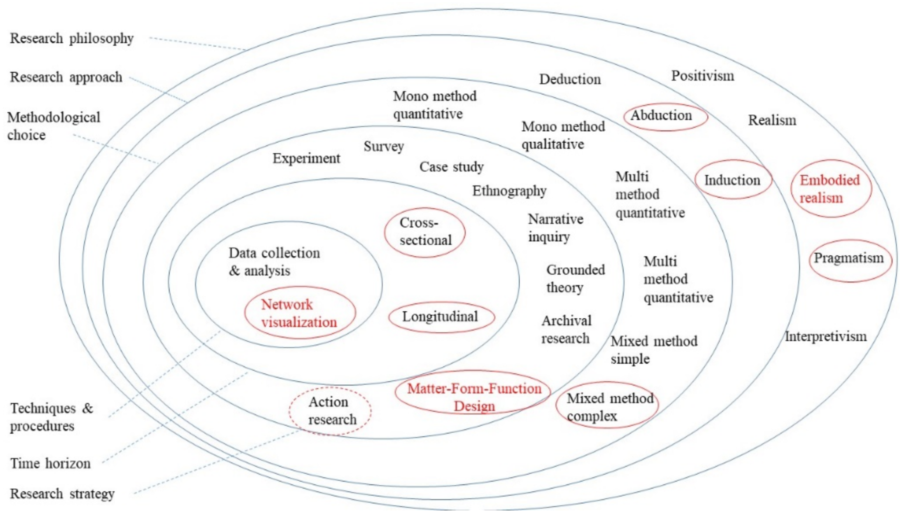

Fig. 2 Research design based on the model of Saunders et al. 2015.

In the following, the layers of the model are described and an explanation provided for the specific choices made in the context of the present PhD thesis. The selected options are circled in red. A dash circle indicates that a given option was partially adopted. Options which are not part of the original model but were added by the author to more specifically describe philosophical positions, research strategies and data techniques appear in red font.

In the original formulation of the model by Saunders et al. (2015), the initial stage of the research process is associated with the outer-most layer, i.e. the layer called 'Research Philosophy'. However, the sequence of steps followed in the actual research of this PhD project has been the reverse, i.e. initial point for inquiry is data. Surely, whether a bottom-up or top-down approach is chosen is also a philosophical question. The data driven phenomenological approach chosen in the thesis is coherent with the philosophical position of embodied realism, so the author feels justified in adding this option to the alternative research philosophies included in Saunders's model. On the compatibility between embodied realism and pragmatism, the reader is directed to Chapter 5, Part II, Sections 5-7.

In the rest of this section the components of the research design are described and explained in accordance with Saunders et al. (2015):

(i) **Research Philosophy.** Research philosophy refers to the assumptions influencing the researcher's view of the nature of the phenomenon that is being investigated. The three overarching positions are described as ontology, epistemology and axiology, which are further disaggregated to four main philosophical positions, namely positivism, realism, interpretivism, and pragmatism.

The research philosophy of the present PhD follows the pragmatist tradition. According to Kelemen and Rumens (2008) pragmatism sees the relevance of research in the context of supporting action. Thus the significance of an idea (or research result) is to be measured in terms of its practical consequences. The research questions of this PhD study focus on the consequences of the present state of dispersed and fractured theoretical and methodological knowledge on risk, resilience and sustainability among multiple disciplines and application areas with the purpose of finding a way to unify knowledge and practice into a common framework. In light of the focus on consequences of decisions and actions in the present PhD study, pragmatism is identified as the most suitable philosophical position.

Furthermore, it should be stated that risk, resilience and sustainability are concepts that are inherently pragmatic in that they are measured based on consequences and outcomes of choices in selecting decision alternatives for actions. Hence, Pragmatism, in the form of consequential utilitarianism, is the overarching axiological position taken in this thesis. Since a pragmatist research philosophy does not specify a particular philosophical position, it should be stated that the particular philosophical position endorsed in the present PhD study is the position outlined in Lakoff and Johnson (1999) as embodied realism. Embodied realism is a synthesis of objectivism and relativism based on the abductive logic of Bayesian reasoning, according to which perception and conception stand in a relation of mutual interaction and feedback. This position is exemplified in process philosophy and systems theory.

(ii) **Research Approach**. Research approach refers to the choice of logical argumentation: deduction, induction, abduction.

In the present PhD project inductive and abductive reasoning is applied. Inductive reasoning is applied when collecting and exploring quantitative and qualitative data for the purpose of identifying patterns, explaining trends and generating a conceptual framework on which a unified theory of risk, resilience and sustainability can be built and a new paradigm for education established. Abductive reasoning is applied in the design of a domain ontology for risk, resilience and sustainability and a blueprint for education in all the design choices following from Bayesian reasoning and embodied cognition.

(iii) **Methodological Choice.** Methodological choice refers to the options of conducting quantitative or qualitative research or a combination thereof.

A mixed method approach is applied in the present PhD study. A mixed approach is compatible with the adopted pragmatist philosophical position. A positivist position would, theoretically, have limited the methodological choices to quantitative methods; the interpretivist position – to qualitative methods. Pragmatism, being consequence rather than cause oriented, has in principle no allegiance to a-priori theoretical considerations. Mixed methods was therefore selected as the most appropriate method design within the context of the present PhD study because of its potential to elaborate, enhance, confirm, further specify, illustrate and link data findings and data interpretation.

(iv) **Research Strategy.** Research strategy is a description of the type of research to be carried out. In Saunders et al.'s (2015) model, these strategies include experiment, survey, archival research, case study, ethnography, action research, grounded theory, and narrative inquiry.

Clearly, the choice of research strategy is influenced by the purpose of the research. In the list of research strategies presented by Saunders et al. (2015) three purposes of research are implied: explorative, descriptive, and explanatory. The present PhD is undertaken for all these purposes, but in addition, it includes prescriptive knowledge in the sense that it seeks to develop a solution. The research strategy adopted is thus the generic strategy for building things, which in the thesis is described as matter-form-function design.

Action research has a number of similarities with design research as it is based on developing solutions to real problems through an iterative and emergent process of inquiry. For Action research, however, stakeholder participation in generating a solution is a critical component (Greenwood and Levin 2007). In the context of the present PhD study, this requirement was not pursued because the scope of the thesis is to establish the logic for a conceptual framework upon which different actors can engage in constructive activities. It is at those later stages that participation becomes crucial to the fulfillment of objectives.

(v) **Time Horizon.** Time horizon refers to whether research is cross-sectional (provides a snapshot representation in a particular instance) or longitudinal (relies on repeated collection of data over extended period).

In the context of the problem statement for this thesis, the consideration of a time horizon applies chiefly to the stage of the research process related to the system identification, i.e. the situation assessments of best practice in research, education and decision-making. All three assessments provide a longitudinal perspective.

(vi) **Data Collection and Analysis.** Data collection refers to the type and source of data. Data analysis refers to the techniques and procedures for analyzing the data reliability and validity.

In the present thesis data collection includes:

- Primary data
  - Quantitative and qualitative observations about best practice in research, education and decision-making
  - Identification of a set of concepts common to the three knowledge traditions of risk, resilience and sustainability on the basis of statistical cluster analysis of co-occurring terms in a corpus of 0.5 million peer-reviewed journal articles, indexed on the Web of Science
- Secondary data
  - Identification of available theories and methods on risk, resilience and sustainability across sciences, disciplines and application areas
  - Identification of available theoretical and operational frameworks for design of knowledge domains.

In the present thesis data analysis includes:

- Pattern identification in the data by means of cluster analysis complemented with hermeneutic interpretation;
- Using inferential-abductive Bayesian reasoning, the establishment of logical rules for: (i) hazard classification based on information type; (ii) a flat domain ontology of concepts; (iii) contextual trans-

disciplinarity as a weighed relevance of the non-informative priors of the flat ontology;

- Using matter-form-function reasoning: (i) reversing the logical sequence of goal setting from a transmission (e.g., mathematical communication theory) to an interaction (e.g., systems theory) model of communication; (ii) using the latter logic to justify a model for adaptive learning that is sample rather than example-driven.

In the problem-context of the present PhD study, the method of network visualization has been central not only as a descriptive statistics method for exploratory data analysis in the situation assessment stage of the research process, but as a technique for visually bringing out the logical relations in the ontology and blueprint for education. As Saunders et al. (2015) research design model does not address the issue of how the research is communicated, the category 'network visualization' has been added to account for this important technique used in the present thesis.

Formally, network visualization is a method of mathematical graph theory, whereby a structure is constructed through a set of vertices (nodes) connected by edges (links). The applied function of graph theory is the visualization of elements in a given topography (space), together with their interactions in order to facilitate understanding of the structural composition of relations and form a visual basis for inferential reasoning.

In a broader sense, visualization is a method for synthesizing perceptual (derived from the senses) with conceptual (derived from logic) information for the purposes of sense-making, orientation and action in a given context. When the topography of a network is a mental space such as the mind, which allegedly houses conceptual information, cognitive science methodology provides semantic input to the formal generic method of graph theory. Theoretical and empirical findings of embodied cognition research provide the methodological basis for classification and categorization rules in the ontology and blueprint.

CHAPTER 3. IMPACTS OF SUSTAINABILITY AND RESILIENCE RESEARCH ON RISK GOVERNANCE, MANAGEMENT AND EDUCATION

Nielsen, L., & Faber, M. H. (2019). Impacts of Sustainability and Resilience Research on Risk Governance, Management and Education. *Sustainable and Resilient Infrastructure*.

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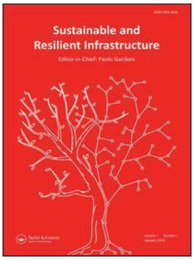

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Impacts of sustainability and resilience research on risk governance, management and education

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Impacts of sustainability and resilience research on risk governance, management and education

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ABSTRACT
Substantial increase in research on sustainability and resilience is changing the traditional disciplinary boundaries of risk assessment and management. To understand the implications of this change and define future strategic directions for risk education, we conduct a comprehensive exploratory study of the knowledge domains encompassing risk, sustainability and resilience between 1990 and 2017. Combining quantitative bibliometric techniques such as term co-occurrence and bibliographic coupling, we show the historical evolution of the knowledge domains of risk, sustainability and resilience on a to-date unprecedented scale, based on 442,171 scientific records. Based on a comprehensive background study involving more than 100 cluster network maps, in the present paper, we illustrate the different disciplinary contributions, important authors, geographic distribution of the research, and the organizations producing the research as well as the extent to which they are integrated into the knowledge domain of risk. A complementary qualitative analysis provides context to the concepts and trends identified in the bibliometric analysis, together with an outlined vision for future education in risk, sustainability and resilience science.

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Risk-informed decision support; resilience; sustainability; risk education

1. Introduction

The challenges of the present and future societies are substantial. The list of specific issues that must be dealt with in the short, mid and long terms is breathtaking. Among others, they include how to best deal with poverty-related diseases, climate change, resource shortages, social unrest, immigration, disturbances of critical infrastructure services, interruptions of business lines, economic crises, events of natural hazards, etc. The challenge for societal developments at global scale may be summarized as: identify possible paths for sustainable developments and ensure that society develops in accordance with these.

The objective to meet this challenge comprises a moving and partly blurred target. This is because our knowledge on what constitutes and facilitates sustainability is both rather limited and at the same time continuously evolving. We have limited knowledge with respect to future natural hazard events which affects sustainability, and whereas we may direct prioritization of technological and organizational developments, we cannot with certainty predict the potential benefits and dis-benefits of these.

It is important to appreciate that the character of the global scale societal challenges outlined above is no different to any decision problem in society at smaller scales, whether in the context of industrial enterprises, public governance or private households; in the face of uncertainty and lack of knowledge, decision alternatives must be identified and ranked in accordance with their expected value of benefit (utility) with due account of limited budgets (e.g., money and resources) and possible constraints imposed by law and regulation, see e.g., Faber (2018, Routledge Handbook). The fundamental issue is that we need to be able to establish a basis for informed decision-making, accounting for our preferences for outcomes of different decision alternatives in full consistency with the best available knowledge – and we must act upon this decision basis. Sustainable developments at global scale depend on our ability to identify and decide rationally among possible relevant decision alternatives at lower scales.

The concept of risk as a measure to deal with and communicate the uncertainties associated with the outcomes of decisions has served to inform societal developments over many decades, see e.g., Hartford (2008). Especially over the last half-century, the concept of risk as a means for decision support has evolved to become an integral part of daily applied best practices in a very wide spectrum of industrial and governmental decision contexts (Soares, 2010). Numerous risk-based regulations of societal activities and frameworks for the

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management of natural disasters and accidents have been developed and implemented (e.g., ISO 2394, 2015; ISO 31010, 2009; ISO 31000, 2018). The utilization of the concept of risk in support of decision-making has significantly contributed to the development of civilization and welfare as we know it today. Nevertheless, as pointed out in Faber, Stewart and Faber (2011) there are several issues impeding the exploitation of its full potential. These include cognitive biases, inadequate and/or inconsistent representation of uncertainty and lack of knowledge, inappropriate criteria for risk acceptability and not least neglect of, or inapt risk communication; in the quest of sustainable societal developments we need to resolve these issues.

By now it is generally understood that the development of decision support for sustainable societal developments must take basis in a joint consideration of society, environment and economy – with due consideration of inter- and intra-generational equity, see e.g., Brundtland (1987), Solow (1991), Faber and Rackwitz (2004) and Faber (2018).

However, until now the developments of and utilization of the concept of risk as a means for informing decisions have been governed by the specific needs arising in different application areas and societal sectors. As a result of this, there is a detrimental variability in the understanding, applied terminology and best practice use of the concept of risk across different application domains. Moreover, this variability not only limits the full benefit of the risk concept within individual application domains but also seriously impairs consistency of decision bases and practical impact when decision contexts involving two or more application domains, as when addressing sustainability, are considered. There is thus a strong need to understand and utilize the concept of risk and risk-informed decision support in a fully holistic perspective where all aspects affecting sustainable societal developments are addressed not individually, not sequentially but jointly.

Moreover, especially over the last 2–3 decades, it is increasingly appreciated, that the management of systems, including engineered, social and ecological systems constitutes a capacity-demand management problem, which is greatly supported by the concept of systems resilience. This perspective not only adequately captures the essence of the challenge of sustainable societal developments at global scale but also greatly facilitates decision support at smaller scales. Whereas it might be stated that many of the aspects covered by the concept of systems resilience are already included in more traditional concepts, which have evolved within individual application domains, such as systems reliability, safety, availability, etc., the concept of resilience is holistic and envelopes the context from a perspective where the interaction between technical systems, the environment and organizations are in focus as basis for providing services supporting welfare and sustainable societal developments.

Based on the foregoing brief outline of developments related to the concept of risk as a means of providing decision support for developments in society we now take basis in the conjecture that risk-informed decision support, enhanced by the concept of systems resilience provides an adequate basis for the identification of sustainable paths for societal developments. A very substantial challenge in this connection is how to synthesize this conjecture and how to educate the next generation of researchers and societal decision makers.

The present study aims to bring order among the multiplicity of concepts and perspectives that join research and discourse on risk, resilience and sustainability. Our main objective with this is to develop a blueprint for a learning design that integrates these concepts. The analysis presented in this paper together with an accompanying comprehensive data report (Nielsen & Faber, 2018) aim to provide the basis for the learning design in terms of relevant subject expertise that future risk education should be built on.

The study combines quantitative bibliometric analysis techniques with an in-depth qualitative and critical literature review of emerging disciplinary fields, concepts, ideas and problems that unite as a result of integrating risk, resilience and sustainability. These methods are used in a complementary manner as an attempt to address methodological challenges individually associated with them. Bibliometric analysis is based on statistical data, which may not always capture nuances that a specialist in a given disciplinary area might, based on a working knowledge of the field. Qualitative literature reviews produced by disciplinary experts, on the other hand, have a number of drawbacks such as selection bias and potentially insufficient degree of representativeness, especially in broader disciplinary fields. A traditional literature review is usually aimed at an audience of peers in a given discipline, whereas bibliometric analysis allows newcomers or outsiders to a discipline to gain an overall intellectual structure of a given knowledge domain. Finally, information visualization techniques utilized in this study such as bibliometric science mapping are not only a showcase for the nexus between science, design and communication but also a didactic instrument, which fits well with the overall aim to establish an understanding of the system comprising the knowledge domain and thereby inform on future directions for both research education in the area of risk-informed decision support.

Sections 1 and 2 outline the aim, scope and background for the research. Section 3, together with the accompanying data report,[1] describes the methodology behind the two types of bibliometric analysis. Section 4 presents the results of the bibliometric analysis. Sections 5 and 6 include a qualitative review and analysis of developments, key concepts and trade-offs associated with sustainability and resilience and the potential for their integration in a common risk framework. Here too, bibliometric information and visualizations are used complementarily. Sections 7 and 8 discuss the impacts of integrating risk, resilience and sustainability for risk governance, risk management and risk education, concluding with recommendations for future direction of risk education.

2. Methodology for the bibliometric analysis

Bibliometric methods are statistical text mining techniques that can facilitate the mapping of scientific fields through discovering patterns in the evolution, structure and composition of large volumes of scientific literature. In the present study we use two such techniques – co-occurrence network of terms and bibliographic coupling – to visualize and analyze the knowledge domains of risk, sustainability and resilience for the period 1990–2017 based on 442,171 records extracted from the Web of Science (WoS).

Because risk, sustainability and resilience research do not constitute any particular scientific field but are studied as part of multiple fields in the natural, applied and social sciences, our approach encompasses the following steps:

(1) Identification of search terms relevant for risk, sustainability and resilience based on expert discussion between the authors;
(2) Data collection;
(3) Bibliometric networks construction;
(4) Data analysis, results and recommendations

2.1. Step I

In step I, we identified a total of 26 search terms relevant to the knowledge domains of risk, sustainability and resilience, which we further delineated into three groups (Table 1).

The search terms in Group 1 are the most general and contextually broad terms that refer to the knowledge domains of risk, sustainability and resilience as well as the combinations thereof. As research in the domain of risk has a significantly longer history and volume of scientific publications than that of either sustainability or resilience, we have split that into approximately three decades: 1990–2000, 2001–2010 and 2011–2017. Nomenclature in the risk domain is highly inconsistent in discriminating among aspects of risk research such as assessment, management or analysis. The use of these terms is strongly dependent on the sub-discipline undertaking research on risk. To be as comprehensive as possible, we designated our risk search term to encompass all three possibilities: Risk Assessment OR Risk Management OR Risk Analysis. We introduced further the three combinations Risk AND Sustainability, Risk AND Resilience and Risk AND Sustainability AND Resilience in order to facilitate analysis on the extent of mutual integration among them.

In Group 2 the search terms are chosen to represent the multi-disciplinary perspectives in which research on resilience is undertaken. There are three such more or less distinct contexts – Ecology, Engineering and Disaster research, however in addition to the overlaps among them, here too matters of taxonomy necessitated that we subdivide the ecology domain into Ecological resilience and Spatial Resilience; the engineering domain – into

Table 1. Expert-selected search terms.

Group 1 (knowledge domains)	Group 2 (multi-disciplinary perspectives)	Group 3 (concepts)
Risk 1990–2000	Ecological Resilience	Planetary Boundaries
Risk 2001–2010	Spatial Resilience	Natural Capital and Ecoservices
Risk 2011–2017	Engineering Resilience	Circular Economy
Sustainability	Infrastructure Resilience	Social OR Urban Metabolism
Resilience	Robustness	Inclusive Economy OR Inclusive Wealth OR Inclusive Growth
Risk AND Sustainability	Disaster Resilience	Degrowth
Risk AND Resilience	Community Resilience	Adaptive Governance
Risk AND Sustainability AND Resilience	Urban Resilience	Social Cohesion
	(economic) Development Resilience	Social Ecological Systems

Engineering Resilience, Infrastructure Resilience, and Robustness; and the Disaster domain – into Disaster Resilience, Community Resilience, Urban Resilience, and (Economic) Development Resilience.

The search terms in Group 3 are specific concepts that underpin the theoretical principles of the overarching risk, sustainability and resilience domains. The choice of search terms here was guided by the qualitative literature review and analysis performed prior to the bibliometric analysis and reflects the themes that emerged as trends in the evolution of risk research as a result of integrating sustainability and resilience considerations.

2.2. Step II

Based on the expert-identified search terms, we extracted a total of 442,171 records from the Web of Science (WoS) database. Only journal articles and book chapters were included. As a general rule, we excluded records which were categorized as part of medical research on risk as this very large sub-domain of risk research was not deemed of relevance to the scope of our study.

2.3. Step III

2.3.1. Term co-occurrence network visualizations

To provide a general overview of the significant topics related to risk, sustainability and resilience research, we constructed term maps using the VOSviewer software. VOSviewer is a text mining software based on the Apache OpenNLP toolkit, which performs part-of-speech tagging and uses a filter to identify noun phrases (terms), for which a relevance score is calculated. A low relevance score indicates that a term co-occurs with other terms following a more or less random pattern whereas a high relevance score is attributed to noun phrases that co-occur mainly with a limited set of other noun phrases (Van Eck & Waltman, 2014). Terms are derived from the titles and abstracts of the records downloaded from WoS. We have largely excluded terms with low relevance scores, which tend to be too general and non-context specific (e.g., 'conclusion', 'findings', 'originality value', 'future direction').

A network visualization is composed of terms and links. Terms are represented by their label and a circle. The size of a label and a circle depends on the number of publications that contain the term in the title or abstract. We have chosen the binary counting option in each map, which means that the number of times a term occurs in the title and abstract is of no significance, rather a term that occurs only once is treated in the same way as one that occurs multiple times. We set the minimum criteria for the inclusion of a term as follows: for 1–1000 publications at 10; 1000–5000 at 50; 5000–10,000 at 100; and above 10,000 at 200. This helps to deal with the problem of very large networks in a consistent manner.

Links are connections or relations between two terms. Each link has a strength, which depends on the number of publications where two terms occur together. The stronger the link, the thicker the line is in the visualization. Terms that co-occur often are located closer to each other whereas terms that have no or almost no co-occurrence are located farther apart. Terms are also grouped together into clusters. A cluster represents a set of terms strongly linked together. A term may belong to one cluster only. In the visualizations, a term has the same color as that of the cluster it belongs to. The clustering technique is based on an algorithm for solving an optimization problem and is discussed in detail in Waltman et al. (2010) and Waltman and van Eck (2013).

In most network visualizations, the clusters display a rather consistent representation of the multidisciplinary structure of a field and its subfields. In addition to the visualizations, we have provided tables listing the terms in their respective clusters, the number of occurrences of each term and the total strength of the links of a term with other terms. We use a color scheme in the tables to highlight (i) the significant concepts and notions related to risk, sustainability and resilience that are also discussed in their proper contexts in the qualitative analysis (blue color) and (ii) the appearance of the exact search terms identified during our expert discussion in Step I (red color).

2.3.2. Bibliographic coupling network visualizations

In a bibliographic coupling analysis the relatedness of items is based on the number of references they share: the larger the number of shared references, the stronger the bibliographic coupling is between them. In our study, we have chosen to represent the relatedness of three items: authors, countries and organizations. In each case, we have chosen the fractional counting method, which purposefully diminishes the importance of highly cited publications. This allows us to be inclusive of perspectives that are not bound by what passes as significant research based on citation numbers. The difference between full counting and fractional counting in technical terms is explained in detail in Van Eck and Waltman (2014).

We have chosen to display the bibliographic coupling of authors and organizations as density visualizations and the bibliographic coupling of countries as network visualizations mainly because the density format is clearer to read in the case of large networks but also because they help to visually identify knowledge hubs and subject experts at a glance. For all density visualizations, item density rather than cluster density is displayed. As with the network visualizations, items (authors and organizations) are represented by a label, whose size is indicative of its relative importance. The colors in the density visualizations range from blue to green to red, which reflects the density of terms at each point. The 'hot' red sections of the map indicate a large number of items in the neighborhood and high weights of the neighboring items. In contrast, the 'cold' blue sections represent neighborhoods with a small number of items and low weights of neighboring items. The technical implementation of the density visualization is discussed in Van Eck and Waltman (2014).

To create the bibliographic coupling network visualizations the same search terms and WoS records were used and a similar procedure was followed as that of the term co-occurrence. After uploading the data into the VOSviewer software and selecting the fractional counting options, a minimum number of (i) publications by author, (ii) publications by country, and (iii) publications by organization were chosen, adjusting that according to the number of publications we had available for each search term.

2.4. Step IV

The data results, analysis and recommendations are the focus of the present paper.

3. General observations

3.1. Historical evolution and growth rate of risk, sustainability and resilience research (1990–2017)

In Figure 1 the historical evolution of research in the domains of risk, sustainability and resilience is illustrated, showing the somewhat longer history of research in risk as well as the significantly larger volume of publications. While all three domains show an upward trend, sustainability and resilience research are still relatively marginal and only picking up from the mid-2000 decade.

In Figure 2 the total number of records on sustainability is compared with those that integrate risk and sustainability (orange) and those that integrate all three – risk, resilience and sustainability (grey).

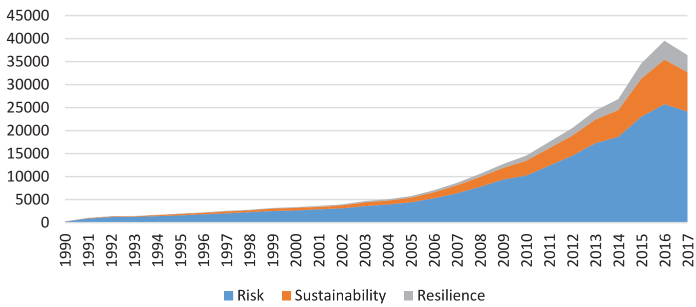

Figure 1. Evolution of research in the domains of risk, sustainability and resilience.

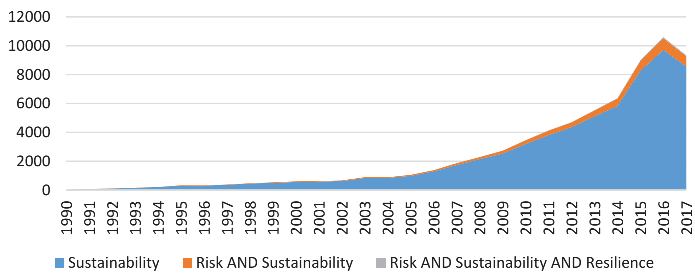

Figure 2. Integration of risk and resilience research into sustainability research.

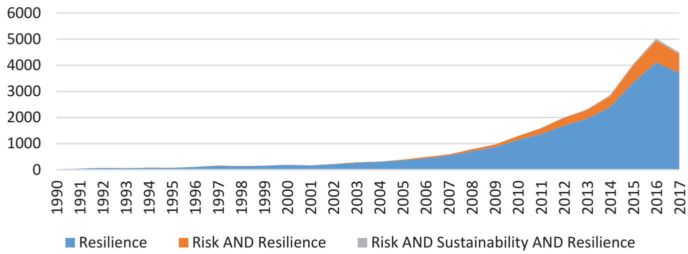

Figure 3. Integration of risk and sustainability research into resilience research.

Similarly, Figure 3 shows the evolution and volume of research on resilience, and the integration of risk and sustainability considerations in resilience research.

From these figures, we can conclude that risk is by far the dominant research field and that while some integration is visible between risk and sustainability and risk and resilience, research that integrates all three domains is at its infancy.

Finally, Figure 4 shows a selection from Group 3 terms. The birth and rapid growth of concepts such as circular economy, planetary boundaries, inclusivity, social cohesion, social-ecological systems, and adaptive governance can be seen as emerging all more or less simultaneously and growing at similar rates.

3.2. *Multi-disciplinary composition of the risk, sustainability and resilience knowledge domains*

In Figures 5–7 some examples of the distribution of disciplinary knowledge among the considered knowledge domains can be seen. First, looking at the general Group 1 terms – Risk, Sustainability and Resilience – we find that the Environmental Sciences and Ecology dominate all three. In the case of Risk, Engineering comes third, with only about 14% contribution and preceded by Public/Environmental/Occupational Health. This can be explained by the division between risk seen from a reliability or a safety perspective. If the reliability and safety perspectives are combined, the Environmental Sciences come second.

In general, for all the 26 terms it could be said that the top three contributing disciplines are Environmental Sciences, Engineering and Economics – mostly in that order, with some minor exceptions. We interpret this as approximating the three systems perspectives: ecological, engineered and social systems. In the case of social systems, we interpret Economics to be the principal discipline (theoretically and methodologically) contributing to research on risk, sustainability and resilience in social systems. Other Social Science or Humanities disciplines are either non-present or extremely marginal.

The leadership of Environmental Sciences and Ecology becomes even more pronounced at the level of Group 3 – specific concepts, where a large number of these concepts are almost entirely dominated by the environmental/ecological perspective, e.g., adaptive governance, social ecological systems, planetary boundaries (Figures 8–11). It is possible to argue that such concepts are then vulnerable to ideology as well as non-intentional, cognitive biases. A somewhat better balance

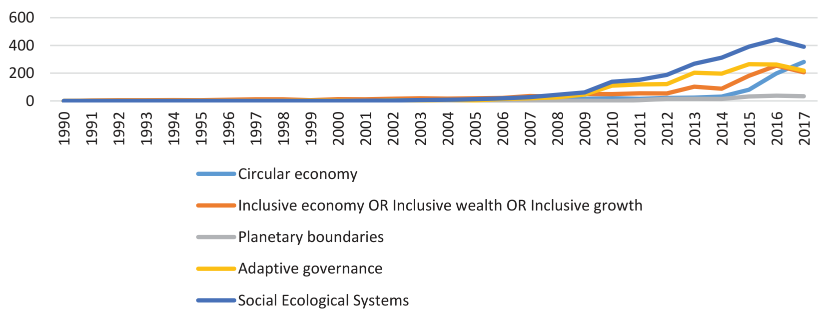

Figure 4. Evolution of research on the concepts of circular economy, inclusive economy/wealth/growth, planetary boundaries, adaptive governance, and social ecological systems.

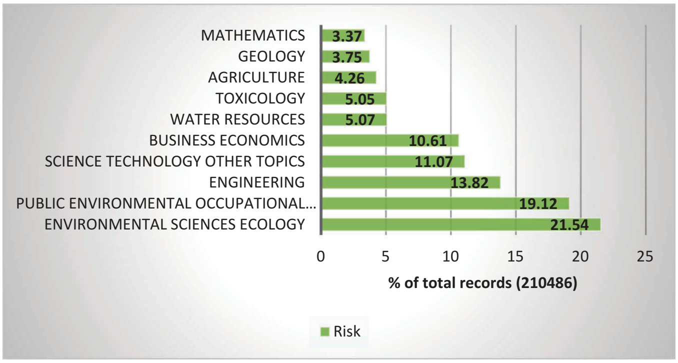

Figure 5. Disciplinary composition for the knowledge domain of risk.

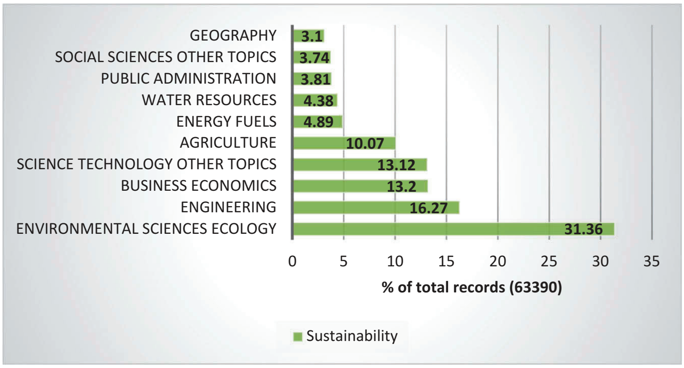

Figure 6. Disciplinary composition for the knowledge domain of sustainability.

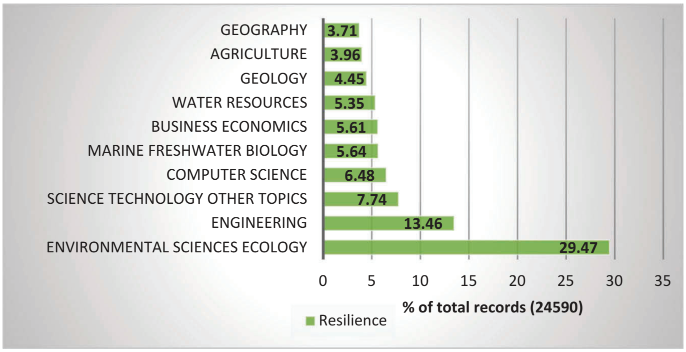

Figure 7. Disciplinary composition for the knowledge domain of resilience.

can be seen in the case of circular economy. The construct social-ecological systems are also interesting from the point of view that here too actual social science research is extremely marginal (Sociology 3%, Geography 8%, Public Administration 5%) in comparison to its hyphened counterpart (Ecology 73%).

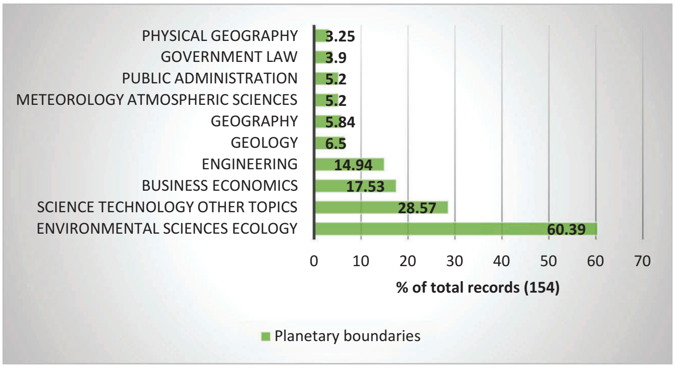

Figure 8. Disciplinary research on the concept of planetary boundaries.

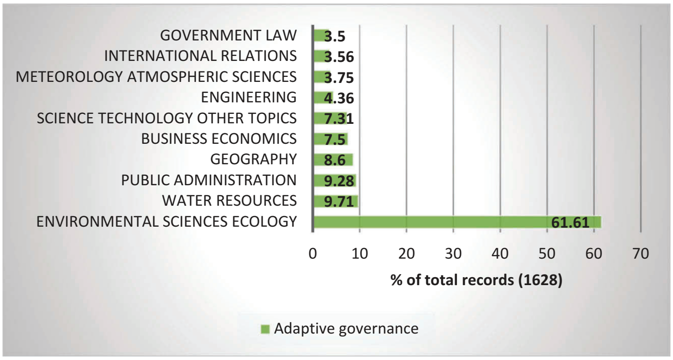

Figure 9. Disciplinary research on the concept of adaptive governance.

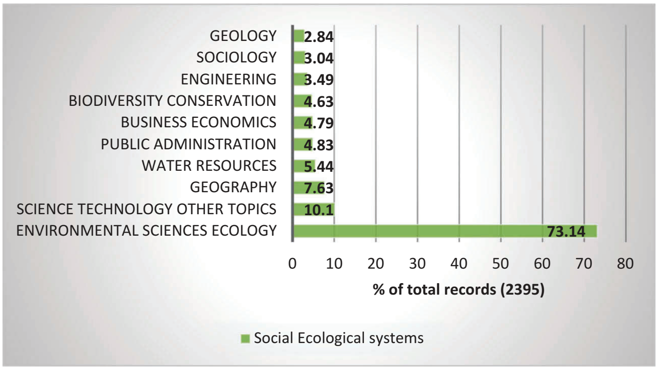

Figure 10. Disciplinary research on the concept of social ecological systems.

As the authors' perspective stems from the context of Engineering decision-making, the contribution of research from the domain of Engineering to all identified terms are shown and compared to the other two dominant knowledge domains: Environment/Ecology and Economics (Figure 12). Unsurprisingly, research on Robustness, Engineering and Infrastructure Resilience is heavily dominated by the Engineering

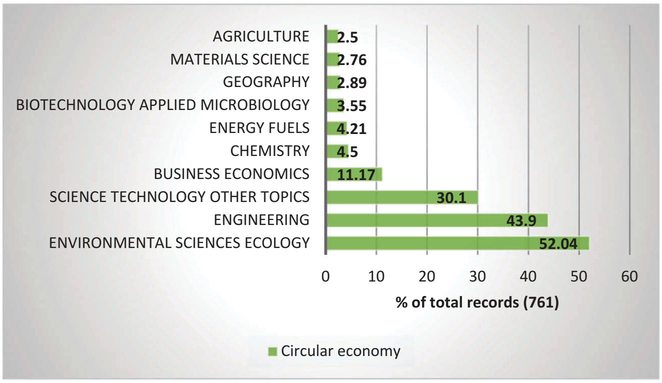

Figure 11. Disciplinary research on the concept of circular economy.

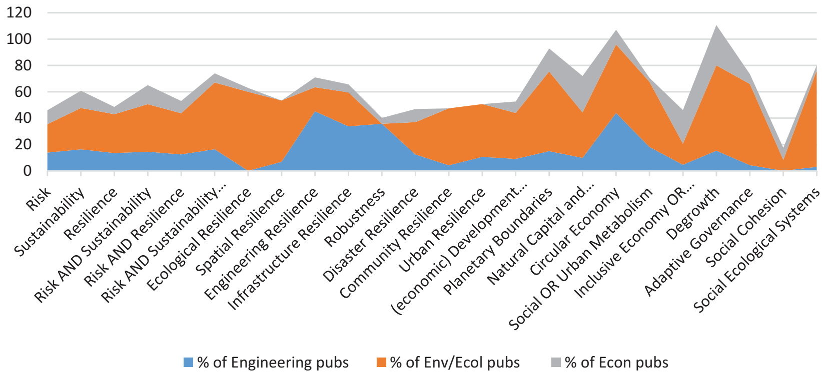

Figure 12. Contribution of research from the Engineering knowledge domain to all expert selected search terms.

disciplines. Figure 12 also shows that Engineering research is a large part in what we believe represents the quantitative sustainability dimension, i.e., circular economy and related concept of urban/social metabolism.

With regard to research in Resilience, the contribution shows a consistent trend at about 15%, making Engineering the second largest contributor. Interestingly, research dominated by the disciplinary field of Ecological Economics shows the same constant percentage, e.g., planetary boundaries, degrowth and ecoservices. Engineering is missing or is very marginal in the Social domains, e.g., social ecological systems, social cohesion, adaptive governance, and all the community-related aspects of resilience.

3.3. Term co-occurrence analysis results

In this section, we look at some examples of the term maps we developed to represent knowledge domain clusters and relations among them. These visualizations we believe facilitate the apprehension at a glance the multi-disciplinarity of many of the concepts (expressed as the number of clusters) as well as the trans-disciplinarity among them (expressed as link strength and distance among individual nodes and clusters). It goes without saying that interpreting these maps has a strong element of subjectivity, but we believe they are an efficient visualization tool that allows a quick screening of trends and patterns in a vast amount of data that can be used to direct further more detailed analysis.

Figure 13(a–c) represents the development of research in risk over the past three decades. The split was necessary due to the very large number of records (over 200,000), which the software could not process in one batch. In the first decade of Risk (Figure 13(a)) we see four clusters – the largest (red) is clearly identified as belonging to the decision-theoretic knowledge domain, with terms like

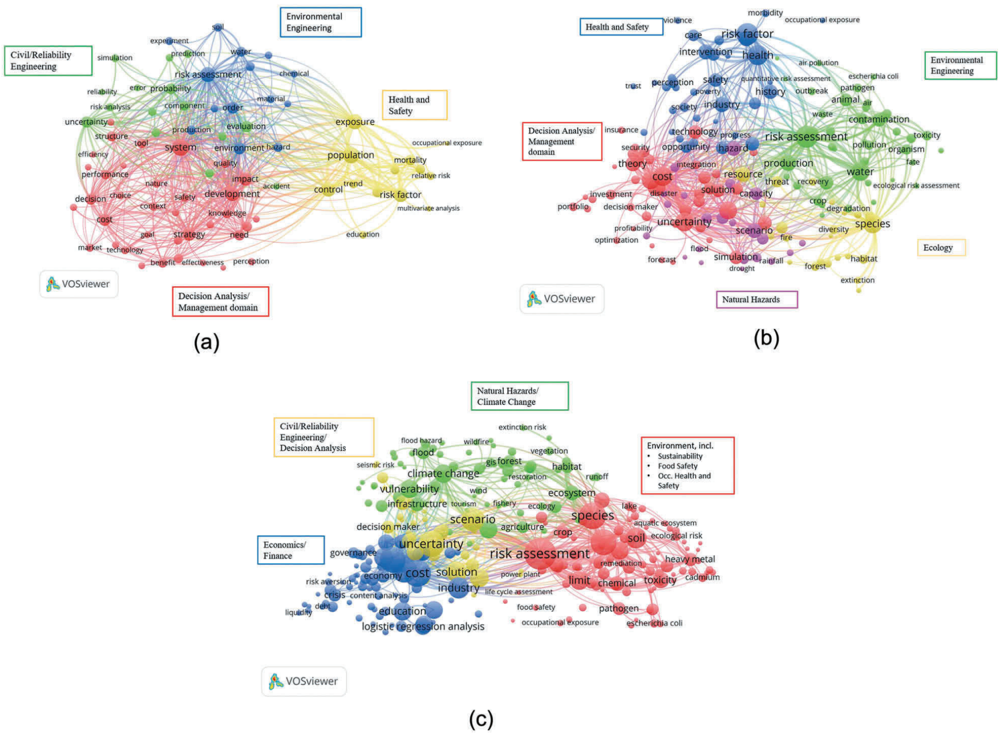

Figure 13. (a) Network map of research in the domain of risk 1990–2000. (b) Network map of research in the domain of risk 2001–2010. (c) Network map of research in the domain of risk 2011–2017.

choice, decision, alternative, efficiency, performance, solution, utility, etc. Closely related are the green cluster of Civil/Reliability Engineering (e.g., uncertainty, probability, reliability, risk analysis) and the blue cluster of Environmental Engineering (e.g., chemical, water, soil, environmental hazard). Rather distant from these three clusters, the yellow cluster is the human domain of Health and Safety (e.g., occupational exposure, mortality, population).

In the second decade of Risk (Figure 13(b)), decision theory/analysis is still the dominant cluster (red). The Environmental Engineering perspective is still clearly visible (green). Health and Safety (blue cluster) seems to have grown in size as well as come closer to the environmental and decision domains. There is no immediately visible sign of Civil Engineering, which seems to have been incorporated into the decision cluster (e.g., uncertainty, forecast, solution, optimization). Here within the red cluster we also see the emergence of a new cluster (pink), highly integrated into the red – it is the natural hazards domain from the perspective of engineering (e.g., drought, hazard, scenario, rainfall). We interpret this to mean that the two principal interests in Risk from the Civil Engineering discipline during 2001–2010 were incorporating decision analysis for optimization problems and natural hazards.

A new knowledge domain has also sprung from or in close relation to the Environmental Engineering perspective, namely the yellow cluster, which we consider to be the Ecology domain (e.g., species, diversity, resource, threat, extinction, degradation).

Moving to the current decade, starting 2011 (Figure 13(c)), the shift in risk research toward environment becomes even more pronounced. Here we see the dominant red cluster is the Environmental risk cluster, where elements of quantitative sustainability have also found home (e.g., life cycle assessment) but also the hybrid area of food safety and security (food safety, pathogen, escherichia coli), and oddly enough health and safety (occupational exposure), which has been reduced from a big cluster in the previous decade to a minor node in the environment cluster.

The next big cluster (green) could be seen as a particular aspect of the environmental one – here we have the natural hazards, grouped together with climate change. Economics and finance (blue cluster) sits rather far from both the Environment and Climate. The decision theoretical and Civil Engineering perspectives are here united in the middle yellow cluster. Although the smallest cluster, it has now centrality in the network with strong links to Economy and Climate change and Natural Hazards domain and somewhat less so with Environment.

From comparing the maps for the three decades of risk, we conclude that risk research has evolved from being

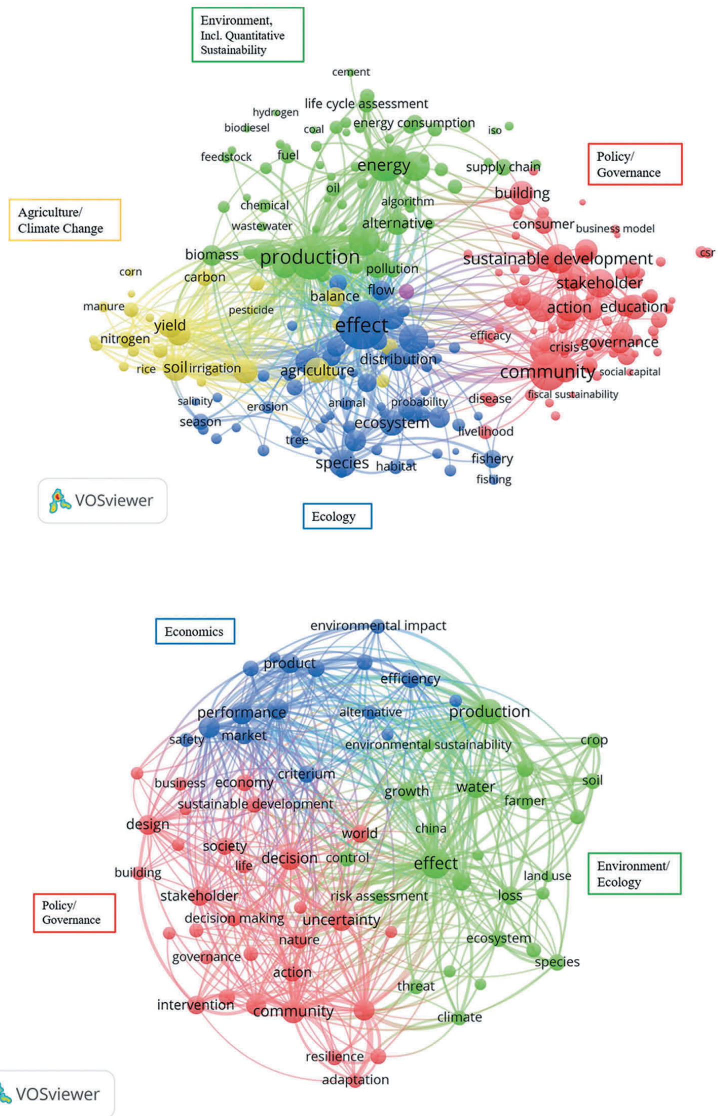

Figure 14. Network map of research in the domain of sustainability. (a) Network map of research combining the domains of risk and sustainability.

strongly dominated by a decision theoretical and civil engineering perspective in the 1990s toward a dominant Environmental/Ecological paradigm. We see the waning significance of areas such as Occupational Health and Safety and the introduction of new ones such as Food Safety, Climate Change and Natural Hazards. While it might seem that the trend in the environmental perspective replacing the engineering perspective is bad news for engineers, we argue that the relative positioning of the engineering perspective in the center of the map depicting the current decade is a favorable opportunity for the engineering knowledge domain to play a central and unifying role among the various disciplines contributing to risk research. From this point of view, a criteria for success would be the manifestation of integration between risk, sustainability and resilience on different levels – in research, in management/practice, and crucially, in education.

In what follows, we analyze a selection of maps related to sustainability and resilience.

In Figure 14 an all-inclusive map of Sustainability is given. There are four distinct clusters. The single pink node in the middle stands for Resistance. We have decided to integrate it into the blue cluster, which is the Ecological perspective cluster as the idea of Resistance is closely associated with Ecological Resilience. The dominant cluster is the red one – we label it the Policy/Governance perspective (e.g., accountability, action, credibility, ecological footprint, capacity building, inequality, stakeholder, transparency). We notice also that this dominant cluster is where all the social/societal systems' terms are located (social capital, livelihood, identity, leadership, education, empowerment). This cluster also stands rather distinctly apart from the natural science domains that are represented in the other three clusters. This shows a rather clear division between the natural and social sciences producing research on Sustainability. The green cluster represents the Environmental perspective, from the point of quantitative sustainability (e.g., life cycle assessment). The blue cluster represents the Ecological perspective (e.g., ecosystem, species). The yellow cluster belongs to Agriculture in combination with Climate Change (e.g., soil, irrigation, pesticide).

Comparing the general map of Sustainability to the more specific one that combines Risk and Sustainability (Figure 14(a)), we observe that the number of clusters has been reduced and that the whole network has become more dense. In contrast to the map in Figure 14 there are no particular dominating single nodes such as action, community, sustainable development, effect, energy, etc. We identify such nodes with largely ideological content or policy buzzwords that do not characterize any particular research discipline but are used as a political instrument to promote any given research. In this respect, we have identified a number of knowledge domains, which are almost entirely dominated by words lacking any specific content (e.g., Inclusive Economy/Wealth/Growth, Urban/Social Metabolism, Degrowth, and Social Ecological Systems). Maps and all meta-information of the maps can be found in the data report.

There appears to be less ideology in the map in Figure 14(a). There the dominant cluster is the red one. We see it as a mesh-up of Decision Analysis, Civil Engineering, Risk Management and Risk Governance. We could also call it the Policy domain as it is less about assessment than about management (e.g., decision-making, evidence, governance, risk management, resilience, uncertainty, stakeholder, vulnerability, action, adaptation). The green cluster is the Environmental and Ecological perspectives combined (ecosystem, landuse, species, threat, climate, effect, crop). The small blue cluster is Economics (performance, market, efficiency, product). Altogether, these three clusters represent the three pillars of sustainability: ecological, social and economic.

Unlike Sustainability, which lost two clusters in the specific risk and sustainability consideration, for Resilience, the opposite is visible. The map of Resilience (Figure 15) shows two very distinct clusters located far from each other. There is a one node outlier (the blue dot), which stands for Redundancy, so we have added it to the green (Ecology) cluster. It is clear that the green cluster is very dense, with terms closely and strongly related to each other. This we argue is the case because Ecology as a discipline is rather homogeneous. There is not much multi-disciplinarity present here even though it is typically authors from the Ecological domain who are the most pronounced advocates of multi and trans-disciplinarity as exemplified by the constructed concept of social-ecological systems.

The distant and weakly related red cluster is composed of many loosely and weakly related nodes. It is the melting pot of just about any discipline that has adopted the term Resilience – for scientific or political purposes or both. Here we see, risk, civil engineering, natural disasters, food security, policy and governance, a bit of economics, a bit of psychology and education. Unsurprisingly, many of these are loose ends and stand as single nodes in the cluster. Links among the nodes in this cluster are weak as are the external links connecting the Ecology cluster.

In the map in Figure 15(a) risk meets resilience in three closely related clusters. It is, in fact, a map of the three dominant perspectives of resilience, which we have identified in Group 2 search terms. The dominant red

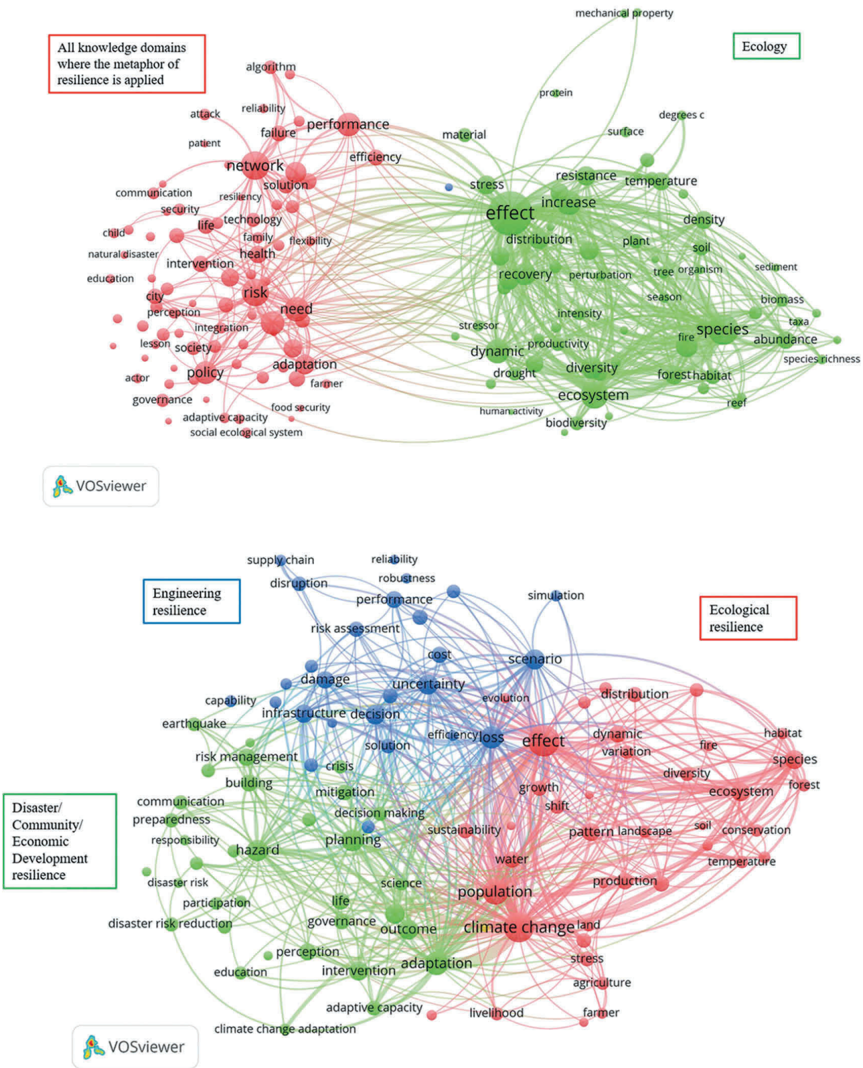

Figure 15. Network map of research in the domain of resilience. (a) Network map of research combining the domains of risk and resilience.

cluster is the Ecological Resilience Cluster (e.g., diversity, ecosystem, growth, shift, population, production). The blue cluster is the Engineering Resilience cluster (e.g., infrastructure, robustness, risk assessment, scenario, damage, performance, reliability, decision, uncertainty). The green cluster is the Disaster/Community/Urban and (economic) Development cluster (e.g., hazard, mitigation, preparedness, adaptive capacity).

The first thing that happens when we add Sustainability and Resilience to Risk is that the number of records drops from 140,000 + to fewer than 400. So is this smaller universe also qualitatively different?

In Figure 16 the dominant cluster is the red one, though it should be noted that it is not as dense as the green cluster. The red cluster here is a combination of the Decision theoretical, Civil Engineering and Policy perspectives (hazard, exposure, loss, reliability, performance, robustness, recovery, effectiveness, etc.) In this cluster, we clearly see the Engineering perspective of risk-informed decision support.

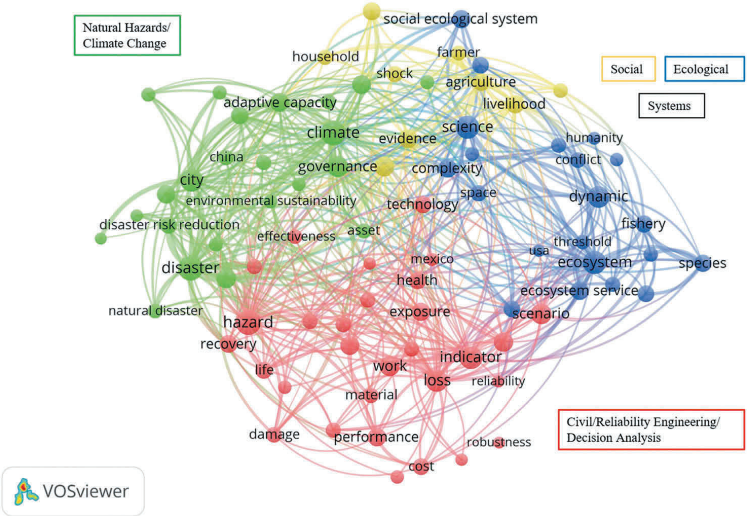

Figure 16. Network map of research combining the domains of risk, sustainability, and resilience.

The closely positioned and denser green cluster is the Natural Hazards and Climate Change domain. The blue and yellow clusters are the social ecological systems domain, where the former is represented through terms like agriculture, livelihood, household, farmer, etc., and the latter by ecosystem, ecosystem service, complexity, threshold, humanity. It should be noted that while the social domain seems to be exemplified by individual entities (household, farmer), the ecological one deals with collective ones (humanity, system, species). The emphasis on the individual in the context of social systems is possibly due to the dominance of Economics and Psychology to account for various types of individual human behavior. It is also evidence for the complete lack of e.g., Anthropological/Cultural research on risk that would account for aspects of collective human behavior. It is only when we look closer at the particular Group 3 terms, where the concept of Social Cohesion is the single case where collective human behavior becomes of concern to risk and resilience.

We conclude from this map that research integrating the three concepts is largely driven by the risk perspective, and more specifically, that of Decision theory/Civil Engineering. This confirms our previous conclusion that the centrality of the Engineering perspective (Figure 13(c)) should be interpreted as an opportunity for the engineering knowledge domain to play a central and unifying role among risk, sustainability and resilience research.

A more radical conclusion is that although the Ecological perspective is the one lobbying for the unification of representing and assessing social and ecological systems jointly, i.e., *Social Ecological Systems*, it appears that no such unification is actually happening in research or in real life. The domain of the 'natural environment' is clusters away from the domain of humans. It appears however that a stronger link can be made between the social and the engineered systems as we see in a number of maps where the social and the engineering terms are often located within the same cluster.

3.4. Bibliographic coupling analysis: distribution of knowledge in risk, resilience and sustainability by countries and organizations

We now turn to the last sample results of our analysis – the bibliographic coupling analysis, where we look at the distribution of knowledge in risk, resilience and sustainability by country and organization. (See also bibliographic maps for all terms in this document in the data report. The data report includes also an additional category – 'author', which facilitates the observation of the relatedness of expert communities or the fragmentation of research.)

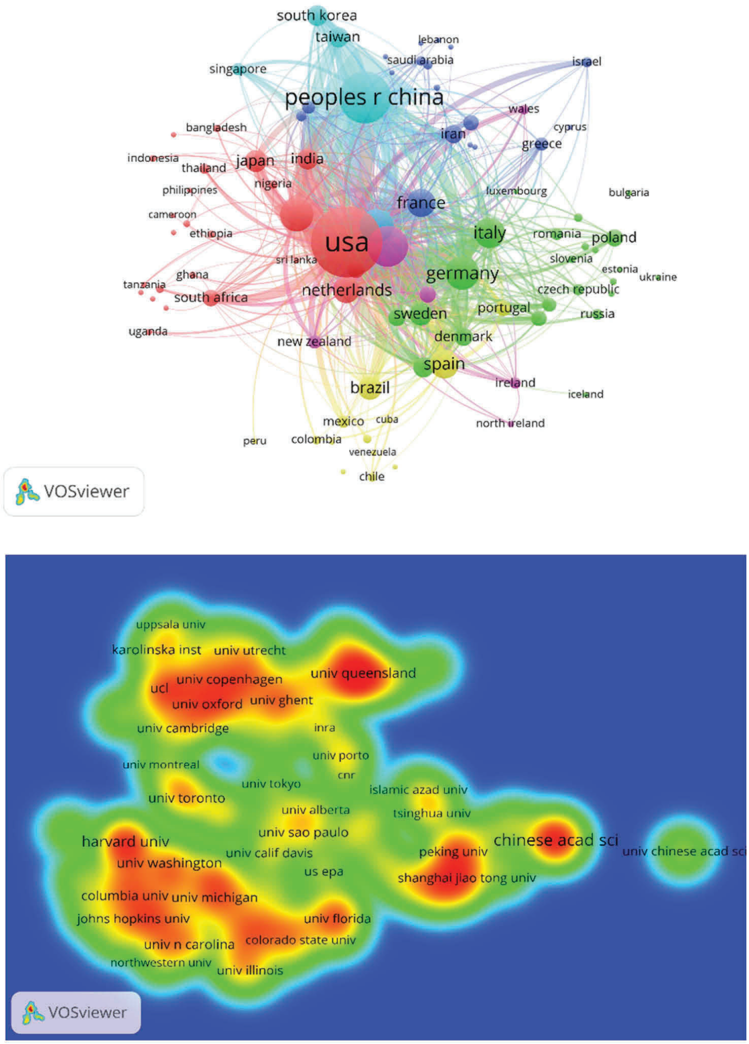

Figure 17. Geographic distribution of research in the domain of risk 2011–2017. (a) Organizational distribution of research in the domain of risk 2011–2017.

In Figure 17, the last decade of Risk research is shown, where the two dominant producers of research are the USA and China, though the exchange between them is relatively week. In the green cluster are located continental and Scandinavian European countries, with Germany and Italy having the lead and to some extent Sweden and Denmark. Eastern and Central European countries are also part of this group, though with lesser contribution and weaker ties to the others and themselves. The yellow cluster we call the Latin cluster, with Spain, Brazil and Portugal having the lead. The red cluster dominated by the US is also where we see strong relations between the latter and Japan, India, the Netherlands, some African countries and some southeast Asian countries. The pink cluster belongs to the Commonwealth countries (except India) – The U.K., Australia, Canada, New Zealand. The

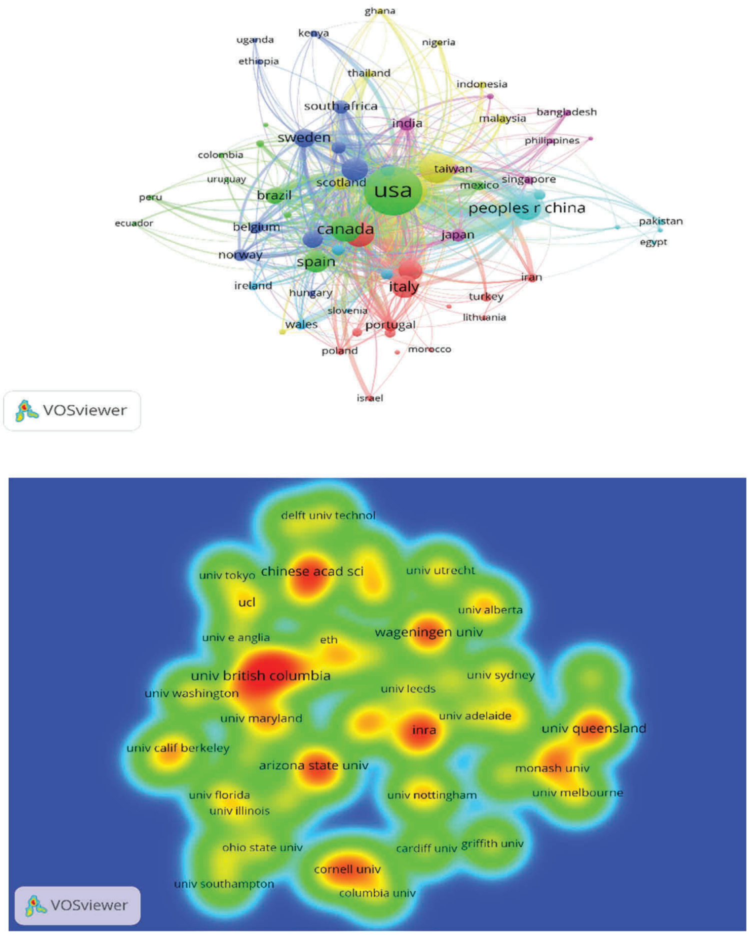

Figure 18. Geographic distribution of research combining risk and sustainability. (a) Organizational distribution of research combining risk and sustainability.

light blue is China and neighbors – South Korea, Singapore and Taiwan. The dark blue is dominated by France and Iran.

So apart from the obvious linguistic patterns that seem to be at work, we could see that exchanges are also based on historical geopolitical relations between countries and spheres of influence. Looking at the map of organizations (Figure 17(a)), we can see a distinct North American knowledge hub in the bottom left, where the main actors are Harvard, Columbia, University of Michigan, University of Washington, Colorado State University, etc. To the right are two Chinese hubs: Peking and Shanghai Jiao Tong universities in close collaboration and the Chinese Academy of Sciences. At the top, a relation is observable between the European hub (Oxford, Ghent, UCL and Copenhagen) and the Australian (University of Queensland).

Less obvious to describe patterns is the country map for Risk AND Sustainability (Figure 18). Here we see the dominant countries USA, China, Canada, Scotland, Spain, Italy, Sweden and Brazil, but we do not see any particular linguistic or historical patterns that might be influencing the exchanges.

The organizations map (Figure 18(a)) looks a lot more fragmented than that of Risk, with many small hubs spread around. The biggest one is UBC in Canada, the Chinese Academy of Sciences, Wageningen in the Netherlands, and

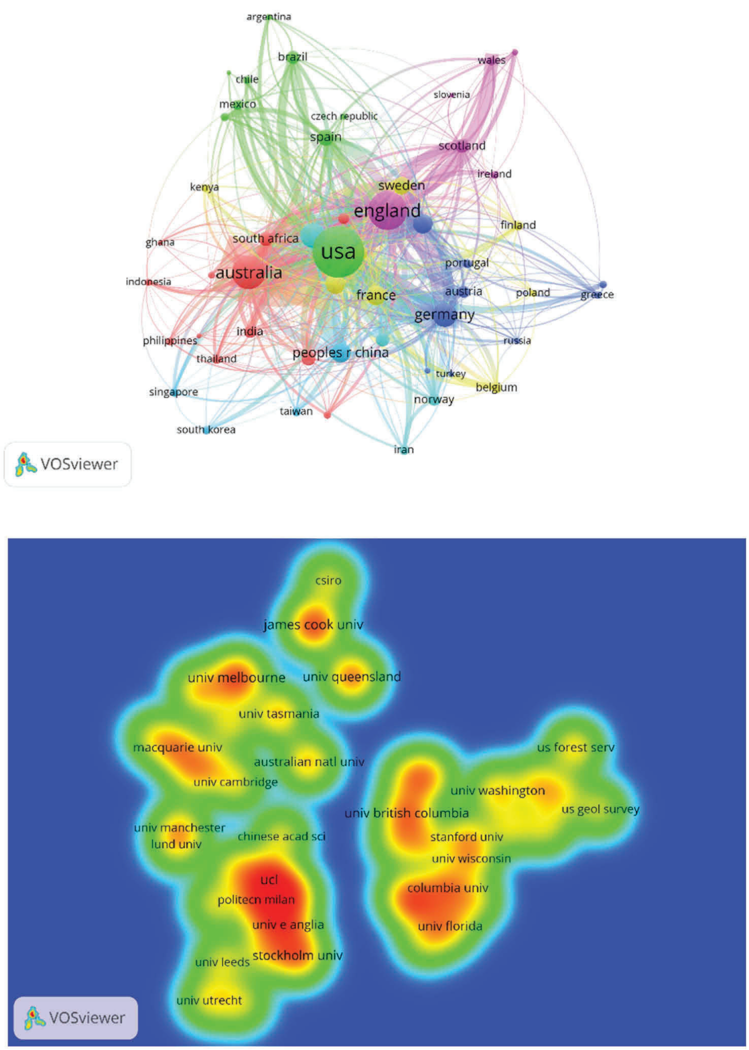

Figure 19. Geographic distribution of research combining risk and resilience. (a) Organizational distribution of research combining risk and resilience.

a trio from Australia: University of Queensland, Monash and University of Melbourne.

Research on Risk and Resilience is largely dominated by what we could call the Anglo-Saxon group: USA, The UK, Australia and Canada (Figure 19). Unlike Risk and Sustainability, China is not a major producer of research. Other important countries are Germany, Sweden and Scotland.

Looking at the organizations map, no doubt the Stockholm Resilience Center is in the hottest area of the map, together with collaborating institutions in the UK and Italy – UCL, Milan Polytechnic and University of East Anglia. (Figure 19(a)). Australia has several small hubs around James Cook University, Melbourne and Queensland. We see also a UK-Australian hub represented by University of Cambridge and Macquarie University in Sidney and a UK – Swedish connection between University of Manchester and Lund University. On the right side of the map is the North American hub represented by University of British Columbia, Canada and a number of US institutions, most prominent of which is Columbia University.

4. Emerging perspectives and concepts

4.1. From risk-based to resilience and sustainability-based decision support

The pursuit to create optimal well-being conditions for society through achieving an acceptable balance between safety and growth in the domains of social-ecological-engineered systems has gradually evolved from risk-based to risk-informed to sustainability and resilience-based approaches to the governance and management of risks. While there are clear differences between these approaches, the terms are often used inconsistently in the literature. In what follows, the differences between these approaches are briefly outlined. Subsequently, the concept of resilience is discussed in detail from the perspective of the different disciplinary fields. Finally, analyzing the commonalities among the different perspectives, it is assessed whether a synthesis of risk, sustainability and resilience in a common framework and metrics is possible and desirable and whether there is evidence of such a framework operationalized in practical application in either the public or private sectors.

At a very basic level, the difference among those approaches is one of scope. The risk-based approach encompasses the technical part of a risk assessment, which typically includes a system and scope definition for a particular problem, a hazard identification, a probabilistic analysis of the realization of the hazard(s), and a consequence analysis (usually constrained only to direct consequences). The risk-based approach helps to identify the risks associated with a given activity and prioritizes efforts to minimize or eliminate them. It is based primarily on a narrow set of model-based risk metrics, which are often highly idealized, i.e., rest on significant assumptions with regard to the target system in the 'real' world the model is supposed to represent. Considerations of indirect consequences (economic, social or environmental) and stakeholder concerns are generally not part of risk-based decision-making. Sometimes risk-based and evidence-based decision support is used interchangeably in policy publications (grey literature) to emphasize a purported 'scientific objectivity' in the risk governance process. The risk governance structure in this case is a top-down structure based on the reliance of public authorities (or business executives) on subject matter experts to procure legitimacy for their decisions. The output of risk-based analyses is typically expressed in quantitative terms, which allegedly adds to the perception of objectivity of scientific evidence.

In contrast, the risk-informed approach is more holistic in that it incorporates the modeling of preferences of the relevant stakeholders, ranking and prioritizing decision alternatives, and defining risk acceptance criteria. It considers both direct and indirect consequences; and accounts for the influence of risk communication and risk perception as powerful drivers of system changes. The risk-informed approach thus goes a step further in drawing a more comprehensive profile of risk by taking in account human judgment into the decision-making process despite its intrinsically subjective quality and precisely because it recognizes that decision-making is a value-driven activity.

Methodologically, risk and sustainability are assessed through different methodologies, the first taking basis in predictive methods and aiming to produce knowledge about the dynamics of a system's constituents or between systems; the latter, in predominantly deterministic methods that result in system representations. To the best of our knowledge, the only framework to date that combines risk assessment with sustainability assessment is proposed by Faber (2018).

Increased interest in the concept of resilience over the past decade can be seen in the light of and as a consequence of trends and shifts in the strategic orientation of risk governance and management. One of the most prominent trends in this respect is the shifting perception of risk as a threat that should be eliminated or controlled through top-down management strategies enforced by policy makers, executives and experts to a perception of risk as a given uncertainty that is better managed through proactive mitigation, capacity building and participatory efforts that are put in place prior to a disruptive event, i.e., during the preparedness stage.

Preference for investing in preparedness over reconstruction is just one driver that has prompted interest in the concept of resilience; another one is the notion of 'inclusivity' in its ubiquitous applications in governance, economics, and ethics. Interest in inclusivity could already be witnessed in the shift from risk-based to risk-informed governance of risks in that for the latter, capacity building is contingent upon the inclusion of a spectrum of societal stakeholders whereby issues like social cohesion, trust, social capital, legitimacy and transparency of decisions, and not least distributive justice are integrated into the overall risk governance framework. Finally, building on the temporal dimension introduced in the sustainability perspective, the resilience perspective goes even further in considering the lifecycle of products and processes as it aims to assure a successful transformation of the system as a qualitative improvement of the

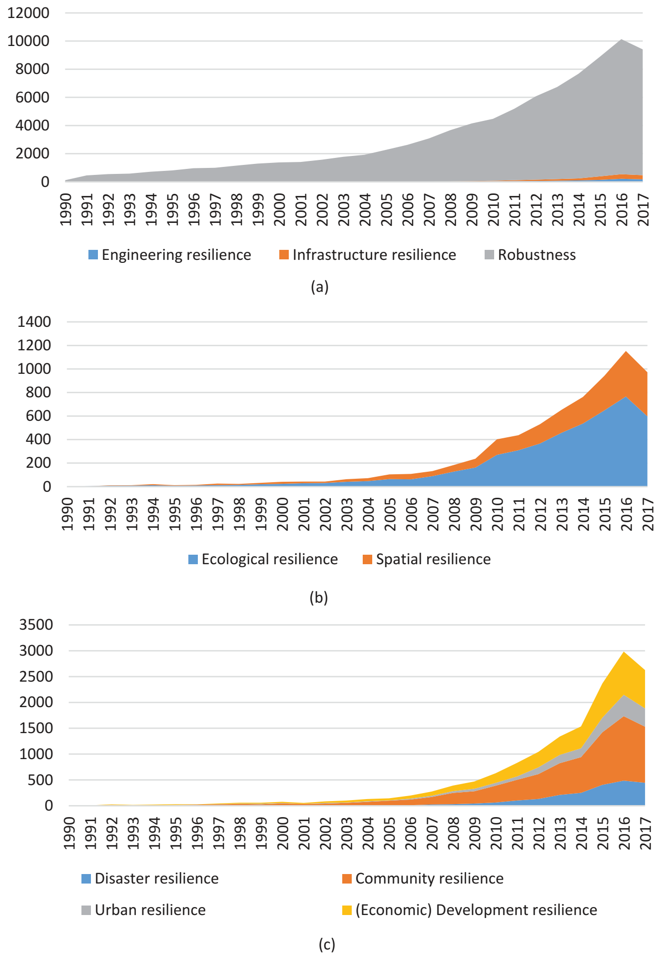

Figure 20. (a) Resilience from the perspective of engineered systems. (b) Resilience from the perspective of ecological systems. (c) Resilience from the perspective of social systems.

system's design and functionality manifested in notions such as *value added, increasing asset value, extending lifecycle, multiple functionalities*, etc.

In the following, the concept of resilience and how it is understood and used in different disciplines is outlined. There is no commonly agreed definition of the term. It is defined differently in each application area from ecology to engineering to mathematics and graph theory, to the health sciences, to psychology to disaster and emergency management to economics to international development. That different types of complex biological and non-biological systems exhibit similar structures, properties and behavior have been exemplified in numerous studies (Barabási, 2009; Gunderson & Holling, 2002; Holling, 2001; Lansing, 2003; Schneider & Kay, 1994; Sundstrom et al., 2014; Watts & Strogatz, 1998). What unifies all the different interpretations of resilience is that resilience theories can be seen as comparative theories of systems and their dynamics, particularly complex adaptive systems (CASs) such as ecosystems, social systems, economies, and infrastructures, or any combination thereof. It is precisely through this general systems perspective that the combination of risk, sustainability and resilience can be approached.

In the present paper, three groups of perspectives on resilience are considered corresponding to ecological, engineered and social systems perspectives. For each, a definition and key authors are provided, together with brief explanations of the main concepts, followed by an examination of the methods and metrics applied or proposed to operationalize resilience, i.e., move from a strategic understanding of the concept and normative goals and requirements settings to operational scientific frameworks for resilience assessment.

Figures 20(a–c) illustrate the composition of the three dominant resilience perspectives. In Figure 20(a) it can be seen that resilience from the perspective of engineered systems is heavily dominated by research on Robustness. In fact, Robustness has by far and large the largest volume of research and the longest history. The adoption of the term *resilience* from the other domains is a very recent phenomenon (mostly in the past decade). Even Ecological resilience, which is often quoted in the literature as the founding discipline of resilience, is a late comer in adopting the term. In the context of ecology, the term *resilience* came to replace an older term – *persistence*. This cannot be seen in the timeline, but it is easily identifiable in the cluster maps and accompanying meta-information tables in the data report.

In Figure 20(b) the evolution of the ecological perspective, with its two complementary sub-fields Ecological and Spatial resilience is shown.

Finally, in Figure 20(c) resilience from the perspective of social systems is depicted through the conceptually related disaster, community, development and urban resilience.

4.2. Resilience from the ecological systems perspective

4.2.1. Ecological resilience

The concept of resilience originated in the field of ecology, from where it spread to the academic community at large and to practical domains of engineering, organizational management, development and the humanitarian aid field. Holling (1973) defines resilience as the amount of disturbance a system can withstand before shifting into an alternative stability domain. In Walker et al. (2004) resilience is defined as 'the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks.' Walker and Salt (2006) use the above definition of resilience to discuss non-linear dynamics of complex adaptive systems such as social ecological systems (SESs), arguing that the dynamics between periods of abrupt and gradual change and the capacity to adapt and transform so as to persevere are what defines the resilience of SESs.

Sharp shifts in the behavior of systems, also termed *regime shifts*, are one of the key concepts in ecological resilience and are fundamental to the subsequent development of the concept of planetary boundaries. The non-linear cause and effect dynamics are discussed in depth in the mathematical literature on dynamical systems (Kuznetzov and Levitin, 1997; Scheffer, 2009). Scheffer (2009) elaborates on the limitations of the dynamical systems theory to account for changes in the nature and properties of the systems themselves over time. Folke et al. (2016) argue that understanding of the qualitative changes of systems can be gained by studying linkages between ecosystems and social systems, and that it is the feedback loops between them that make them interdependent and determine their overall dynamics. Adaptability and transformability are seen in this context as the main capabilities that make a system resilient. Adaptability refers to the capacity of SESs to learn, synthesize knowledge and experience, adjust behavior to both internal and external forces and processes while maintaining stability, or *basin of attraction* (Berkes et al., 2003; Folke et al., 2016). Transformability, on the other hand, is defined in Walker et al. (2004) as 'the capacity to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable.' Although most of the literature on ecological resilience is deliberately non-normative, concepts such as adaptability and transformability are loaded with normative socio-political content, especially with regard to the social transformation of variables such as identity, values, established relations among actors, institutional power arrangements, shifts in perceptions and re-framing of worldviews and perspectives, and deliberately forced transformational changes set in motion by particular governance objectives and policies. Thus, the claim for non-normativity that the ecological resilience school strongly emphasizes is empirically non-tenable. This is especially the case where building systems resilience is a normative objective of sustainability, itself a loaded normative concept.

The ecological school makes a distinction between *specified* and *general resilience*. Specified resilience addresses the question 'Resilience of what, to what?' (Carpenter et al., 2001), which is analogous to posing a question about the boundaries of risk: risk of what, by whom, to whom? Put in this manner, resilience (and risk) refer only to a part of the system and some particular control variable related to one or more identified disturbances (or hazards). Cifdaloz et al. (2010) drawing on Highly Optimized Tolerance theory developed by Carson and Doyle (2000) discuss how increasing resilience of a system's component to specific shocks may result in loss of resilience in other components or undermine the resilience of the system as a whole.

General resilience refers to any and all parts of a system. It does not focus on specific disturbances;

rather, it is associated with the capacity to respond to any uncertainty. Specified resilience is easier to operationalize as quantitative metrics and indicators can be developed with respect to specific disturbances. It is this view of resilience, which is typically adopted in the engineering domain. General resilience has resisted operationalization, and to-date is largely used to describe normative goals and requirements.

From the distinction between specific and general resilience, it is clear how another distinction has emerged between resilience seen as an *outcome* and resilience as a *process*. As an outcome to a goal or a set of priorities, resilience can be characterized as a measure of performance, retrospectively, from some defined stability state of the system in the past through the disturbance event and the time it takes to recover functionality to the level existent prior to the shock. This perspective is linked to *engineering resilience* and *community resilience* in the context of disaster and emergency management. From the process-related perspective, resilience comes closer to the general resilience in ecology. A number of studies have proposed that process-related resilience can be measured in actions rather than system properties (Hollnagel et al., 2011; Seager, 2014, 2016). Actions here refer to the system's ability to sense and organize information, anticipate a disturbance, adapt its behavior, learn, and function at all times in response to internal and external stressors.

In addition to the outcome and process views of resilience, another perspective identifies resilience with *resources* that act as system redundancies or internal capabilities (Eisenberg et al., 2014, Linkov et al., 2013a, 2013b). According to Snell et al. (2016), this perspective is largely undertaken by the U.S. Department of Homeland Security and applied to the National Infrastructure Protection Plan (NIPP 2013).

Resilience, stripped of particular context is neither good nor bad for human welfare. In the majority of literature on ecological resilience, where resilience is seen as a process, there is a deliberate disassociation from normativity. Gunderson et al. (1995), Gunderson and Holling (2002), Walker and Salt (2006) have emphasized that while humans play a role in changing the biophysical ecosystem conditions, they are not the primary indicators of system change, arguing that a resilience approach is not intended to choose among outcomes but rather to understand which system dynamics might be favored over others. Similarly, Walker et al. (2006) and Folke et al. (2010) have pointed out that operationalizing resilience should aim at increasing natural and social capital, preparing for cascading consequences, adjusting to mismatched cross-scale linkages, and steering the system out of undesirable basins of attraction. Poverty traps are an example of an undesirable basin of attraction (as discussed in the economics literature), which exhibit high level of resilience but are a non-desirable system state. Sundstrom et al. (2014) further point out that the cross-scale resilience model developed in ecology to explain the emergence of resilience from the distribution of ecological functions within and across scales can be applied to non-ecological systems, i.e., anthropological, economic, etc., for the non-normative quantitative assessment of resilience.

When, however, resilience is seen as an outcome, it is strongly associated with sustainability and takes basis in rigorous normative values focused on identifying desirable future alternatives, assigning values to these alternatives through developing sustainability indicators and promoting policy interventions that advocate fundamental transformations of the socio-political system in which decisions are made.

In what follows we discuss the extent to which the ecological resilience perspective is operational and what have been to date the methods and metrics used to measure it.

At the more qualitative, conceptual end of the spectrum, the notion of *panarchy of nested adaptive cycles* provides a heuristic understanding of the interplay of resilience, adaptability and transformability across multiple scales (Allen et al., 2014).

Another method is the development of early warning (EW) indicators, which allows the assessment of when a system approaches a critical threshold and potentially impending regime shift. Dakos et al. (2012) present a summary of currently available EW methods and apply them to two simulated time series typical of systems undergoing critical transition.

Classification and Regression Tree analysis, and their Bayesian implementation have been used to identify scaling structure based on size characteristics in ecological (e.g., animal size) or urban (city size) systems (Sundstrom et al., 2014).

Finally, time series and spatial modeling are additional methodologies used in the domain of ecology. Angeler et al. (2016) for instance identify discrete temporal frequencies at which patterns in complex systems manifest. Allen et al. (2016) have used spatial modeling techniques to reveal discrete geographical extents and variation in relevant variables, showing how such methods have the potential to assess how entire regions at a landscape level, i.e., beyond ecosystems, affect and are affected by local and regional environmental processes and governance.

4.2.2. Spatial resilience

Stemming from the ecological resilience knowledge domain, the concept of spatial resilience has the potential to unite many of the other resilience perspectives by looking at various spatial attributes of ecological, social and engineered systems to understand the identity (or boundaries) of a system, its structure (components and their distribution), and its behavior (flows, feedbacks and connections among the components as well as external interactions). The concept was first used by Nystrom and Folke (2001) in studies of coral reef and rain forest disturbance to underline the importance of *ecological memory* in keeping a system's identity during re-organization.

The first comprehensive description can be found in Cumming (2011) who defines spatial resilience through the spatial arrangement of, differences in, and interactions among internal and external elements of a system, arguing that both internal and external elements must be considered in relation to other aspects of system resilience, including the system's structure, interactions, ability to maintain its identity while undergoing change and, finally, a system's inherent learning capacity. The spatial boundaries of a system are not necessarily a layout in space but more in function. Internal elements are thus those that are related and interact with each other and may be defined in social, economic or ecological terms by a geographical boundary at a *landscape level*. The external elements include the context, which is to be understood as the non-focal spatial surroundings, connectivity and spatial dynamics that influence a system's identity from outside the system boundaries.

Quantifying spatial resilience is still in an early stage of development. Allen et al. (2016) provide an extensive literature review of spatial resilience research and propose a procedural roadmap for operationalizing spatial resilience. The roadmap includes explicit consideration of spatial variability in both the system and disturbance under consideration; inclusion of internal and external spatial elements in the definition of the system's spatial boundaries; the identification of thresholds and tipping points; and the determination of ecological memory that influences present and future system states.

4.3. Resilience from the engineering systems perspective

In the context of technical systems, three terms are used, often interchangeably, to talk about resilience: engineering resilience, infrastructure resilience and robustness.

Scientists from the ecological field of resilience have been keen to draw a distinction between their work and that of their peers in the engineering domain. Allen et al. (2016) and Angeler and Allen (2016) point out that the assumption made in engineering resilience with regard to a single equilibrium state in complex systems is not applicable to complex adaptive systems such as SESs. Engineers, on the other hand, have embraced much of the resilience theory stemming from the ecological perspective. Fiksel (2003) argues for an alternative to traditional engineering practices focused on anticipating and resisting disruptions, embracing the idea of developing sustainable systems through 'designing systems with inherent resilience by taking advantage of fundamental properties such as diversity, efficiency, adaptability, and cohesion.'

Hollnagel (2014) defines engineering resilience in basically the same terms as general resilience in ecology, namely as 'the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions.' He then outlines four main characteristics of resilience engineering: (i) the ability to respond to known and unknown disturbances; (ii) the ability to monitor system states; (iii) the ability to learn from the consequences of past events and decisions; and (iv) the ability to anticipate and proactively adapt to change. While Fiksel's and Hollnagel's understanding of engineering resilience is entirely compatible with the ecological perspective, most other sources contrast the two in terms of divergent views on singular or multiple states of equilibrium in complex systems dynamics and the focus of engineering resilience to restore system functionality to a previously defined level of performance.

In structural reliability and risk analysis, the concept of *robustness*, not resilience, is used to characterize the sensitivity of an engineered system's performance to a well-defined set of disturbances, or loading conditions. The Joint Committee on Structural Safety (JCSS), a pre-normative body in the field of civil engineering, defines the robustness of a system as the ratio between direct risks and the total risks (where total risk is the sum of all direct and indirect consequences) for a specified time frame and considering exposure events and all relevant damage states for the constituents of a system (JCSS, 2008) Robustness can be understood then as the degree of resistance relative to a particular set of exposures. When potential regime shifts are not considered and the context of the analysis is a regime's steady state, the concept of robustness is the same as that of specified resilience (Yu et al., 2016)

Janssen and Anderies (2007) examine robustness-fragility trade-offs in SESs – a notion that refers to the observation that designed features meant to increase robustness of particular system component(s) to particular stressors, lead to weakening or 'fragilizing' of other stressors and/or components. It is in this notion that the main incompatibility between (i) specified and general and (ii) ecological and engineering resilience resides. In engineered human-technical systems the robustness-fragility trade-off can be seen as two opposing strategies in the design of systems, namely *'fail-safe'* design based on robustness vs. *'safe-fail'* design based on resilience considerations (Park et al., 2013).

Like ecological resilience, the engineering resilience perspective tends to be more descriptive than normative in the sense that it is concerned with measuring the *elasticity* of a system in absorbing and recovering from disturbances. The product of such descriptive analysis is typically a technical risk assessment. However, once the assessment results are contextualized into a decision problem, where stakeholder preferences are taken into account, the degree of normativity increases both with regard to economic and ethical considerations.

Quantifying resilience of engineered systems has typically been based on: (i) networks modeling; (ii) system performance modeling; (iii) composite indicators development and early warning methods; and (iv) hybrid modeling, comprising two or more of the above methodologies. Some examples of state-of-the-art methodologies and their applications are provided below.

In the case of networks modeling, computational methods and graph theory form the basis. Newman (2006), Barzel and Barabási (2013), Barabási (2016) apply network theory as a basis for system representation, arguing that topological similarities in engineered, natural and social networks (e.g., roads, rivers, communities) show functional self-similarity and scale independence.

In the case of system performance modeling, which is also the more widespread method in applied engineering contexts, quantitative data from historical events, computational infrastructure models and subject matter estimates are used to model the performance of a given system. The resulting performance measures are then applied in planning and decision-making processes as the metrics can be used to estimate and evaluate the costs and benefits of proposed resilience interventions.

Hollnagel (2011) develops the Resilience Analysis Grid (RAG) also called 'RAG profile for an ability', which summarizes the balance between the abilities to monitor, anticipate, respond, and learn. RAG is a process measure providing information about the current situation and can be used to monitor performance at discrete times, defining areas for improvement.

Hollnagel (2012) uses the Functional analysis Method (FRAM) – traditionally applied to model human error in the context of operational safety in the health and transport sectors – to study the dynamics of complex socio-technical systems by modeling the potential variability of each function and possible dependencies among functions.

Indicators and Early Warning methods are more attribute-based and include categories of system properties, which are typically regarded as enhancing resilience, e.g., robustness, adaptability, resourcefulness, etc. Their products are usually qualitative or semi-quantitative estimates of resilience, which can, in turn, be operationalized through procedural processes. Such methods are typically applied in the military, civil defense and the disaster risk management and emergency contexts. Øien et al. (2012) describe what is termed Resilience-based Early Warning Indicators (REWI) method, which has been applied in the evaluation of causes and factors leading to the Deep Water Horizon accident, showing retrospectively that the accident may have been prevented had insight from relevant indicators been taken into account in the management process. Empirically tested in a case study on the successful recovery of high-risk incidents (Størseth et al., 2009), the REWI method incorporates some fundamental attributes of resilience, termed contributing success factors (CSFs): risk understanding, anticipation, attention, response, robustness, resourcefulness/rapidity, decision support, and redundancy. For each CSF, measurable indicators are then developed.

In the context of facilitating resilience assessment of critical infrastructures, Linkov et al. (2014) propose a similar indicator-based methodology, starting with a functionality curve of the critical infrastructure system and adding resilience dimensions as sequential time phases: understand risks, anticipate, prepare/adapt, be aware/attentive, absorb, respond, recover, and adapt. While both methodologies explicitly link risk and resilience assessment, the REWI method's outputs are early warnings, whereas Linkov's application is intended to provide a measure of resilience for each dimension or temporal phase along the functionality curve.

Woods et al. (2013) propose the Q4-Balance framework (Balancing Economy-Safety Trade-Offs), utilizing a balanced portfolio of indicators, grouped into four classes: economy-reactive, economy-proactive, safety-reactive, and safety-proactive.

Furthermore, a number of hybrid methods have been proposed and applied. Vugrin et al. (2011) apply the Infrastructure Resilience Analysis Methodology (IRAM), which combines performance-based metrics and resilience attributes whereby the consequences of a specified disruption in an infrastructure system can be modeled deterministically and/or probabilistically while three resilience attributes (absorptive capacity, adaptive capacity and restorative capacity) can be used to identify resilience limiting properties, thus providing input at the system design level. An additional component of IRAM is a six-step process that guides the user through the application. This process has been applied in the contexts of transportation, chemical manufacturing, public health and energy (Vugrin et al., 2011, 2014, 2014, 2015).

A logic model is proposed by Willis and Loa (2015) of the Rand Corporation as a way of aligning resilience metrics with strategic and operational decision-making. Based on a hierarchy of metrics that connects inputs to outputs, the model can help explain from an operational perspective how resources (budgets, equipment, spare parts, people) contribute to desired strategic outcomes (reduced costs/damage, improved welfare, increased economic activity.

Moore et al. (2016) attempt to quantify resilience of SESs using network theory by focusing on two state variables: *system performance* (e.g., functions such as ecological, social or infrastructure-related) and *adaptive capacity*.

Ganin et al. (2016) propose to measure resilience as critical functionality based on performance recovery from a single shock by using multi-level directed acyclic graphs and interdependent coupled networks.

Klammler et al. (2016) develop a model of interdependence for urban technological systems (infrastructure) and socio-economic systems (institutions), using multiple metrics of coupled systems performance under a stochastic disturbance regime.

Finally, two methodological frameworks should be mentioned which combine risk, sustainability and resilience assessment under one umbrella. Anderies et al. (2013) argue for a synergetic approach to resilience, robustness and sustainability as a means of developing a global change policy that addresses the multi-scale and multi-level challenges associated with global change. Sustainability is referred to as the analytical framework that structures the decision-making process at multiple scales and comprises multiple actors that together can identify, rank and select development pathways that meet performance criteria: 'When sustainability is conceptualized in this way, the importance and respective roles of the full range of academic disciplines, including the humanities, social and natural sciences, decision science, and engineering become clear.' Robustness and resilience ideas can be used within the overarching sustainability framework to help inform decision support across scales (specified vs. general resilience) and systems boundaries as well as levels of organization.

An operational integrated model of risk, resilience and sustainability is developed by Faber (2018), where an underlying decision analysis framework facilitates the decision optimization of alternative pathways for sustainable development. The framework provides a rationale for how resilience, efficiency and sustainability relate to each other. Methodologically, it demonstrates how failure events for inter-linked social-ecological-industrial systems propagate through failure of the global environmental system, failure of the social system and failure of the infrastructure system. The framework takes basis in Bayesian decision analysis, life cycle assessment (LCA), the concept of planetary boundaries, and the concept of the Life Quality Index (LQI), used to model impacts to welfare and social capacity.

4.4. Resilience from the social systems perspective

The context of the social systems perspective of resilience is rather broad and encompasses recovery processes in the aftermath of disaster events for social-ecological and technical systems. Four terms may be used in this context: disaster resilience, community resilience, urban resilience and (economic) development resilience. The terms disaster and (economic) development resilience are typically used in reference to developing countries only. Community resilience and urban resilience are used in reference to both developing and developed countries.

In the area of disaster risk management (DRM), the concept of resilience is approached from two distinct perspectives, which follow the traditional division in the DRM field between the natural and applied engineering sciences on one hand, and the social sciences, on the other hand. The former focuses primarily on the temporal aspects of resilience before the occurrence of a hazardous event, with an emphasis on mitigation measures aimed at reducing the frequency and magnitude of hazards and strengthening property to prevent damage (Bruneau et al., 2003). Here resilience is understood as a function of (i) reduced failure probabilities, (ii) reduced consequences (e.g., fatalities, structural damages and socio-economic consequences), and (iii) reduced time to recovery (e.g., restoration of system functionalities to a pre-defined 'normal' level of performance. This view of resilience is essentially the same as that of engineering resilience and as such depends on properties such as robustness (the capacity to withstand stress without loss of functionality), redundancy (the extent to which system components are substitutable), resourcefulness (the ability to make sense of a crisis situation and apply resources accordingly), and rapidity (the ability to restore the system to 'normal' functionality in a timely manner (Bruneau et al., 2003; Liao, 2012).

In the DRM literature on resilience, the term 'community resilience' is typically used rather than engineering resilience, especially in the context of disaster management, which largely falls in the social sciences domain. Regardless of which term is used, there are many overlaps between engineering and community resilience. In an attempt to develop a quantitative framework for the seismic resilience of communities, Bruneau et al. (2003) identify four dimensions of community resilience: technical, organizational, social, and economic. They link these dimensions to key community infrastructural elements: power, water, hospital, and local emergency management system. Such coupling allows them to identify and quantify system performance criteria measures for resilience.

In the context of flood risk management, the concept of engineering resilience has been applied by Garvin (2012) but supplemented by the broader social-ecological resilience from the ecological perspective (Dawson et al., 2011; Huntjens et al., 2011; Sayers et al., 2002; Zevenbergen et al., 2013) with the aim to counter-balance the focus on protection through large-scale structural engineering measures such as flood embankments, channelization, etc., with organizational and land use prevention and preparedness measures. Quantitative flood resilience models are based on indicators, which relate system response to flood waves (Mens et al., 2011). However, despite broadening indicators to include reaction threshold, amplitude, graduality, and recovery rate (Gersonius, 2008), a measure of the overall resilience of a system remains elusive as the indicators cannot yet be aggregated and expressed in one numerical value (Zevenbergen, 2007).

A second stream of research on disaster resilience stemming from the social sciences focuses explicitly on the situation after a disaster has occurred and is particularly concerned with the reduction in the flow of goods and services, often referred to in the literature as *business interruption* (Tierney, 1997). Economic resilience and international development resilience could also be included in the DRM context of resilience.

The most recent definition of resilience in the DRM context can be found in the Hyogo Framework for Action 2015–2030. Their resilience is "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner including through the preservation and restoration of its essential basic structure and functions (UNISDR, 2015a). This definition is practically the same as that of engineering resilience; however, the operational context is somewhat different. There is significantly higher normativity in DRM – a landscape dominated by high-level public sector stakeholders at the national and international organizational level. Their normativity, coupled with a strong impetus for measuring outcomes of policy directives is by necessity biased toward searching for linear cause-effects and predictability as preferences for action.

Stemming from the research domain of ecology and building on the concept of *planetary boundaries*, Homer-Dixon et al. (2015) develop an integrated framework to represent the causal patterns, intermediate processes and ultimate outcomes of what they call *'synchronous failure'* – a new type of global crisis resulting from multiple, simultaneous and interacting global stresses, such as population growth, climate change, resource scarcity and financial instability. Synchronous failure results from the combination of (i) unsustainable economic activity induced by demographic pressure; (ii) increased connectivity and speed in the channels transporting material, energy and information among the components of human technological, economic and social systems (Helbing, 2013) and (iii) homogeneity in human social systems, institutions and cultures whereby efficiencies achieved through economies of scale reduce redundancies that are essential for systems resilience. For Homer-Dixon et al. (2015) the global energy system has a synchronizing role in the evolving behavior of other systems such as water, food, climate, etc. It is therefore argued that interventions that enhance societal resilience and reduce the risks of synchronous failure must incorporate the concept of planetary boundaries for disaster preparedness at the global level.

While much of the literature on resilience in the DRM context is related to framework formulations aimed at (i) identifying goals and requirements for what hypothetically constitutes a resilient society or (ii) providing a system representation of the causal interactions between systems components, some methods have been proposed to measure resilience so that the concept can be utilized not only for strategic normative goal setting but be operationalized through pragmatic application. There is a strong consensus in both the scientific and policy communities on sustainability and resilience goals; however, when it comes to what to measure and to how to measure it, disagreement is widespread and organized quite distinctly around separate disciplinary fields.

Economists working in the domain of international development and humanitarian resilience emphasize the integration of the knowledge on poverty traps into the measurement of resilience. This is because countries with high poverty rates, food insecurities, inadequate infrastructure, and shattered social institutions are particularly exposed to systemic disturbances that contribute to tipping over threshold boundaries and generating failures that cascade through social-ecological systems (Barrett & Carter, 2013). Moreover, resilience as a systems characteristic is stripped of its neutrality that a descriptive scientific perspective, purely interested in systems dynamics provides it. From a socio-economic perspective, resilience is a desired outcome of the current non-poor whose aim is the maintenance of the present stable state. For the current poor, the objective is the opposite, i.e., to disrupt the present balance, seeking transformational change.

Building on Sen's concept of capability (1999), Barrett and Constas (2013) propose a person's well-being, or a scaled up aggregate, e.g., household, village, nation's, as the key variable in measuring resilience, and express resilience as a function of well-being and resource availability for current and future temporal dimensions. They combine probability estimates of poverty in each sequence of time periods with normative assessment of an appropriate tolerance level for the likelihood of being poor over time as a heuristic to classify individuals, communities, etc., as resilient or not.

Rose (2016) argues that economic resilience can be measured through established economic models related to the behavior of producers, consumers, government agencies, markets, and entire economies through a combination of effectiveness and cost measures. He distinguishes between *static economic resilience* (the efficient use of remaining resources at a given point in time) and *dynamic economic resilience* (the efficient use of resources over time for investment in repair and reconstruction). He then proposes that static resilience can be measured as an expression of the amount of business interruption (BI) prevented by the implementation of some resilience intervention measure (or set of measures). Dynamic resilience can be expressed as the reduction in recovery time in addition to the reduction of BI. The baseline for measurement can be taken to be the maximum potential BI loss in the absence of an intervention (Rose, 2016).

Cutter et al. (2013) develop a qualitative classification scheme that uses sets of indicators according to which a community can be classified as resilient or not. The sets are composed of aggregates such as community competence, infrastructure, and institutional, economic, social, and ecological indicators. Each indicator is comprised of about 10 variables and their respective positive or negative effect on resilience.

A similar classification tool is the Disaster Resilience Scorecard for Cities developed by the UNISDR and the IBM Corporation (UNISDR, 2015b). The scorecard is intended for urban planning whereby cities can evaluate their preparedness or current level of disaster resilience, identify priorities for action and investment, and track their preparedness over time. The scorecard facilitates the evaluation of institutional collaboration, risk assessment, building codes, natural buffers, and warning systems.

4.5. Trade-offs between risk, sustainability and resilience

In this section, we examine how emergent concepts in the context of integrating risk, sustainability and resilience considerations have been framed to highlight trade-offs between growth, efficiency and the preservation of a safe operating space for humanity with respect to ensuring the functionality of the Earth system. Our discussion focuses on the Group 3 concepts identified in the bibliometric analysis: (i) Planetary Boundaries, (ii) Natural Capital and Ecoservices, (iii) Circular Economy, (iv) Social/Urban Metabolism, (v) Inclusive Economy/Wealth/Growth, (vi) Degrowth, (vii) Adaptive Governance, (viii) Social Cohesion, and (ix) Social Ecological Systems. Cluster term maps are provided for selected concepts. The interested reader can find term maps and all accompanying metadata in the bibliometric report.

4.5.1. The concept of planetary boundaries

In risk analysis and quantitative sustainability assessment based on life cycle assessment (LCA) methodology, defining the system boundaries is the initial step in the process. In the context of risk analysis, a system definition is the spatial, temporal and relational representation of all relevant hazards (also termed exposures), the assets (e.g., buildings, structures, components, lifelines, technical equipment, procedural processes, humans and the environment), direct consequences (consequences related to damages on the individual constituents of the system, also termed marginal losses), and indirect consequences (consequences related to the loss of the functionalities of the system). According to Faber (2009), the chosen level of detail must be such that it can facilitate a logical representation of events and scenarios of events related to the constituents of the system, which individually or in combination may lead to adverse consequences. The purpose of identifying the spatial, temporal and functional boundaries of a system is to set the scope for the decision problem, facilitate the consistent ranking of decision alternatives as well as allow updating of the knowledge about the individual constituents that may become available in the future.

Similarly, goal and scope definition is the first phase in LCA methodology, which is applied in the context of quantitative sustainability assessment. The goal and scope definition includes the reasons for carrying out the study and the intended application and audience. It is also the place where the system boundaries of the study are described and the functional unit is defined. According to ILCD, 2010, three decision context situations of practical relevance in LCA can be differentiated, termed, respectively, 'Situation A: Micro-level decision support', "Situation B: 'Meso/macro-level decision support', and 'Situation C: Accounting'. While the first two deal with scaling effects of the system boundaries, the latter relates to consequences that have resulted in the past or may result in the future based on decisions already taken, hence it is not scale specific.

It is clear from the practice of risk and sustainability analyses that the process of defining the boundaries of a system under consideration is directly related to decision-making and risk governance. But while risk governing structures and institutional and institutionalized processes are more or less clearly defined at the micro- and meso-scales, there is no such governance structure at the global-scale, i.e., that of the planet. In this context, the concept of planetary boundaries, first outlined by Rockström et al. (2009) and updated in Steffen et al. (2015), accounts for the capacity of the Earth system and its biosphere to sustain adequate living conditions for humanity. Stemming from a long tradition in ecology science research on dynamics in social-ecological complex systems, thresholds and regime changes, the concept of planetary boundaries was proposed in light of accumulating evidence that exponential growth of human activities is putting such stresses on the Earth system that could destabilize critical biophysical systems and lead to abrupt and irreversible environmental changes at continental to global scales, possibly pushing the planet out of the Holocene state – the only known state of life-sustaining conditions for humanity.

In the original formulation, the planetary boundaries concept is advocated as a framework for estimating a safe operating space for humanity with respect to the functioning of the Earth system (Rockström et al., 2009). The authors identify key Earth system processes and attempt to quantify for each process the boundary level that should not be exceeded if unacceptable global environmental change is to be avoided. Unacceptable change is defined in relation to the risk and uncertainty humanity faces in the transition of the planet from the Holocene to the Anthropocene. Drawing on research from the discipline of ecology (Carpenter et al., 2001; Folke et al., 2004; Hughes et al., 2007; Scheffer, 2009), they present evidence from local to regional scale ecosystems that incremental changes in key control variables such as biodiversity, harvesting, soil quality, freshwater flows, and nutrient cycles, can trigger abrupt system change states once a certain threshold is exceeded. Nine planetary boundaries are identified: climate change, stratospheric ozone depletion, atmospheric aerosol loading, ocean acidification, biochemical flows, freshwater use, land-system change, biosphere integrity (functional and generic diversity), and novel entities. In the updated concept outline, Steffen et al. (2015) elaborate on the scientific underpinnings of the PB framework and present the status of the control variables for seven of the planetary boundaries. The authors further claim that climate change and biosphere integrity are the 'core' planetary boundaries based on their fundamental importance to the Earth system.

The concept of planetary boundaries builds on and extends approaches based on various sources. One such inspiration is the *limits-to growth* notion outlined in the book of the same title, where the problem of exponential economic and population growth is modelled in the context of finite resources (Meadows et al., 1972, 2004). Another one is the concept of *safe minimum standards*, originally proposed by the German natural resource economist Ciriacy-Wantrup as a way to eliminate catastrophic risk outcomes in the context of conservation and the management of natural resources, and applied in cases where probabilistic consequences assessment and cost-benefit analysis are unreliable (Bishop, 1978; Ciriacy-Wantrup, 1952; Crowards, 1998). A third relevant concept is the *Precautionary principle* in the formulation of Raffensperger and Tickner (1999) in their handbook guide for the science and environmental health network, where they state: 'When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause-and-effect relationships are not fully established scientifically.' Finally, the *tolerable windows* approach (Petschel-Held et al., 1999; WBGU 1995) a scheme for integrated assessment of climate change, adds to the theoretical basis of the planet boundaries.

In its scientific basis, the concept of planetary boundaries merges several scientific domains, which could be grouped around the following areas: (i) ecological economics, (ii) geoscience and sustainability science, and (iii) resilience and complex systems dynamics. In the following, some examples are given of the state-of-the-art research in PB as it relates to the aforementioned three areas of scientific inquiry.

Crépin and Folke (2014) relate current knowledge on biosphere dynamics and the PB framework to the economics literature on safe minimum standards, precautionary approaches, economic growth, regime shifts and thresholds. They argue that PBs can be interpreted as risk thresholds, which would help create consensus around them. While societal preferences of risk acceptance may be driven by risk aversion, they claim that preferences should have no impact on the location of the boundaries themselves. They further propose that the concept of resilience can be applied in the context of risk management whereby resilience could be conceptualized as an insurance in relation to growth within PBs.

van den Bergh and Kallis (2012) compare two alternatives to the growth paradigm in institutional economics, namely *a-growth* and *de-growth* in the context of the sustainability of economic growth given the concept of PBs. The a-growth approach proposes to ignore GDP as an effective indicator of social welfare as it (i) estimates the costs, not the benefits of market-related activities, excluding informal or non-market activities and (ii) fails to capture unpriced effects of growth related to the use of natural resources and ecoservices. Unconditional GDP growth is thus seen as incompatible with progress in areas such as climate, labor, health and public utilities. The a-growth paradigm supports developing environmental, social and economic policies irrespective of their effect on economic growth. The de-growth approach goes further than merely proposing a substitute for the GDP. In Kallis (2011) and Schneider et al. (2010), de-growth is defined as the equitable downscaling of economic production and consumption to ensure that society's resource use and waste stay within safe biophysical boundaries.

While the concept of PBs has been criticized because of a presumed conflict between global equity and environmental sustainability goals, Steffen and Smith (2013) have argued to the contrary that coupling social equity considerations regarding access to resources and ecosystem services with the biophysically oriented PBs builds a synergetic, powerful basis for working toward global sustainability. Building on empirical research that links income inequality to social outcomes at the national level (Wilkinson & Pickett, 2009) they show how greater income equality is not only beneficial to society as a whole, but is of particular benefit to those who are well off in that the wealthy in less equal nations have poorer social outcomes than the wealthy in more equal nations. They speculate that this phenomenon, which has been observed at the sub-national and national levels, could actually be an emergent system property at the global level, implying that it would be in the social interest of wealthy developed nations to reduce the income inequality between themselves and developing countries for both biophysical and social reasons.

Ryberg et al. (2016) examine challenges related to the development and operationalization of a PB-based Life Cycle Impact Assessment (LCIA) method. The challenges are related to technical issues such as modeling and including the Earth system processes and their control variables as impact categories in LCIA and to theoretical considerations with respect to the interpretation and use of LCIA results in accordance with the PB framework.

Fang et al. (2015) discuss the complementary linkages between environmental footprints and PBs. Environmental footprints (water, chemical, carbon, phosphorous, nitrogen, biodiversity, material, etc.) can be regarded as indicators of human demand for ecoservices or environmental pressure in relation to resource extraction and waste emissions. The PB concept provides a set of expert consensus-based estimates of the regenerative and absorptive capacity of the Earth's life-supporting systems. Despite conceptual differences, calculation methods and policy relevance, the authors see significant benefit in the synergy of metrics, which would make possible the benchmarking of contemporary footprints against maximum sustainable footprints thereby indicating the extent to which thresholds have been crossed.

Baum and Handoh (2014) compare PBs and global catastrophic risk (GCR) paradigms and propose a unified PBs-GCR conceptual framework – Boundary Risk for Humanity and Nature (BRIHN) – that integrates the systems resilience perspective of PBs with the probabilistic risk perspective of GCR. Uncertainty here is seen through two different mutually compatible system attributes: the resilience of the system to particular forcings (PBs) and the tendency of the system to result in collapse (GCR). The proposed framework could be applied in analyzing the risk and resilience of any two interacting systems. However, it comes short in its ability to account for interactions between different threats and multiple systems.

Faber (2018) proposes a methodological framework for a joint assessment of risk, sustainability and resilience, where the concept of PBs is applied in the context of a limited budget decision analysis problem. He considers the PBs as a representation of constraints on sustainable societal development at global scale, where the allowable impacts of human activities, over time and space, are limited, and sees the role of governance comprising two essential tasks: the assessment of the total allowable impacts and their allocation. To this end, a decision analysis framework and metrics are developed for optimizing welfare and quantifying sustainability and resilience.

4.5.2. The concepts of natural capital and ecoservices

At a most fundamental level, the trend that shapes the impetus to re-define core concepts such as wealth, growth and utility lies in the shift from studying social systems and institutions on one hand and natural systems and biophysical process on the other hand as separate domains of inquiry. The social ecological systems approach that emerged from the synthesis of ecology and economics emphasizes the embeddedness of social systems and institutions into the all-encompassing envelope of the biosphere, arguing that human well-being in all its dimensions (e.g., material needs, security, freedom, choice, justice, health, and intellectual growth and fulfillment) rests on the capacity of the biosphere to support these. Its main tenet is that social and ecological systems influence each other in reciprocal ways and co-evolve because of mutually reinforcing feedbacks (Folke et al., 2011).

The concept of natural capital emerged in the 1980s from the field of ecological economics as a first attempt to broaden the notion of capital, which in traditional economics refers exclusively to money, tools and machinery used in the production of goods and services, to now also include energy, nonrenewable resources, ecosystem services, and the life-supporting biophysical ecosystems that generate these (Costanza & Daly, 1992; Ekins et al., 2003; Jansson et al., 1994; Kareiva et al., 2011). The traditional model of production of an economy based on the three input factors land, labor and capital, is revised in Folke et al. (2016) so that these factors correspond to natural capital, human/social/cultural capital and human-made capital. The trio human/social/cultural capital is an extension of the traditional labor and human capital and is to be understood as those human institutions involved in the value setting and governance of human actions (Baland & Platteau, 1996; Berkes & Folke, 1992; Dasgupta & Serageldin, 1999; Folke et al., 2016; Pretty & Ward, 2001; Putnam, 2002). Human-made capital is an extension of the traditional notion of capital and includes, e.g., technology and capital markets (Costanza & Daly, 1992; Folke et al., 2016). Human-made capital is also referred to as manufactured capital by some authors (e.g., Dasgupta 2014).

Similarly, while early formulations of sustainability (WCED 1987) viewed the environment, society and the economy as three distinct 'pillars of sustainability,' ecological economists have proposed a re-defined conceptual framework of sustainability, where human well-being is defined and influenced by the inter-relations of the following factors: physical, social, environmental, economic, and psychological (Folke et al., 2016). This coupling of fundamentally social issues (e.g., democracy, health, equality, justice, security) with environmental issues concerning the life-supporting system of the biosphere (e.g., natural resources, ecosystem services, biodiversity) advocates a multi- and trans-disciplinary scholarship and approach to governance and decision-making that is integrative of the natural sciences, the social sciences and the humanities and is polycentric, participatory and inclusive. Renn (2016) refers to this approach as 'inclusive resilience', which he sees as the emerging approach to risk governance. The social-ecological approach is furthermore cross-scale in that landscapes and seascapes are transformed through processes in which local events can produce global consequences while global dynamics are responsible for shaping particular local conditions. How the interaction between scales produces trade-offs that need to be managed through a sustainable, fair and scientifically consistent manner is targeted by both competing and complimentary platforms and frameworks stemming from ecological economics, sustainability science, applied engineering sciences and social sciences and can be approached through a re-evaluation of the notion of growth, which is central to the study of both social and natural systems.

4.5.3. Re-evaluating the concepts of wealth and growth

The authors who originally formulated the concept of PBs take particular care to emphasize the scientific basis of their work as strictly comprising the identification and description of biophysical processes and alterations in the Earth system's functionalities because of human activities. Folke et al. (2009) recognize that human choices and actions will to a large extent determine whether critical thresholds are exceeded, but they distance themselves from any normative proposition by stating that 'the identified thresholds in key Earth System processes exist irrespective of people's preferences, values or compromises based on political and socio-economic feasibility such as expectations of technological breakthroughs and fluctuations in economic growth.' Similarly, the updated conceptual paper of 2015 concludes: 'The PB framework does not dictate how societies should develop. These are political decisions that must include considerations of human dimensions, including equity, not incorporated in the PB framework.' (Steffen et al., 2015)

Normative questions related to population and economic growth, the Earth's carrying capacity, the economic value of natural capital and ecoservices, the circular economy, and inclusive wealth all relate directly to the concept of PBs but are largely studied under the umbrella of ecological economics, applied ethics and branches of engineering and social sciences. While in the 1970s, when ecological economics emerged as an amalgam of ecosystem ecologists and environmental economists, many of the concepts and values they promoted were the fringe of both scientific and political discourse, it is clear that in the past 10–15 years, most of these formulations have infiltrated the full spectrum of scientific disciplines from the humanities to the social, natural and applied sciences and become the norm in policy and scientific circles. Where once mainstream economics promoted value-free analysis through methods such as cost-benefit analysis in the attempt to make economics a 'hard science,' the alternative understanding of concepts such as wealth, capital and growth that emerged from ecological economics, is now re-defining society's understanding, perceptions and expectations at large with regard to the very notions of well-being, happiness, wealth, social and ecoservices, the equitable distribution of all of the above, and the legitimacy of the institutional arrangements responsible for distributing commonly shared resources at local, landscape and global scales.

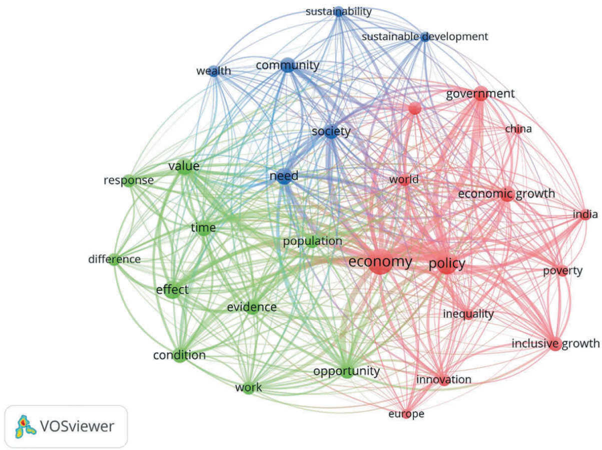

Figure 21. Network map of research on the concept of inclusive economy/wealth/growth.

In what follows, some essential concepts and strategies from the ecological economics domain are briefly outlined as well as how these are applied in theory and in practice to re-define concepts and strategies in the domain of risk and decision-making.

The concept of growth is central to discussion of trade-offs in the context of risk, sustainability and resilience. While economic growth might help produce resources and technologies that could mitigate natural and man-made hazards, help minimize negative consequences of adverse events, and speed up recovery processes in the aftermath of disasters and industrial accidents, economic growth is for the most part achieved at the expense of the planet's natural capital in the form of extraction activities and pollution.

At a very fundamental level, growth is imagined and experienced as a positive attribute, which is a priori desirable. Belonging to the domain of all things living, growth implies vitality. Conceptually, growth can be framed as a natural phenomenon, a dynamic property that can increase or decrease. Generally, the increase and decrease is imagined as a vertical movement, where more points upwards and carries various positive connotations such as wealth, health, self-realization, fulfillment of potential, etc. Moving down this scale, the decrease in growth spells stagnation, decline, underdevelopment, and halt. Growth can be framed through the metaphor of a living organism going through different life processes: birth, development, maturity, death; or through a mechanistic process metaphor (White, 2003), where growth occurs alongside words such as *trigger, kick start, spark, fuel, drive, accelerate, catalyst, main engine, locomotive, lever, put a damper on, put the brake on, keep on track, pick up steam, derail*. In the latter framing, it is clear that the dynamics of growth are not that of the upward/downward scale of the organic metaphor, which promotes an understanding of growth as a succession of creative and destructive cycles, but rather deviations from a controlled path, whose ultimate purpose is the maintenance of perpetual continuity.

In addition to the organic and mechanistic framings of growth, the notion of limits has been extensively used in the economic literature. Malthus (1798) developed an exponential model of population growth bounded by limited resources. Meadows et al. (1972, p. 1992) examined energy and material limits in a seminal publication 'Limits to Growth.' Ecological economist Daly (1978, 1996) advocated the concept of a steady state economy, which in contrast to the classical economics concept of the stationary state, is framed as a deliberate political action to create a steady economy made of constant stock of wealth (various forms of capital, including natural capital) and population size. Georgescu-Roegen (1971) applied the thermodynamic concept of entropy to economic analysis, arguing that all natural resources are irreversibly degraded through economic activity. Daly (1996) attempted to quantify these entropy limits through the concept of net primary productivity (the solar energy captured by plants and other photosynthetic organisms minus that used by the organisms themselves for respiration) as an input limit of the economy. Ehrlich and Ehrlich (1981) developed the concept of biodiversity limits based on the idea of species extinction and biodiversity loss as a possible limit to human population and economic growth. The concept of the planetary boundaries (Folke et al., 2009; Steffen et al., 2015) is the latest of such theoretical approaches that seek to define boundaries for growth through the notion of limits or thresholds that if exceeded could push humanity off the brink of the safe operating space known as the Holocene.

As goals and priorities are re-defined and put forward in global sustainability and resilience frameworks such as the UN Millennial Development and Sustainability Goals, the UNFCCC Paris Agreement on Climate Change, the UN Agenda 21, the (UNISDR, 2015a) Hyogro Framework for Disaster Reduction (2015–2030), etc., a clear trend can be observed in the conceptualization of economic growth and its effects on both the biophysical and the social environment and the use and distribution of resources: natural, financial, manufactured, social and human capital. Traditional economic growth theoretical models do not include natural capital except the availability of non-renewable fossil fuels and minerals. Known collectively through terms like the *environmental Kuznets curve* tradition and *'trickle-down theory,'* they posit that equity is a deterrent for growth and efficiency (Okun, 1975) and that initial inequality is both a natural byproduct of growth as well as a necessary factor to generate growth. Accordingly, economic growth follows a cycle where wealth generated at the top eventually 'trickles down' to the poor. Similarly, the literature builds on empirical studies that show the relationship between economic growth and adverse environmental impacts as an inverted U shape.

Criticism of this conceptualization of growth, spurred a new perspective termed *pro-poor growth* in the economic literature on development. It takes basis in the idea that growth alone will not benefit the poor, so strategies aimed at enhancing economic growth must intentionally focus on reducing poverty (Kakwani et al., 2004).

Over the past decade, a formidable amount of literature has emerged theoretically and empirically showing that the traditional economics claim that equity slows down growth is unsupported, and that inequality actually hinders growth (Berg & Ostry, 2011; Eberts et al., 2006). Moreover, inequality of all kinds (economic, political, and cultural) is seen to erode social cohesion and willingness to cooperate to protect common resources such as ecoservices (Cushing et al., 2015).

The most recent attempt to redefine growth and measure social welfare is the notion of *inclusive growth* (related terms include *inclusive wealth, inclusive economies*), which like pro-poor growth takes theoretical basis in arguing that equity is good for the economy. It focuses not only on the conditions of the poor but on the relative conditions of both poor and non-poor, arguing that all members of society should be able to contribute to and benefit from economic growth. Two schools of thought focus on inclusive growth from an outcome and process perspective, respectively. When growth is seen as an outcome, the focus is on the view that growth should benefit all members of society expressed through low-income inequality as well as non-income measures of well-being such as access to health and educational services (Thorat & Dubey, 2013). The process perspective of growth emphasizes the creation of opportunities and access to greater participation in the economy (Ali & Zhuang, 2007).

In Figure 21(a) cluster map of the literature on inclusive growth and related terms such as inclusive wealth and inclusive economy is given. It is difficult to ascertain any distinct knowledge domains from the three clusters, as the majority of terms that appear on the map are completely generic and non-context specific. We interpret this map as evidence for the primarily ideological nature of the concept. Inclusive growth, at least at present, is a rhetorical instrument for articulating particular policy goals; it is not a scientifically operational concept, with explicit theory and methodology.

Finally, two alternative perspectives of growth – *de-growth* and *a-growth* must be mentioned as of particular relevance to the field of ecological economics. Stressing the negative rather than the positive sides of growth, the de-growth perspective has a long tradition in the environmental activism domain. Its goal is to downscale production and consumption, and in some cases stop economic activity altogether, in order to decrease adverse anthropogenic impacts on the environment (e.g., Georgescu-Roegen, 1977; Kallis, 2011; Latouche, 2009; Martinez-Alier, 2009; Schneider et al., 2010).

A-growth is the less radical, precautionary position between pro-growth and de-growth. It posits that GDP is not a good indicator of social welfare as it estimates only the costs and not the benefits of market-related activities and does not include informal or non-market activities such as the use of natural resources and ecoservices (van den Bergh, 2011). A-growth theorists argue that policy should be directed towards correcting market inefficiencies that create environmental problems, ensuring that economic growth does not compromise the sustainability of life-supporting ecosystems (Crépin & Folke, 2014; van Den Bergh & Kallis, 2012).

We turn now to an examination of some proposed metrics in the context of re-evaluating the concepts of wealth and growth.

The traditional indicator for measuring economic growth is the Gross Domestic Product (GDP), which was developed by economist Simon Kuznets in the

United States in the context of finding a measure for the nation's productivity in the aftermath of the Great Depression (Kuznets, 1934). Although criticized strongly over the past decade for not being a good indicator for social welfare, the GDP nevertheless provides a good aggregate measure of productivity. Rackwitz (2002) argues that it 'provides the infrastructure of a country, its social structure, its cultural and educational offers, its ecological conditions among others but also the means for the individual enjoyment of life'. Faber et al. (2019) similarly argue that health and literacy are implicitly captured by the GDP as their development is facilitated by economic development and growth, which is adequately measured by the GDP.

The most widely used indicator to measure development is probably the United Nation's Human Development Index (HDI), which is based on the average of three other demographical indices: the GDP, the Education Index (EI) and the Life Expectancy Index (LEI).

Following the same principle of coupling economic growth and human development, Nathwani et al. (1997) developed the so-called Life Quality Index (LQI) to facilitate the development of societal risk acceptance criteria. The model takes basis in the philosophical idea that the only available resource to humans is time and that a model of life quality must reflect the time available to individuals in good health. The LQI is a utility function that represents societal preferences for trade-offs between life expectancy, time spent at work vs. leisure and GDP per capita invested into health improvement. Faber et al. (2019) apply the LQI in their methodological framework for a joint assessment of risk, sustainability and resilience.

New approaches and measures of social welfare that propose to do away with the GDP include the Happy Planet Index, the Inclusive Wealth Index and the Social Opportunity Function. The Happy Planet Index, introduced by the New Economics Foundation in 2006 is also based on the utilitarian principle of maximizing well-being in good health and longevity. It is calculated as a function of a given country's subjective life satisfaction, life expectancy at birth and ecological footprint per capita. On the positive side, the HPI contributes to the study of economic growth in that it attempts to measure the positive consequences of growth, namely well-being and health. It has also met with some strong criticism about the subjectivity of life satisfaction reporting, the controversiality of the footprint concept, which narrows its usage, and not least using the term happiness to measure not happiness but rather the degree of environmental efficiency supporting well-being.

Since 2012, the UN Sustainable Development Solutions Network has been publishing an annual World Happiness Report. Variables used to calculate a given country's happiness score include: GDP per capita, social support, healthy life expectancy, freedom to make life choices, generosity, and perceptions of corruption.

The Inclusive Wealth Index (IWI) is a joint initiative of the UN University International Human Dimensions Programme, the UN Environmental Programme

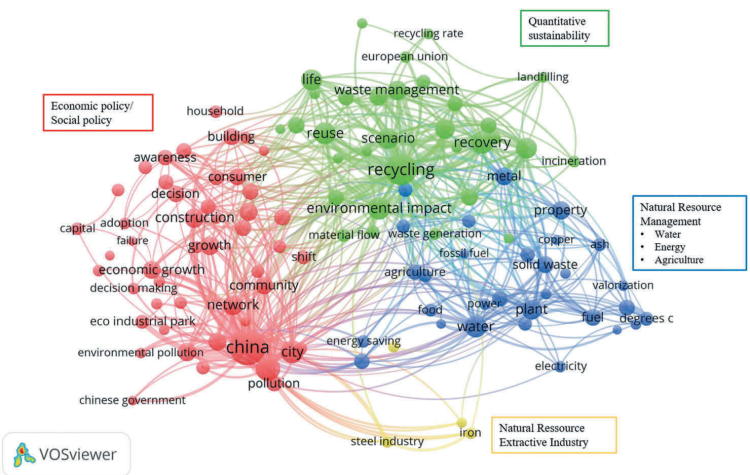

Figure 22. Network map of research on the concept of circular economy.

(UNEP) and the UN Educational, Scientific and Cultural Organization (UNESCO). It measures the wealth of a given country in terms of progress, well-being and long-term sustainability. Inclusive wealth is the aggregate sum of the social value of manufactured, human and natural capital. One significant innovation behind the effort to measure inclusive wealth is to try to disassociate the market value of goods and services from their wider social value in a societal context and attempt to measure the latter. Another one is the attempt to measure the stock of wealth-inducing conditions rather than flows of wealth (as the GDP does) thereby providing an inter-generational understanding of wealth and wellbeing. Nevertheless, the IWI has met with strong criticism based on theoretical assumptions, gaps in data availability, and inability to account for distributional issues (Roman & Thiry, 2016).

Finally, Ali and Son (2007) propose the Social Opportunity Function as a relevant measurement for inclusive wealth. They argue that inclusive wealth leads to the maximization of the social opportunity function. The increase of the latter depends on (i) average opportunities available to individuals in society and (ii) how these opportunities are shared or distributed. A particular weighting scheme that assigns greater weight to opportunities created for the poor ensures that growth is inclusive thus expanding not only average opportunities but improving their distribution among the population.

4.5.4. The concept of circular economy

While all organizations, public or private, aim to create value through their activities or business models, the concept of value creation has different meaning for different stakeholders and in different contexts. A common measure for value is the value that the stock market gives a company, i.e., market value. Value can also be expressed in terms of the value in a balance sheet, which is the accounting or book value of a company's assets minus its liabilities. Value can have different temporal dimensions as in the value based on expected future performance. In financial terms, value creation is the revenue (return on investment) that exceeds expenses (costs of capital). Traditional methods for assessing organizational performance are based precisely on profit and asset bases. A traditional model of value creation is a function of economies of industrial-scale characterized by mass production, high efficiency of repeatable tasks and constant, hierarchical structures of organization. Risk management in such a context is not much different from accounting.

Introducing contextual factors to value creation such as sustainability and resilience considerations does not disregard the relevance of financial value but it exposes its insufficiency. Thus, the notion of value creation has shifted over the past two decades to include a wide range of interactions and cause–effect relationships that take place in a market, regulatory, societal and environmental contexts. Organizational performance is now evaluated based on human social and natural capital than simply on profit and asset

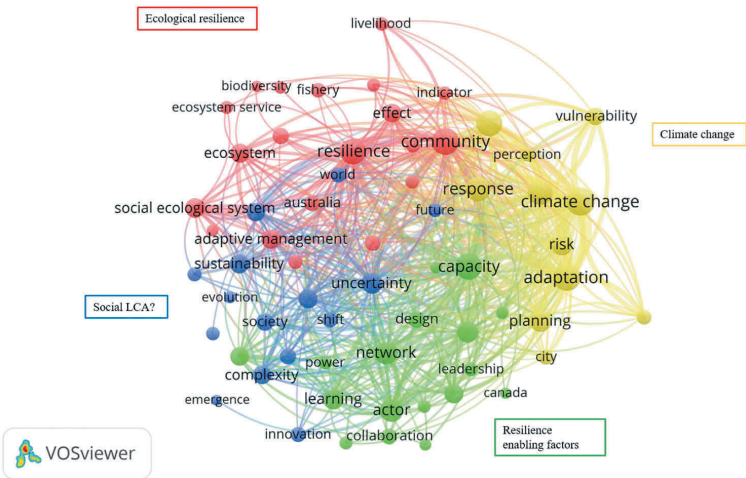

Figure 23. Network map of research on the concept of adaptive governance.

bases. Assets contributing to value creation are therefore not only tangible assets but also intangible, e.g., innovation, ideas, talent, reputation, well-being, etc. From mass production based on economies of scale, value is now created through mass customization, contextualization and creativity, favoring network rather than hierarchical organizational structures that are fluid, dynamic and capable of reconfiguration. Risk management similarly has had to be adapted to fit redefined perceptions of value creation through considering new, integrated frameworks for risk analysis, and going beyond traditional cost-benefit analysis of direct consequences with identifiable market values to consider both direct and indirect consequences of risk for which market values are not readily available (e.g., many environmental and social consequences).

At the same time, introducing concepts such as the circular economy into strategic risk management and governance is presently changing best practices in how risks are assessed and mitigated across industries and sectors. The new model of value creation rests on four crosscutting principles: (i) extending the use-cycle length of an asset, (ii) increasing the utilization of an asset or resource, (iii) looping or cascading an asset through additional use cycles, and (iv) regeneration of natural capital (WEF, 2015). The technocratic solution for enabling the new value business models rests on continuous development and implementation of smart technologies whereby the latter enhance knowledge about the location, condition and availability of assets, which in turn adds value to the product or service.

Unlike the concept of inclusive growth/wealth, the concept of circular economy takes scientific basis in quantitative sustainability. In Figure 22 four distinct clusters can be identified. The red cluster is the policy and governance cluster, which combines socio-economic considerations of sustainability. The closely related green (Quantitative Sustainability) and blue (Energy, Water and Agriculture) clusters relate to various aspects of Environmental engineering and natural resource management. The small and largely disconnected yellow cluster represents the extractive raw materials industry.

4.5.5. The concepts of adaptive governance and social ecological systems

The strategic principles for managing risk in accordance with sustainability and resilience considerations is first and foremost a governance issue. Governance and management are not the same but to be effective they require coherence and unison between them. Governance can be understood as the institutional arrangements in society that shape the decisions and behavior of societal stakeholders. Institutional arrangements can be understood as rules and norms (Ostrom, 2005). Management, on the other hand, explicitly refers to the processes of decision-making that involve the distribution of resources. In the following, the trend of transitioning from governance based on centralized expert management to adaptive governance is outlined. Principles and attributes of adaptive governance are briefly explained, and the conceptual framing of adaptive governance is critically discussed in the context of its application to risk, sustainability and resilience.

In Figure 23 Adaptive Governance is visualized. The map has four clusters. The yellow cluster is unified around the concept of climate change. We find it difficult to make sense of the other three clusters. It could be argued that all nodes in the other three clusters represent aspects of Policy. In the red cluster, we see resilience from an ecological and perhaps long-term perspective. In the blue cluster, social systems seem to appear through notions of Sustainability, Innovation, World. We label this cluster with hesitation Social LCA. The green cluster is also in the human/social realm of leadership, learning, collaboration, design, power, and capacity, or in other words factors that enable resilience.

Although the term *adaptive governance* is relatively new, it draws on extensive scholarship in the field of ecology, particularly the *adaptive management* notion as ‘active’ scientific hypothesis testing ‘in the field’ in the context of social-ecological systems proposed by Holling (1978) whereby management interventions are treated as experiments from which both managers and scientists can learn and adapt. The notion of panarchy was subsequently developed (Gunderson & Holling, 2002) as a possible framework describing stability and change dynamics in complex systems through a nested set of adaptive cycles (analogous to birth, growth, maturation, death, and renewal). Resilience is then explained through the adaptive cycle process and interactions among fast and slow variables that affect the adaptive cycles (Gunderson, 1999; Plummer, 2009).

Another line of scholarship on adaptive governance focuses on the study of cooperative strategies for the management of common pool resources (Carlsson & Berkes, 2005; Olsson et al., 2004; Folke et al., 2005; Plummer, 2009; Ostrom, 1990, 2010; Dietz et al., 2003). Key notions here include the concept of co-management as a dynamic, multi-level and policy-centric process that tries to achieve a balance between centralized and de-centralized control through the integration of local knowledge and formal scientific knowledge of natural resource systems and social-ecological systems inter-relations.

Adaptive governance is also studied in the context of collaborative governance of environmental problems

(Holley, 2010; Holley et al., 2011; Sabatier et al., 2005; Wondolleck & Yaffee, 2000), natural hazards management (Djalante et al., 2013), sustainability (Folke et al., 2005; Hatfield-Dodds et al., 2007), participatory civic democracy (Brunner et al., 2005; Dorf & Sabel, 1998; Freeman, 1997–1998) and adaptive experimental learning (Dewey, 1948/1920]); Holling 1978; Walters, 1986).

There is no formal definition of adaptive governance as it draws from various knowledge bases and is applied across a spectrum of concerns. Schultz et al. (2015) provide a general description, which could then be adapted to the different contexts of natural, human and social capital: 'Adaptive governance refers to flexible and learning-based collaborations and decision-making processes involving both state and non-state actors, often at multiple levels, with the aim to adaptively negotiate and coordinate management of social-ecological systems and ecosystem services across landscapes and seascapes.'

In order to understand the common principles and attributes of adaptive governance whether applied to ecosystems or social systems or a combination thereof, a contrast is made with the traditionally applied mode of management, namely that of the 'centralized expert management'. Critics of the traditional approach (Brunner et al., 2005; Dietz et al., 2003-Folke et al., 2005; Holling, 1978; Ostrom, 1990, 1999; Walker & Salt, 2006) have argued that the top-down, centralized institutional arrangements, which typically rely on reductionist science, may work for engineering problems and strictly controlled systems but are inadequate in the context of complex social-ecological systems. Hatfield-Dodds et al. (2007) locate adaptive governance in the middle of the spectrum, between centralized expert management and what they call 'romantic agrarianism' (a form of management that resonates with the de-growth governance philosophy). Adaptive governance is different from the other two types fundamentally because it is based on a philosophy of holism and systems science as opposed to that of reductionism. Unlike centralized expert management, which is based on silo disciplinary scientific knowledge, or romantic agrarianism, which only recognizes local traditional knowledge and customs, adaptive governance is about integrating different types of sources and knowledge that would add value to decisions. In this respect, adaptive governance is fully compatible with the notion of risk-informed decision support vs. the technocratic risk-based approach.

The state-managed approach derives its source of power and legitimacy through externally imposed government powers and resources implemented through carrot and stick policies in the belief that individuals are generally uncooperative. Targets are met through re-aligning the incentives of the resource users under the assumption that individuals are principally motivated by self-interest. Self-reliance and self-sufficiency (values cherished by the agrarian romantics) have no place in such a governance system. The relationship between policy and science in the technocratic model can be described as one where politicians use scientific experts as tools for behavior control.

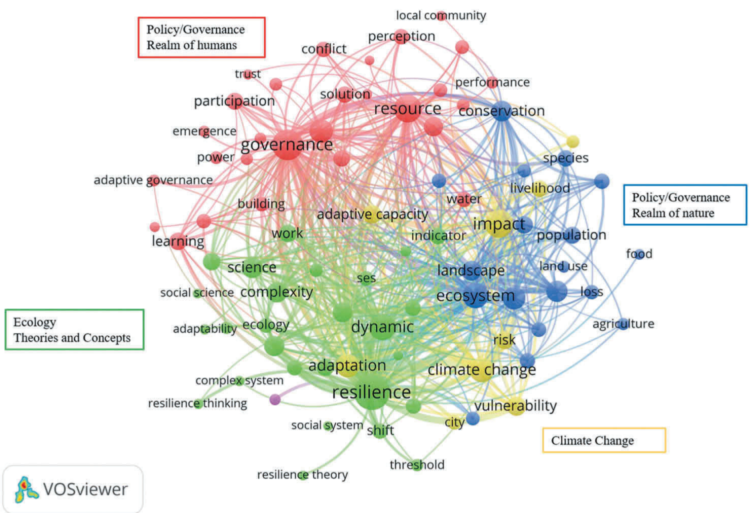

Figure 24. Network map of research on the concept of social ecological systems.

Adaptive governance, through its inclusion of multiple groups of interests from both state and non-state actors, derives its source of authority and legitimacy on the basis of multiple sources of participation and open civic democratic process of decision-making which is typically bottom-up. It attributes a mix of motives, including self-interest and regard for others, and grants individuals the capacity for cooperation and self-organization. The power dynamics in this system of governance are based on respect, trust and cooperation – all elements of the degree of social capital in a given society. The role of the scientific expert is seen as that of learning partner and facilitator on par and in cooperation with local practitioners and governance representatives. Reductionist scientific methodologies are not applicable in such an open and evolving context. Instead, continual trial and error experiments are advocated that can be replicated locally for faster and more effective learning thereby facilitating solutions to problems that are evolving and context-specific.

Learning is key to the concept of adaptive governance as it is seen as the capacity (social or natural) to respond to changes in a way that ensures survival and thriving, both literally and metaphorically. Social and transformational learning are explicit aims in adaptive governance and management.

How social learning is understood and defined depends on the epistemological tradition in the various application areas that have adopted the concept. Ison and Watson (2007) define social learning 'as achieving concerted action in complex and uncertain situations.' Reed et al. (2010) critique the misuse of the concept of social learning has been misused to describe not social learning itself but the conditions that enable it, i.e., stakeholder participation. They distinguish furthermore between social learning as an outcome and as a process, and clarify differences between individual and social learning. For them social learning is a type of practical learning by doing based on experience, and successful group processes based on the social interactions among the actors involved. Social learning implies a change in understanding in the individuals involved in-group learning, but this change goes beyond the individual and becomes embedded within wider social units. Ison et al. (2013) provide an analysis of metaphoric clusters associated with social learning, identifying seven semantic domains: performance, action, governance mechanism, balancing act, paradigm, cognition, and communication.

Social learning in the context of governance of social ecological systems should be understood as a governance mechanism as well as a set of practices that favors collaborative learning arrangements of different stakeholders and different types of knowledge, emphasizing participation, negotiation and team performance. Social learning unsurprisingly helps build social capital, or those social relations of trust, reciprocity and engagement that are said to be key for developing the adaptive capacity that makes systems resilient.

Folke et al. (2005) elaborate on what they consider the critical factors of the social sources of resilience that are instrumental in securing a system's integrity during periods of disturbance, change and transformation. *Social memory* has a central role in this process. In the present context, social memory can be understood as the collective experience of past disturbance events and the responses to those both on part of the community and the responsible governance structures. Social memory is thus the 'lessons learned, linking past experience and future adaptive response' (Folke et al., 2005). The effectiveness of social memory is

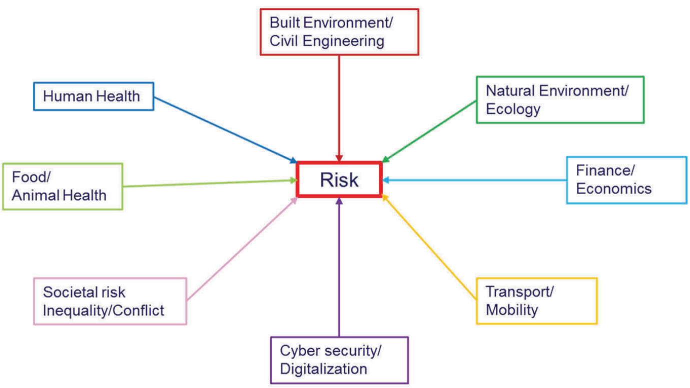

Figure 25. Illustration of disciplines and application areas where risk-informed decision-making is typically applied from a disciplinary or more rarely interdisciplinary perspective.

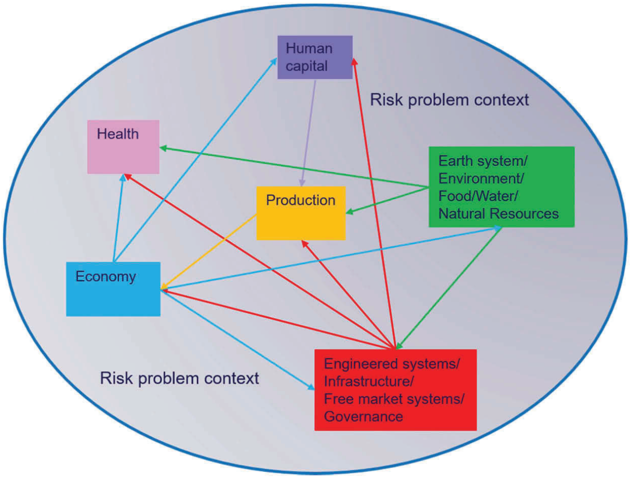

Figure 26. Illustration of necessary trans-disciplinary perspective for the integration of sustainability and resilience into risk (adapted from Faber 2018).

facilitated through different actors and teams of actors who all have distinct roles in getting a social network to respond and collaborate in the face of a disturbance, emphasizing the importance of diversity in the social fabric composition from diverse knowledge bases and practices to diverse psychological and personality traits of the group. Experimental studies of collaborative (learning) environments show that team size, newcomers and previous alliances all affect group performance (Guimerá et al., 2005) and that in the process of collaboration distinct roles such as leaders, critics, knowledge generators, knowledge transmitters, stewards, interpreters, visionaries, innovators, experimenters, followers, and reinforcers spontaneously emerge and organize (Folke et al., 2003; Gladwell, 2000; Holling & Chambers, 1973; Olsson et al., 2004).

In an overall strategic framework aiming to enhance the resilience of a given system, adaptive governance can be viewed as the strategic direction in pursuit of the goal, while growing learning institutions, based on social learning and experimental, in-context problem-based learning would be the means to strategy.

Finally, we consider the concept of Social Ecological Systems. On the map in Figure 24 we see four distinct clusters and a pink single node. The node stands for Social Ecological Resilience, and we have incorporated it in the green cluster. The green and red clusters share almost the same size, but the link strength of the green cluster is closer. The red cluster is the social/policy cluster of humans (governance, learning, participation, conflict, perception, resource) while the green is the theoretical or conceptual ecological domain (e.g., SES, resilience, adaptability, threshold, shift). The blue cluster is the non-human natural capital cluster (land use, landscape, ecosystem, species, conservation). The yellow cluster with nodes spreading all other three clusters is climate change.

Our interpretation and conclusion from comparing the maps in Figures 23 and 24 are that the apparent absence of the Engineering knowledge domain in issues pertaining to policy and governance and the strong dominance of the Ecological domain comes from the lack of ability of Engineering to position itself as a strategically relevant discipline influencing the long-term direction of research due to its myopic focus on operational and tactical issues. The implications for Engineering risk-resilience-sustainability decision support are that the Engineering knowledge domain faces the danger of being marginalized as a contributing body of knowledge by the more strategically and ideologically related realms of Environmental sciences and Ecology.

5. Implications for education

As a result of integrating resilience and sustainability considerations into risk assessment and management, new concepts have been formulated which go beyond disciplinary or even multi-disciplinary boundaries and are instead truly trans-disciplinary in nature, e.g., social ecological systems, circular economy, planetary boundaries, inclusive growth, adaptive governance, etc. At the

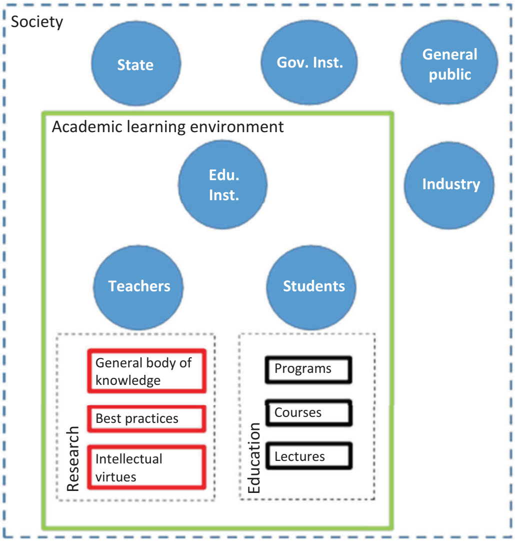

Figure 27. Illustration of main stakeholders (blue circles), assets (red frames) and instruments (black frames) in future risk education (Faber & Nielsen, 2017).

forefront of research are studies aiming at joint operational methodologies for risk, sustainability and resilience, accounting further for possible trade-offs among stated societal preferences. The bibliometric trends analyzed in this paper, together with a survey[2] of existing risk education programs have revealed that there is a significant gap between research and education, where education in the area of risk is stuck somewhere in the 1990s at best in terms of the disciplinary content (scientific theories and methods) as well as the classification of risks according to sector-specific or discipline-specific procedural models. Figure 25 shows the disciplinary view of risk, which at present is how the vast majority of risk educational programs are organized.

From the disciplinary and occasionally multidisciplinary perspective, risk education typically has the following components, taught more or less in the same sequence:

- Sources of risk in discipline X
- Regulative frameworks in X
- Procedural models for Risk Assessment in X (typically, assessment and management are separated through formal regulative frameworks as is the case in e.g., Environment and Food so that no political bias can enter the 'scientific' assessment of risk or an informal separation of quantitative 'hard' science vs. qualitative 'soft' managerial practice as is the case in e.g., Built Environment, Transport, Economics, etc.)
- Procedural model for Risk Management in X
- Scientific models in X (theories and methods)
- Data and metrics in X

When we compare this with the trans-disciplinary perspective, which the integration of sustainability and resilience into risk necessitates (Figure 26), we realize that our educational practice is simply inadequate due to the complexity of interactions and dependencies among engineered, natural and social systems.

To define any particular risk, its networked structure and the extent and strength of dependencies must first be identified within a system's boundary. Only after such trans-disciplinary and trans-sector system identification is performed can we begin to discuss theories, models, methods, metrics, and regulative constraints. Seen in this trans-disciplinary perspective, all risks are decision problem contexts and systems in and of themselves. They are furthermore complex systems because they are dynamic, evolving and have non-linear dependencies. Knowledge about a risk decision context cannot be known to the teacher a priori nor can it be taught as it is traditionally done through a curriculum that is based on the transmission from teacher to students of theories and methods to be applied to pre-identified and structured problems. Knowledge in the domain of risk is liquid and trans-disciplinary. By liquid, it is meant that the focus is on problem scenarios that could be taken in any order rather than on the notion of solid content that follows a pre-determined sequence (Savin-Baden, 2008). By trans-disciplinary it is meant that different disciplinary perspectives are merged together, resulting in new knowledge, which is co-created by all participants. In this sense, it is also a product of transitional and social learning, which are at the root of the adaptive capacity that fosters resilience on both the individual and the collective levels.

In addition to the trans-disciplinary and liquid characteristics of the knowledge environment of risk, a design for risk education must be informed by stakeholder engagement, social responsibility and the acquisition of both intellectual and civic values. As an applied discipline, risk must ensure that in educating future practitioners, a professional code of ethics must be adapted for the risk professional, modeled in principle after the Hippocratic oath future professionals in the medical field must adhere to (First, do no harm). As such, the design for risk education must formulate learning objectives, based on societal needs and preferences rather than narrow individual interests or industry preferences that are not in harmony with societal goals for sustainable development. In Figure 27 a system representation of the knowledge environment in which risk operates is given as an outline of the system boundary for a future design of risk education. It can be seen that education and research go together and that the general body of knowledge has to be developed continuously, with new findings and insights from the research community finding way into practice and educational activities. However, it is also important to appreciate that even in areas of education where the research front is not moving, or moving very slowly, there is a tremendous task for the educational institutions in preserving the already available knowledge.

The design basis for risk education should build on the theoretical foundations from systems thinking, Bayesian decision analysis, research problem-based learning, and transitional and social learning. As such, risk education will be based on the integration of multiple disciplinary perspectives, the inclusion and participation of stakeholders representing different societal sectors in the processes of establishing the risk problem context. The production of knowledge and the process of learning will be a joint endeavor of academic subject expertise, pedagogical facilitation and student active learning through inquiry-based project work.

Box 1. Key conclusions from bibliometric analysis.

- All 3 domains – risk, sustainability and resilience show an upward trend in production of research. Risk is dominant field. There is some integration between risk and sustainability and between risk and resilience. Research combining all three is in its infancy.
- The top 3 contributing disciplines are: (i) Environmental Sciences/Ecology, (ii) Engineering, and (iii) Economics representing, respectively, ecological, engineered and social systems perspectives.
- Risk research over the last 30 years has undergone a transformation from a predominantly decision theoretical/Civil Engineering perspective toward an environmental/ecological perspective. The traditional Engineering area of Health and Safety (OHS) has been strongly marginalized. New areas of research have gained importance: Climate Change, Natural Hazards, Food Safety.
- Research in sustainability and resilience is dominated by the developed western countries (USA, the UK, Canada, Australia, and Sweden). China is a major contributor to quantitative sustainability and circular economy research.
- Despite lower output of research in comparison with the Environmental Sciences/Ecology knowledge domain, the centrality of the Engineering knowledge domain in the network representations could be interpreted as the Engineering systems perspective affording a potentially unifying role among the 3 systems perspectives. The success criteria for living up to such a role would be the integration of risk, resilience and sustainability into joint strategic, operational and tactical frameworks for assessment, management and education.

6. Conclusion

The ability of notions such as risk, resilience and sustainability to integrate within conceptually different knowledge domains has promoted their diffusion across a wide range of disciplinary areas. As descriptors of desirable and undesirable system states across biotic lifeworlds and man-made built environments, they can be found in every activity we seek to acquire knowledge about that may assure our continued existence and well-being. The systematic scientific study of risk has a significantly longer history than that of resilience and sustainability, dating back to the evolving understanding of probability since the 17th c. that allowed predicting future events and the resulting empowerment to make deliberate decisions based on informed choices. The application of probabilistic methods has since driven capital markets, insurance, industrial development, transport, and healthcare. Since the second half of the twentieth century, the knowledge domain of risk has broadened to include theoretical and empirical behavioral aspects of decision theory, game theory, and neuro-cognitive sciences.

While in the second half of the twentieth century the field of risk was characterized by a narrow technocratic and expert-driven assessment of risk, a fundamental shift was initiated at the turn of the millennium as a response to a policy demand for pragmatic, evidence-based decision support that would legitimize the decision-making process by making it more transparent and participatory, and, at the same, take explicit consideration of sustainability and the optimization of scarce natural resources. Integrated risk management frameworks were promoted across public and private sector organizations and academia, calling for an explicit consideration of the interaction between all relevant agents – technical and structural elements, nature, humans and organizations – in the assessment of the risks associated with a given system. The idea of integrated risk management offered a contrast to the previous technocratic approach. It advocated a holistic perspective not only in terms of considering multiple risks through a portfolio approach (a so-called *all hazards approach*) but also taking time into consideration. This meant that risk assessment should be performed to consider all phases of the life of a system, from the early design phase to the end of the service life, including decommissioning. Furthermore, economic development in the present time should not jeopardize the ability of future generations to meet their needs (WCED, 1987). In the disciplinary domain of environmental risk assessment and management and related Life Cycle Assessment methodologies, this concept was popularized through the term 'cradle to grave' approach. Once established as a normative sustainability goal, it quickly spread to other disciplines and industrial sectors, e.g., 'farm to fork' – in the context of human and animal health, but was soon to be replaced by the 'cradle-to-cradle' philosophy that has now come to epitomize the principles behind the concept of circular economy that is presently a strong normative component of sustainable growth. But while the sustainability discourse entered the risk domain largely through economic considerations of efficiency and optimization of scarce resources and ethical considerations of inter-generational justice, thus bringing the technical aspects of risk assessment closer together with the socio-economic aspects of risk management, resilience was more a qualitative reformulation of a concept that was already part of the risk knowledge domain; namely, robustness. Over the past 30 years, the notion of resilience, with its firm roots in ecology, became transplanted and adapted to the risk domain, resulting in an explosion of academic and gray literature. Risk, formerly studied and taught primarily as a specialization in civil engineering, economics and finance or through the lens of safety in transport and industries such as oil and gas, mining and petrochemicals, has become a much broader knowledge domain that could be seen as a discipline in its own right.

As a result of incorporating resilience and sustainability considerations in the assessment and management of risk, the systems of interest have also expanded in scale from mainly closed industrial engineered systems to open social-ecological systems. Problematically, not all theories and methods can be exported from one knowledge domain to another, creating both strategic challenges for risk governance and operational challenges for risk management. Educational objectives and methods must be re-evaluated to align with both academic research and societal needs.

The principle aim of this study has been to bring order among the multiplicity of concepts and perspectives that join research and discourse on risk, resilience and sustainability through combining a transparent bibliometric analysis of the literature with a rich contextual qualitative description of established and emerging concepts. In the present study founded on an assessment report by the authors, based on 442,171 records and three decades of research, we show the historical evolution of the knowledge domains of risk, sustainability and resilience on a to-date unprecedented scale. Based on this assessment and more than 100 cluster network maps we illustrate the different disciplinary contributions, important authors, geographic distribution of the research, and the organizations producing the research.

Our main conclusions are summarized in Box 1.

The focus of the qualitative analysis has been to describe emergent concepts as a result of integrating resilience and sustainability considerations in the knowledge domain of risk as well as how such integration might impact future research and education. We have identified four characteristics of the knowledge environment relevant for the development of risk education (i) liquid knowledge, (ii) trans-disciplinarity, (iii) social responsibility and stakeholder engagement, and (iv) intellectual and civil society values. These characteristics call for a high level of plasticity in designing a learning environment that can accommodate both the dynamic nature of knowledge content and the dynamic engagement among multiple societal stakeholders. We conclude that a future learning design encompassing risk, sustainability and resilience must build on the theoretical principles of systems thinking, Bayesian decision analysis, inquiry problem-based learning and transitional learning.

Notes

1. Available at: http://vbn.aau.dk/files/286815989/Data_report_for_the_bibliometric_analysis_of_risk_sustainability_and_resilience_research_from_1990_to_2017.pdf.
2. A copy of the survey can be obtained by writing to the authors.

Disclosure statement

No potential conflict of interest was reported by the authors.

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CHAPTER 4. FAITH AND FAKES – DEALING WITH CRITICAL INFORMATION IN DECISION ANALYSIS

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Faith and fakes – dealing with critical information in decision analysis

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ABSTRACT

Decision making subject to uncertain information, whether fake or factual, in the context of management of socio-technical systems, is critically discussed from both philosophical and operational perspectives. In dealing with possible fake, incorrect and/or factual information we take the perspective that any information utilised as basis for supporting decisions, has to be dealt with in exactly the same manner – in accordance with Bayesian decision analysis. The important issue is to identify and model the scenarios through which information may cause adverse consequences and to account for their potential effects. To this end we first provide a mapping of how information affects the decision making context and a categorisation of causes for information leading to adverse consequences. Secondly, we introduce a decision analytical framework aiming to optimise decision alternatives for managing systems including not only one possible system model but a set of different possible system models. As a means for assessing the benefit of collecting additional information, we utilise Value of Information analysis from Bayesian decision analysis. Finally, a principal example is provided which illustrates selected aspects of how possibly fake information affects decision making and how it might be dealt with.

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1. Introduction

Public concern with the phenomenon of 'fake news' has highlighted the risks and fears of information gone out of control and the associated force multiplier effects of digital connectivity in affording both the spread and the speed of disinformation. In 2016 the Oxford Dictionaries selected 'post-truth' as word of the year – an adjective defined as relating to or denoting circumstances in which objective facts are less influential in shaping public opinion than appeals to emotion and personal belief. In the same year, 'fake news' became mainstream during the U.S. election campaign, used by Donald Trump to describe unfavourable media portrayals of himself in the media but also by various official and academic entities monitoring and analysing the misuse of digital platforms for the purposes of, e.g. influencing voting results or causing havoc during emergency situations (Pomerantsev and Weiss 2014; Silverman and Alexander 2016; Starbird 2017). The 'threat' of fake news has in the span of several years turned into a mixture of hysteria and nihilistic

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skepticism. A comprehensive literature review of academic studies on the phenomenon of fake news is provided in a recent report of the European Commission's Joint Research Centre (Martens et al. 2018) which shows that there are in general two types of investigations: (i) quantitative studies that model the propagation of fake news through various media and (ii) empirical surveys of public opinion that attempt to draw conclusions about the impacts of fake news on e.g. voter behaviour, ideological (re)alignment and citizen activism. The focus of the present paper is rather different; namely, we aim to provide an operational framework for how to deal with fake news in the context of ranking decision alternatives. We do not consider possible strategies of identifying whether given news is fake or not.

This paper aims to contribute to an unemotional and rational discussion on how to manage information of different degrees of 'truth' in the context of risk-informed decision support irrespective of disciplinary or application domains. The introductory section provides the rationale for the proposed methodological framework through a historical, cultural and philosophical contextualisation of the notions of truth, reality and their perception. It explains why a phenomenological and consequentialist approach forms the basis for the proposed framework and the motivation for our choice of operational definition of information. Thereafter, a generic system representation, which facilitates the utilisation of the suggested approach for the management of information is introduced. The application of the proposed generic system representation is then illustrated and discussed in the context of a principal example where also parallels are drawn to practical cases where different categories of information are of significance.

2. A philosophical and historical view to truth, reality and their perception

2.1. Is there anything new about fake news?

Why is the phenomenon of 'fake news' currently selected as an elevated societal concern even though disinformation is as old as the history of human warfare and transcends geographical and cultural boundaries? Depending on how constrained a definition of disinformation we choose to adopt, we could even argue that fake news is not a uniquely human invention but is also attested among non-human biological organisms whether as a means to take advantage of an adversary or to escape harm. Why are certain variations of 'fake' information such as that found in marketing and advertising campaigns perceived as less threatening to society than a fake news tweet or blog entry about a politician or a current scientific assessment? The present societal preoccupation with fake news and related terms, e.g. post-truth, alternative facts, etc., is typically explained in terms of the risks associated with digital connectivity and the rise of 'information society'. Information has been labelled the 'currency' of the digital age; it is pervasive in all public and private spheres of life. Once largely under the control of societal institutions (governments, churches, universities), it has largely been liberated from the institutional monopolies of control – at least in Western democracies – at the price of diminishing public trust.

The spread of information through digital technology is not the only explanation; neither the most significant one. The perception of fake news as a risk with adverse consequences is largely driven by cultural and educational factors. Thus we see that the target of fake news are typically western democracies whereas the origins are typically traced to Russia or a number of small countries on the European eastern periphery. The former has both an ideological and an opportunistic motivation, a long professional experience of information and psychological operations (denial and deception) during the Cold War, and the actual technical ability to carry out such operations (i.e. a good supply of IT professionals). The latter may not be concerned with influencing ideology, but use fake news as a financial opportunity to compensate for the lack of employment or decent wages (Davey-Attlee and Soares 2017). Fake news is not news in societies which have a long experience in state censorship and propaganda. There fake news is the reality that doesn't make it to the news. By contrast, fake news becomes news because of the surprise effect it has on a society accustomed to lack of censorship and trust in the societal institutions to represent the interests of its constituents. Culture need not be understood along national borders alone. According to anthropologist Mary Douglas writing in the context of risk perception, the selection of dangers a society decides to prioritise is an expression of the choice of social organisation of that society (Douglas 1992). Thus, what a society perceives as true depends on cultural categories created along with the social relations they are used for defending. A society where the governance structure is hierarchical, i.e. where individual members are encompassed by the whole is typically enshrined in bureaucracy and tradition. It is strongly risk-averse and ignores or fears uncertainty. It needs therefore 'truths' which are stable, reliable and unchanging – it needs 'true facts'. A society whose governance structure reflects that of a free market places value on the individual rather than the collective institution. Here uncertainty is not to be feared, rather it is perceived as opportunity. The risk portfolio of such a society is risk seeking. Individuals, not the state are responsible for their welfare (social and health benefits, education, etc.) and losses are blamed on chance or on stupidity. The ideology of 'true facts' has little meaning to such cultural mentality.

Finally, the outcry of the danger of fake news illuminates a discrepancy (at least in the context of Western societies) between scientific research and our education systems. It would be difficult to find scientific research after roughly the middle of the twentieth century which subscribes to an objective and solid idea of truth as imagined by e.g. Plato or the positivist movement in both science and philosophy (roughly from the end of the 18th to the early 20th c.). Our educational institutions, however, have been slow and reluctant to change educational models and methods, many of which stem from precisely the positivist period, when facts and certain truths were the only serious pursuit of science, all else being labelled speculative metaphysics. As a society that values research and innovation as a means of improving life for humanity, we owe it to ourselves to examine where our prior beliefs of unshakable true facts comes from.

Finally, we wish to highlight that all current definitions of fake news miss an important semantic domain. Common to all these definitions is that fake news are intentional wrong messages sent out to the benefit of the transmitter. This omits a class of fake news, which may be sent with the intent to benefit the receiver, and thus, not necessarily malevolent. Under this class could be included moral instructions aiming to benefit a recipient which are not based on scientific evidence. In the present paper, we thus adopt a broader semantic range for what constitutes 'fake'.

2.2. Truth, reality and perception from a philosophical and historical perspective

The concept of truth is fundamental to philosophy and science. In the context of truth, science (Gk. *episteme*) is just one branch of philosophy. Hence an inquiry into the historical development of the concept of truth provides an explanation of the motivation behind the methodological framework outlined in this paper. The question of what truth is and what makes something true is central to all five main branches of philosophy: ontology (or metaphysics) is concerned with what is true, i.e. what exists in reality; epistemology – with what can be known and how we come to acquire knowledge; logic (and subsequent modern analytical philosophy) – with the validation of truth; phenomenology – literally, with appearances (Gk. *phainomena*) or the perception of truth through experience; and ethics – with right or wrong action in respect to truth. It could be argued that historically humanity during the classical period of philosophy (e.g. Plato, Aristotle) was primarily focused on problems of truth related to metaphysics and ethics. The Enlightenment period (e.g. Descartes, Hume) was primarily interested in truth from the point of view of epistemology. The Victorian era and early 20th c. (e.g. Russel, early Wittgenstein) was preoccupied with logical problems of truth. The 20th c., when coincidentally many of the applied sciences were born, was interested in truth as it appears through our perceptual experiences (e.g. Husserl, Heidegger). Our present position derives from the phenomenological school of thought, however, given the normative nature of decision support, it additionally accounts for ethical implications. In the context of fake information, constructivist epistemology may be used to justify the (im)possibility of objective knowledge. In Hennig (2010) explicit consideration is given to the application of the constructivist paradigm with relation to data analysis based on frequentist (objective) and Bayesian (subjective) interpretations of probability. In the present paper, we identify with the constructivist perspective of reality in so far as we see it as a manifestation of the phenomenological tradition in philosophy and in science. While it is not our purpose to define truth or what can be true but to offer an operational framework for dealing with problems where the extent of true and false information cannot be ascertained a priori, we nevertheless find it important to offer some background on the motivation for choosing a phenomenological and consequentialist basis as a rationale for the proposed framework.

2.3. On the relevance of phenomenology and consequentialism in risk-informed decision support

Phenomenological models are typically defined as models that represent only empirical observations of the physical world without resorting to a-priori assumptions. Data models or statistical models (e.g. regressions) are a kind of phenomenological model in that they do not attempt to form an explanation or theory of why given variables are correlated in a particular way, but rather aim to represent the relation among the variables. In phenomenological models truth is always subjective and dependent on the interpretation of the observer. In contrast, models of theories make a claim on the truthfulness of a proposition, which is derived on logical principles and require no evidence of observations in the physical world. The polarity truth-appearance is a legacy of the split between the pre-Socratic doctrine of flux of Heraklitus and Parmenides' doctrine of denial of the existence of change. Heraklitus held that what is real is constantly changing and that no object retains all its constituent parts or qualities from one moment to the next. Parmenides developed a logical argument against the existence of change. From the premise that it is impossible to think or talk about what does not exist, he deduced that (i) there is no coming into existence or ceasing of existence, i.e. nothing can be created and nothing can be destroyed; (ii) alteration or change is therefore impossible; (iii) movement is therefore impossible; (iv) plurality is therefore impossible. Here we have in a nutshell the two opposing views of truth – the Heraklitean notion that what is true or real is constantly undergoing change, so at no given point in time is truth or reality monolithic and absolute and the Parmenidean notion of truth as an absolute and of eternal duration. These views were further developed by Aristotle and Plato respectively and have been used to distinguish scientific, phenomenological and experimentalist view of truth and reality from the theological and analytical- mathematic perspectives. In the present paper when we apply the term truth we distance ourselves from the Platonic logico-analytical interpretation. Our approach bears a connotation to the flux doctrine of Heraklitus and to Aristotle's application of the phenomenological method. Essentially this implies the underlying assumption that the truth about a system of consideration can be established in phenomenological terms. The available knowledge about the truth of the system (what in the social sciences might be referred to as the 'lifeworld') is fundamentally subjective as we perceive it.

In taking this position we are further considerate of the applied context in which risk management or decision support take place. In this sense the operational framework is not only about truth and method but also about the ethics of the method we endorse. Given the normative purpose of risk management to provide societal decision support through a rational and transparent ranking of decision alternatives in conjunction with utility principles, our framework follows an essentially consequentialist approach. While there are different schools in the consequentialist paradigm (e.g. classical utilitarianism, hedonistic, pluralistic, actual, and expected consequentialism, and pragmatism), the common view that unites them is that normative properties of an act (we can substitute here decision) depend only on the effects, not the causes of an act (decision). It is not difficult to see why applied disciplines such as engineering or decision analysis adopt a consequentialist approach to truth whereas basic or fundamental sciences such as mathematics, logic, philosophy, physics, etc. rely on causal explanations to validate their theories and truths.

A consequentialist approach, however, does not address the question of relevance. In analytical philosophy, the notion of 'truthlikeness' is the idea that propositions should be assessed not simply in binary terms (true-false) but according to their proximity to the truth or degree of truthlikeness (Oddie 2014). It is pointed out that some false propositions might serve to get to the truth (e.g. Popper's idea of fallibilism) and that different truth propositions contribute to varying degrees to the realisation of objectives. We could think of these objectives as the 'truth, the whole truth and nothing but the truth'. The possibility of estimating truthlikeness relies on probabilistic methods for evaluating the evidence (in the phenomenological sense – the empirical observations). In this context we can speak of degrees of belief or degrees of certainty as propositions or sets of possible worlds or truth propositions. An extensive literature has grown around the epistemological foundations of Bayesian probability. Some classical texts that discuss concepts such as truth, belief and uncertainty from a Bayesian perspective include Ramsey (1926, 1978), Dretske (1971, 1981), De Finetti (1975), Walley (1991), and Olsson (2005). Using Bayesian probability theory we can model the probabilistic characteristics of events based on cumulative evidence. A best estimate based on evidence has more practical value to decision-making than truth arrived at on the basis of logical proof. In this sense Shannon's mathematical theory of communication (Shannon 1948) is compatible with our proposed approach as it provides essentially a probabilistic explanation of the relations between the states of two systems (sender-receiver in the context of MTC and electronic engineering; unrestricted application in the sense we propose).

2.4. Physical and semantic conceptions of information – do content and intent really matter?

In Figure 1 a system representation is given of the flow of consequences generated as a result of an exposure event. It can be observed that changes in the system state can be accounted for on the basis of adding the direct consequences (e.g. loss of life, damage to infrastructure, etc.) and indirect consequences (e.g. loss of business continuity, reputation losses, etc.). It is crucial to underline that societal risk perception regardless whether it is true or false, has impact on the system in that it has the potential to change the system's state. In other words, in the event that a system undergoes change as a result of perception, the information is equally relevant regardless of whether it is true information (objective facts) or false information (fake news or any type of intentional disinformation or misinformation or any type of unintentional error). However, as elaborated in Section 3.1 perception also importantly affects the preferences and objectives which decisions are based on. Moreover, it should be highlighted that the causes of system changes, e.g. such as natural hazards, acts of terrorism or political interference must be thoroughly understood to facilitate identification of relevant and efficient decision alternatives for managing the system and reducing risks.

Following Shannon's MTC, Weaver (1949) argued that the analysis of information can be viewed in terms of: (i) quantification of information in accordance with Shannon's

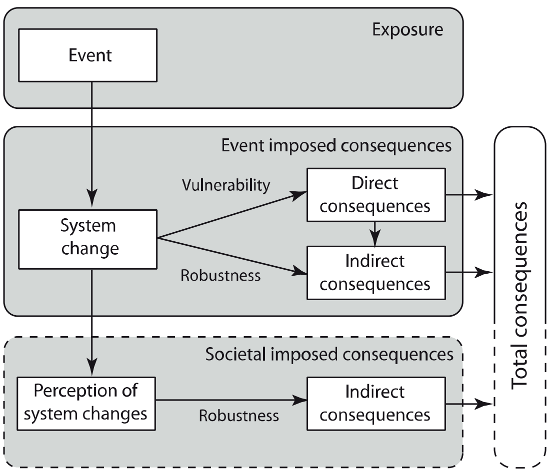

Figure 1. The JCSS framework for systems risk modelling (from JCSS 2008).

theory for the purpose of solving technical problems; (ii) analysis of semantic problems related to meaning and truth; and (iii) analysis of 'influential' problems with regard to effects of information on human behaviour. Clearly, in the context of risk management in support of societal decision making, all the above are relevant.

Given the pervasiveness of the concept of information in a wide range of application areas from computer science to linguistics to biology, there is no agreed definition of information, rather a multiplicity of operational definitions that fit particular contexts. Before we say which of these definitions we prefer as befitting the context of our present inquiry, we briefly look at implications of the physical and semantic conceptions of information with regard to decision-making under uncertainty. The physical conception of information is formulated through Shannon's MTC in the context of electrical engineering. It deals with the problems of data compression and data transmission. MTC is not concerned with the content or meaning of the data, but it does provide meaning about the potentiality of meaning through the concept of statistical significance. In the words of Weaver (1949): 'The mathematical theory of communication deals with the carriers of information, symbols and signals, not with information itself. That is, information is the measure of your freedom of choice when you select a message'. By treating information as a physical entity, MTC postulates that a lower degree of randomness or entropy is associated with less information and vice versa.

The semantic conception of information considers the content of information through the satisfaction of three criteria: meaningfulness, consistency and truth. Those who require the first two criteria only are proponents of the theory of weakly semantic information; those who require all three subscribe to the theory of strong semantic information. Floridi (2008) distinguishes further between instructional information (which must be meaningful in order to convey the need for action) and factual information (a declarative statement which may be true or false). Floridi has come to be known as the academic authority on the newly coined branch of philosophy – philosophy of information, particularly on ethical aspects of the uses of information. He argues (2004, 2008) that truth is a defining criteria of factual information and that misinformation and disinformation regardless of intent, or the lack thereof, are not to be considered as factual information. Opposed to this view, Fetzer (2004) and Dodig-Crnkovic (2005) have argued that false information, including contradictions are also instances of semantic information by virtue of fulfilling the truth-neutral criteria for meaningful and well-informed data. The weak semantic information school is closer to a probabilistic approach to semantic information in that it defines that in relation to a data model and its (in)consistency.

We find Bateson's (1972) definition of information best captures our proposition that information which has the potential to make a difference, i.e. generate change in a system of consideration, should be treated equally disregarding relation to truth and intent, and in accordance with Bayesian probability theory. Bateson, an anthropologist by education, but mostly known for his work in combining cybernetics with ecology, defined information as a 'difference' or negative entropy: 'In fact, what we mean by information – the elementary unit of information – is a difference which makes a difference'. Bateson's definition captures also Shannon's basic proposition to treat information as a measure, not as the true or false proposition of a theory. It fits well with the Bayesian method of extracting meaningful patterns from data without having to specify what the meaning is. What the method offers is a ranking of which differences make a bigger or smaller difference, which is a measure of the relevance of information. As such, it is of primary concern for risk-informed decision support as even true information when not relevant will be of little value at best.

3. Problem framing and approach

Starting point for the problem framing is taken in the premise that decision ranking is normative and based on Bayesian decision analysis (Raiffa and Schlaifer 1961) in conjunction with the axioms of utility theory (van Neumann and Morgenstern 1953). The theoretical framework for the representation of knowledge is selected as the Bayesian probability theory with due consideration of both aleatory and epistemic uncertainties, see also Faber (2005) and Der Kiureghian and Ditlevsen (2009). When attempting to rank decisions with respect to management of socio-technical systems by utilisation of information as basis for knowledge building, inevitably a discourse on the concepts of knowledge, systems and truth is encountered. As elaborated in Section 2 we take the perspective of the phenomenologist and represent the available knowledge in full appreciation that this is subjective and model this probabilistically in accordance with e.g. JCSS (2008) to represent how different decision alternatives may affect achievement of the preferences of the decision maker. At this point it is important to highlight that the preferences of the decision maker often involve and depend on the perception of stakeholders concerning consideration of and choice of decision alternatives (strategies) as well as the outcomes of these. Moreover, the freedom of the decision maker to choose among strategies may also depend on the perception of the stakeholders.

3.1. Information flow in risk management

As illustrated in Figure 2 there are important dependencies and back-couplings between information, the decision maker and the stakeholders to the decision making.

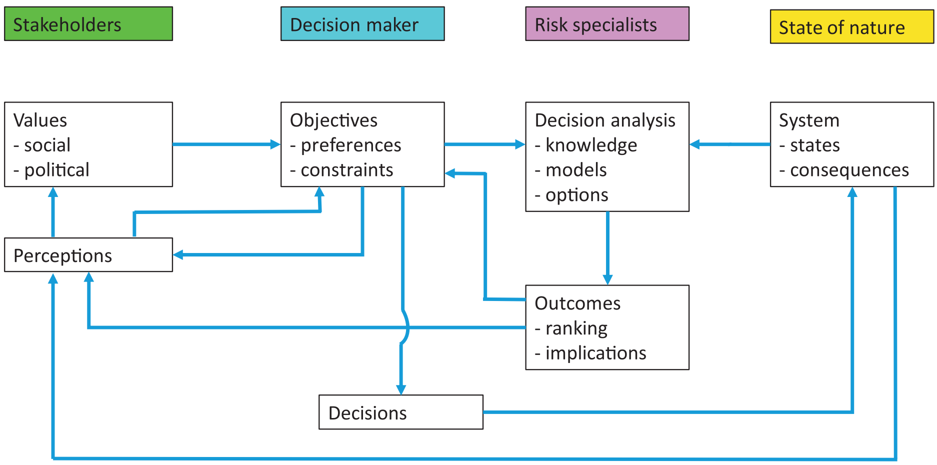

Figure 2. Illustration of the system and stakeholders in the decision making context with focus on the flow (arrows between boxes) of information affecting decision ranking and outcomes of decision making.

Whereas the general understanding of risk management and also the current practices focusses on the modelling and management of what is indicated as the system in Figure 2 (representing the role of the 'True state of nature') it should be underlined that the system which ideally should be considered in the risk-informed decision analysis envelopes all processes (nodes and flows of information) in Figure 2 – including the tasks of the 'Risk specialist'. In this manner the node with the title 'System' should be understood to comprise the full contents of Figure 2.

Generally, the best available knowledge about a systems is understood to be comprised of fundamental phenomenological physical understanding and experience combined with information (often referred to as evidence) – collected and processed over time. From the mechanism of knowledge building and information flow within the context of decision making, see Figure 2, it is evident that decision making is faced with a number of important conditions of information affecting the outcome of decisions. These conditions of may be categorised as:

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

It is important to note, as evident from Figure 2, that the interaction between 'decision-maker' and 'stake holders' as well as the perception of stakeholders with regards to consequences of decisions play an important role in the formation of the preferences, objectives and available decision alternatives defining the domain of possible decisions of the decision maker. Moreover, over time the preferences of stakeholders will shape the value setting which forms the basic premises for risk management. In practical risk management it is often seen that perceptions of stakeholders may significantly affect the premises of societal decision making, not least due to the political pressures imposed by public opinions, press coverage and social media. In such cases it is not rarely seen that the public opinion exerts pressures on societal decision making to an extent where more fundamental values on e.g. equity with respect to life safety may be violated, see also Faber, Schubert, and Baker (2007). As emphasised in Faber et al. (2012) this calls for identification and implementation of a common rationale for the management of risks, which defines the space within which perceptions and public opinions may be allowed to affect the premises of decision making. A common rationale for the management of societal risks necessarily must be established in a dialogue between stakeholders and decision makers. Such a dialogue is challenging but may find substantial support in a structured process of risk communication and by taking benefit from risk communication protocols, where emphasis is directed on the development of informed preferences for societal risk management, see e.g. Faber and Lind (2012).

As highlighted in Section 2, we do not intend to address the specifics of risk management task related to the identification of the sources and causes of different states of information in any detail. However, a general appreciation of potential sources which may be of crucial importance to facilitate relevant and adequate system identification and risk-informed decision support as described in Section 4 may be achieved by considering in particular the carriers of information, as well as the sources of risks in general. The carriers of information (transferred between the stakeholders as illustrated by the arrows in Figure 2) are in general manifold and include formalised channels and procedures defined e.g. in protocols (see e.g. Faber and Lind 2012), informal channels such as the free press and social media, as well as technological information transmitters, such as wires and micro waves. In principle, information belonging to any of the above-listed categories may be relevant for all the links indicated in Figure 2. Fake news as such may be a cause for any of the conditions of information belonging to the above listed categories (2)–(5).

3.2. Information channels and types of hazards

Especially with respect to the information flow between stakeholders and decision-makers, where formal channels are not well established and for which the open press and social media play a significant role, there is an increased potential for information being distorted with the purpose of promoting particular agendas of individuals or groups of stakeholders; such cases include what is commonly referred to as 'Fake News'. It should, however, be kept in mind that other intentional and also malevolent (or well-meaning) means for affecting the information flow may be relevant to consider in risk management. Such means include interferences with the information flow, e.g. in the form of information disruptions and information corruptions.

In addition to the appreciation of the different possible carriers of information and their role in the management of risks, also the different possible types of hazards should be devoted attention. In Faber (2018) four types of hazards are categorised, namely:

- Type 1 hazards: Large scale averaging, rare and high consequence events: Rare in place and time, potentially associated with catastrophic consequences. Over sufficient large scales in time and space the associated risks are predictable, which greatly facilitates their management. Typical examples of this type of hazards include geo-hazards, such as earthquakes, floods, strong wind storms, etc. In the context of the how information affects decision making as illustrated in Figure 2, technical failures of technological information carriers within systems of some size, such as power plants, wind turbine farms, etc. would belong to this type of hazards. This type of hazards have resemblance to the hazard class labelled as the 'Sword of Damocles' in Klinke and Renn (2002).
- Type 2 hazards: Frequent in time and space with relatively small consequences, which is why they are commonly overseen or collectively ignored. Cognition biases such as tunnelling and framing (see Kahneman and Tverski 1984) play important roles in this. Over sufficient scales in time and space they might be associated with devastating cumulative consequences. Moreover, their cumulative effects may trigger more disastrous consequences of the same characteristics as those of Type 3 hazards. Typical examples are emissions to the environment, exploitation of resources, extinction of species, inefficient or inadequate regulations, inadequate budgeting, human errors, etc. Smaller biases associated with the technological transfer of information caused by e.g. inadequate control and calibration procedures as well as e.g. slightly delayed transfer of information caused by organisational inefficiency would belong to this type of hazards. This type of hazards have resemblance to the hazard class labelled as 'Cyclops' and 'Cassandra' in Klinke and Renn (2002).

- Type 3 hazards: Extremely rare and potentially disastrous events which are unpredictable even over large extents in time and space and for which basically no knowledge is available. May be triggered by the cumulative effects of Type 2 hazards. Examples include super volcano eruptions, impacts by asteroids, high-intensity solar storms, global climate change as well as major malevolent actions. Also at small scale risk management such as e.g. for regions or communities the same type of hazards as mentioned under Type 1 hazards may belong to this group, since no sufficient averaging effects are involved.

  The management of risks due to this type of hazard cannot be planned for in the same manner as Type 1 hazards since little is understood with respect to the probability of occurrence and evolution of consequences. Conditional risk assessments might be utilised to quantify speculation on the robustness and resilience of society at different scales – by basing risk assessments on certain extents of damages of the systems providing societal functionality – conditional, or 'what if' assessments. Examples of Type 3 hazards of relevance for the transmission of information might include solar storms shutting down electronic communication systems at large scale, malevolent disruptions of satellite communication systems as well as interferences of GPS navigations systems. This type of hazards have resemblance to the hazard class labelled as 'Pythia' and 'Pandora's Box' in Klinke and Renn (2002).
- Type 4 hazards: Events triggered by incorrect information and knowledge. Examples include consciously and unconsciously omitted or manipulated information, 'fake news' as well as censored and erroneous observations. The characteristics associated with events of this type of hazard may resemble those associated with Type 1–Type 3 hazards. The management of this type of hazard may be supported by means of sensitivity analysis (see e.g. Faber 1997) and by means of the inclusion of options for validation of the information and knowledge playing a significant role, for the ranking of decision alternatives. This type of hazards, as mentioned under the forgoing hazard types, may indeed play a role for all types of hazards and for this reason deserves special attention. The condition of information appears not to be specifically addressed in Klinke and Renn (2002) but could be termed 'Hermes' after the god from Greek mythology, who's the main role is that of a messenger.

In Section 5 we will discuss generic cases enveloping theses situations in more detail, and also draw parallels to situations encountered in practical decision making.

However, before this, we first briefly introduce the Bayesian decision analysis framework for ranking of decision alternatives subject to uncertainty originally introduced by Faber and Maes (2005) and later elaborated in Glavind and Faber (2018).

4. Decision analysis in the face of uncertainty

The only available basis for decision making is our perceived knowledge of the systems we are aiming to manage; information. The representation of systems in terms of information thus constitutes a crucially important step in the context of risk-informed decision analysis. The principle idea we propose here is to incorporate the possible effects of the various types of conditions of information described in Section 3.1 into the system representation through their possible implications with respect to the probabilistic representation of possible competing or alternative systems, in addition to the normally addressed probabilistic phenomenological representations of individual most probable systems, see also Hennig (2010). Noteworthy contemporary challenges for risk-informed decision support, which calls for an adequate representation of possible competing systems concerns climate change risk management (Mastrandrea et al. 2011) and national security in the face of hybrid warfare (Hoffman 2009). Our proposed approach facilitates for such representations as well as adaptation and refinements (through Bayesian updating) over the course of time, as more information may be collected or otherwise becomes available.

In the remaining part of this section we will first outline a general approach to the probabilistic representation of systems and thereafter propose a decision analysis formulation which facilitates for the identification of optimal decisions with respect to risk management and collection of additional information as well as the assessment and maximisation of the robustness of decision alternatives with respect to possible systems as well as system assumptions.

4.1. General approach with respect to the representation of systems

As outlined in Glavind and Faber (2018) the identification and probabilistic representation of possible systems may take basis in bottom-up, i.e. phenomenological models where the whole (the system) is established by combining its parts (constituents) or top-down systems modelling approaches, where the parts may be derived from information concerning the performance of the whole, or combinations of the two. The important issue, however, is that the probabilistic representations must be fully consistent with the available knowledge and that it is documented transparently which scenarios affecting relevance, precision and correctness of utilised information have been accounted for; i.e. an elaboration of the important task of system identification and documentation in risk-informed decision analysis, see e.g. JCSS (2008).

To account for the scenarios affecting relevance, precision, correctness and availability of information necessitates that specific efforts are undertaken to ensure that these are established, i.e. identified and modelled probabilistically, by use of bottom-up or/and top-down approaches. To this end it is important to note that use of top-down approaches in this case requires careful consideration of which information, e.g. in terms of databases and covariates, to include as basis for the modelling. If there is no clear idea on how to select such information, the modelling will not serve its purpose.

A starting point for the identification of relevant databases as well as covariates may be developed on the basis of engineering understanding and/or bottom-up phenomenological models. In this light it is immediately realised, as emphasised in Glavind and Faber (2018), that so-called data-driven modelling techniques (top-down) are equally subjective as traditional phenomenological approaches (bottom-up). In addition to the identification of the different scenarios a next step is to identify different decision alternatives of relevance for the management of the systems of consideration. In the present context it is of special importance to identify strategies including options for collection additional information over time and adapt strategies accordingly; this with the aim of identifying optimal as well as robust decisions.

Assuming that all relevant scenarios and decision alternatives for the management of a considered system have been identified the following steps are proposed:

(1) Based on available knowledge, identify and represent possible systems probabilistically (see Section 4).
(2) Formulate and undertake a prior decision analysis for the ranking of decision alternatives, accounting for the possibility of different systems.
(3) Based on the prior decision analysis formulate and undertake a pre-posterior decision analysis for the ranking of decision alternatives with respect to collection of additional information and commissioning of adaptive strategies.
(4) Evaluate the robustness of the ranked decision alternatives with respect to expected value of benefit (utility) contributions from system realizations.
(5) Assess possibilities for improving the robustness of decisions by means of alternative strategies for collection of information and adaptive measures – and repeat step (4).

In Section 4.2 the general principles of the systems modelling and the corresponding decision analyses are outlined.

4.2. System representation and decision making

As an example a framework for systems modelling in the context of assets integrity management for technical facilities is illustrated in Figure 3.

In Figure 3 the concept of indicators is introduced as a means to incorporate information into the modelling, which is related to the performances of the system, see also Faber and Sorensen (2002) for examples. The concept of indicators provides a strong means for including information in systems modelling. In a bottom-up based modelling of the system, first the phenomenological models of the parts of the system are established and the parts are combined to the best of available knowledge to represent the performances of the system as a whole. Information is thereafter collected through indicators and utilised for a probabilistic updating of the phenomenological system model. In a data-driven model the systems model is established through information collected from joint observations of indicators and system performances. Whether bottom-up or top-down modelling approaches (or combinations) are applied it is of central importance that that probabilistic system models consistently account for and distinguish between uncertainty associated with sparsity of evidence and possible model uncertainty and associated lack of fit. This is of crucial importance in the context of model optimisation, where an optimal trade-off between complexity (in terms of system, constituents, and parameter models), and the associated statistical uncertainties must be identified.

Following Glavind and Faber (2018), a model $\mathbf{M}(a)$ is a relationship between input and output as a function of a decision a. In general the performance of the system is associated with uncertainty, which is why the output of the system with which we associate utility $U(a)$ in the following is random.

Accounting for the possibility that different systems are possible $\mathbf{M}(a)$ can be described as

$$\mathbf{M}(a) = (\Sigma(a), C(a), X(a))^T \tag{1}$$

where the actual system is represented by the random event Σ, with possible realizations belonging to the set $\boldsymbol{\sigma}$ of n_s known components. It is assumed that each possible system realisation, e.g. represented by a graph model σ_j has n_{c_j} constituents which

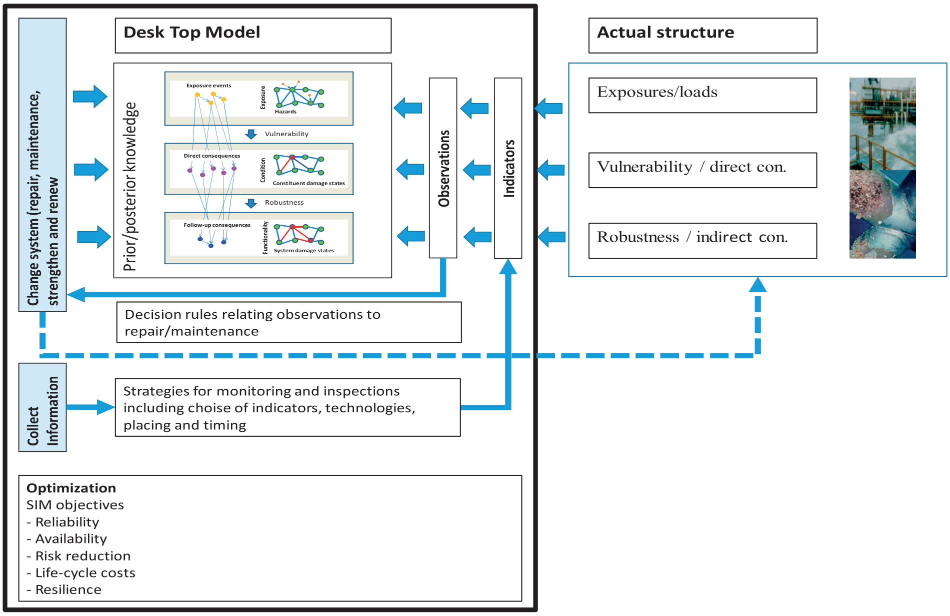

Figure 3. Illustration of systems modelling framework in the context of assets integrity management for offshore facilities (Faber 2017).

interact together to provide the functionalities and associated utility of the system. As indicated previously different possible systems may be identified through bottom-up phenomenological considerations or as a result of top-down data driven modelling. The identification of optimal decision alternatives a must in general be undertaken simultaneously with an assumption or choice of the system s, which is realised. For a given choice of s, the performances of the constituents are represented by a set of constituents models C_s and a prior probabilistic model for all uncertainties entering these, i.e. $P'(X|s)$. It should be mentioned that all probabilistic representations in principle have temporal and spatial references, which for the sake of simplicity of notation are omitted here.

4.3. Decision analysis and robustness of decisions

The following concerns Step 2 in Section 4.1, namely the formulation of a prior decision analysis for the cases where the system is unknown. Starting with the normally considered case where the considered system may be regarded as known, following Raiffa and Schlaifer (1961) and von Neumann and Morgenstern (1953), the optimal decision is identified from the maximisation of the expected value of utility, i.e.:

$$a^* = \arg\max_a E'[U(a)] \tag{2}$$

Accounting for the possibility of uncertainty associated with the system itself (Faber and Maes 2005; Hennig 2010), the principal decision event tree can be formulated as illustrated in Figure 4, (adapted from Faber and Maes (2005)).

In Figure 4 the variable s_i represents one choice of system representation out of a set of system representations and σ_i represents a realisation of the real system. The optimisation of decision alternatives is further complicated by the fact that some of the decision alternatives within **a** may only be relevant for one or some of the competing system representations. The optimisation of decision alternatives must thus be undertaken jointly with a choice of system representation.

The optimisation of decision alternatives, including system choice, may now be written as (Faber and Maes 2005):

$$(s^*, a^*) = \arg\max_{s} \left(P(\Sigma = s) \arg\max_{s} \left(E'_{\mathbf{X}|a}[U(a, \mathbf{X})]\right) + E'_{\Sigma\backslash s}[E'_{\mathbf{X}|\{\Sigma\backslash s\}}[U(a^*, \mathbf{X})]] \right) \quad (3)$$

where a^* is determined in accordance with Equation (2). In Equation (3) the robustness of the decision with regard to the choice of system may be assessed as the ratio of the first term to the sum of the two terms. This ratio, which will take values between 0 and 1 (1 = robust), indicates how sensitive the decision is with regard to the possibility that the optimisation is undertaken under an erroneous system assumption.

Ultimately, model building should be seen as an integrated part of the decision optimisation. On one hand, it is important that the model captures all relevantly possible systems and their uncertainties; on the other hand, there is no need for a model to be accurate in the domains of 'reality' which are irrelevant for the decisions subject to optimisation. By embedding the model building operation inside the optimisation of decision alternatives, the available knowledge may be fully utilised to optimise the utility associated with the system under consideration, and thus consistently rank decision alternatives.

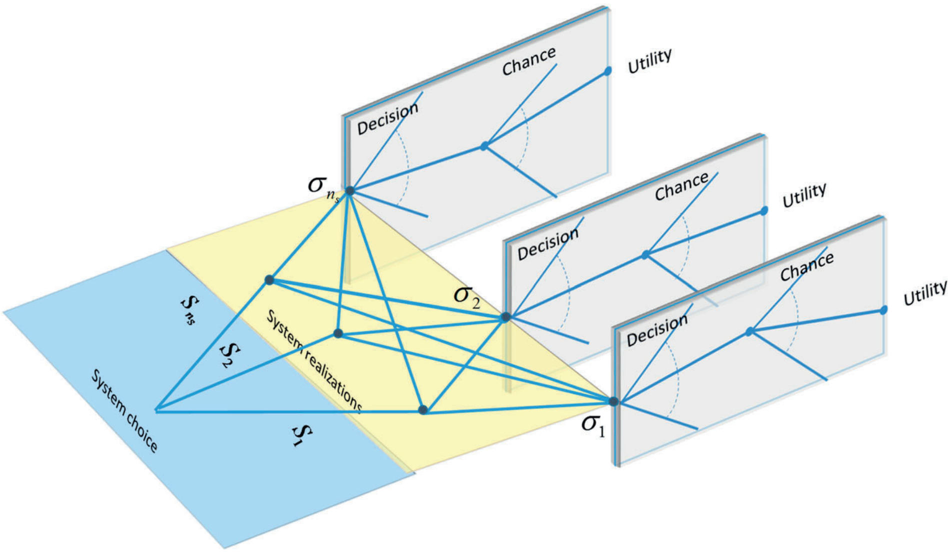

Figure 4. Illustration of the decision event tree applied in prior decision analysis of systems with uncertain possible system realizations (adapted after Faber and Maes 2005).

4.4. Value of information analysis

We now turn to Step 3 from Section 4.1, namely the formulation of a pre-posterior decision analysis for the purpose of identifying how additional information may support the choice of system *s* and the corresponding optimal decision alternatives *a*.

The decision event tree for this case is shown in Figure 5.

The pre-posterior decision analysis for the optimisation of the joint problem, which considers optimisation of collection of additional information *e*, selection of system *s* to optimise decision alternatives for, and finally optimisation of these decision alternatives **a**, may be formulated as

$$(e^*, s^*, a^*) = \arg\max_{e} E'_{\mathbf{Z}} \left[\arg\max_{s} \left(P(\Sigma = s|\mathbf{z}) \arg\max_{a} (E''_{\mathbf{X}|a}[U(a, \mathbf{X})]) + E''_{\Sigma\backslash s}[E''_{\mathbf{X}|\{\Sigma\backslash s\}}[U(a^*, \mathbf{X})]] \right) \right] \quad (4)$$

where **Z** represents the uncertain outcomes of the experiment strategies with realizations **z**, and E'' indicates that the expected value operations are undertaken based on an updated probability assignment for the possible different realisations of **X**, i.e. $P''(X|s) = P'(X|s, \mathbf{z})$.

From Equation (4) it is seen that new information will affect both the assignment of probabilities to the different possible system realisation and the probability assignments for all the state variables **X** for a given choice of system *s*.

Step 4 and Step 5 from Section 4.1 may now be invoked successively until decision alternatives are identified which at the same time are (closed to) optimal and also adequately robust with respect to possible competing systems and system assumptions.

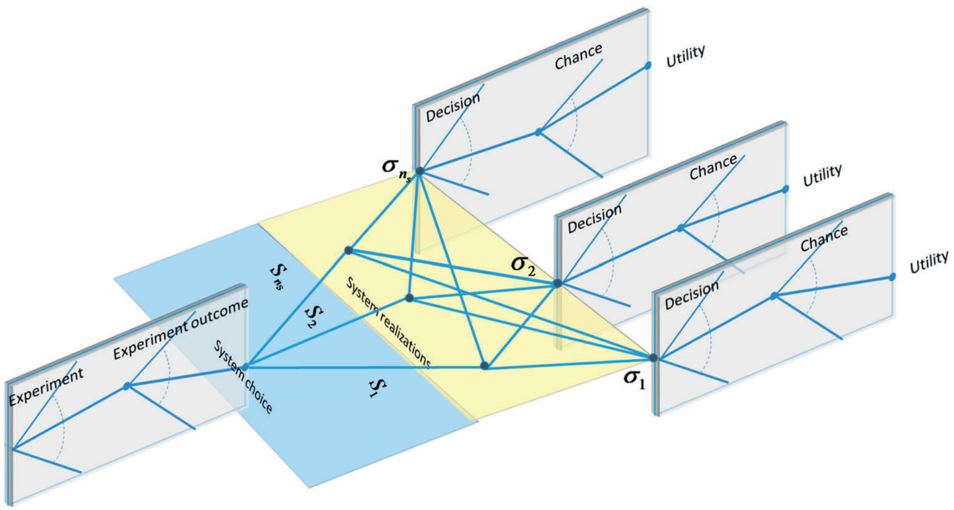

Figure 5. Illustration of the decision event tree applied in pre-posterior decision analysis of systems with uncertain possible system realizations.

In Glavind and Faber (2018) the approach outlined in the foregoing concerning the joint identification of system representation and optimal risk management options is illustrated on an example considering evacuation planning of offshore oil and gas production facilities in the event of an emerging storm. The reader is referred to this example to obtain more detailed information concerning how multiple systems and various types of uncertainties are modelled and treated in the decision making process.

5. On the application of the suggested approach

Taking basis in the foregoing discussion of information and how information might affect decision making presented in Sections 2 and 3, together with the generic framework for decision analysis subject to uncertainties – including deep systemic uncertainties – as presented in Section 4, we now consider a very simple principal example to discuss some of the implications of different categories of information on decision analyses and how these analyses may be adequately synthesised.

Decision problems subject to uncertainty often involve information belonging to Category 1 (i.e. relevant and precise, see Section 3). Examples of this type of information include the event that a bridge has survived an earthquake with damages below a tolerable level, a welded joint in an offshore structure has not failed after 20 years of fatigue loading and the reduction of the concentration of pollutants below critical levels in a groundwater reservoir, after the implementation of an environment preservation policy limiting emissions from industrial activities.

Information may however also be associated with uncertainty in the form of imprecision; in which case the information belongs to Category 2. There may e.g. be uncertainty associated with the level of observed damages of the bridge, measurement errors associated with the sizing of fatigue cracks as well as errors associated with the measured concentrations of pollutants. In either cases the decision event tree to be considered in the decision analysis is of the general character illustrated in Figure 6.

In Figure 6 the flow of actions is (1) to collect information **I** (at a cost) and based on the collected information to identify a decision which affects the perceived state of nature **X** in such a manner that the benefits are maximised.

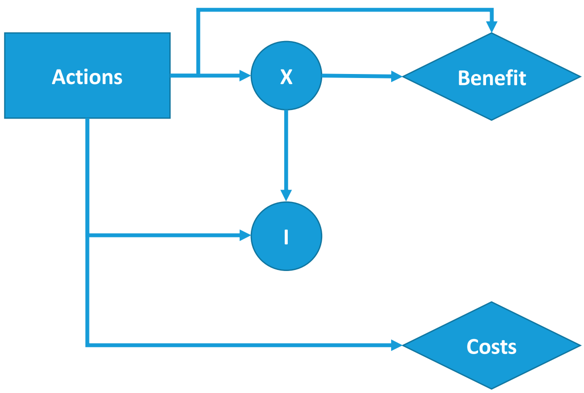

Figure 6. Illustration of principal decision analysis when Category (1) and Category (2) information **I** about a system subject to uncertainty represented by **X** is collected.

It is important to keep in mind that the information collected, i.e. **I** may not always be relevant for the decision analysis. It can originate from another system than the system considered, i.e. **X***. In descriptive statistics such information is often referred to as 'outliers' – in fact originating from a population of events, different from the population of interest. Considering the case of the bridge damaged by earthquake, information regarding the damage state might relate to past overloading and not the recent earthquake, in the case of a welded joint, the information collected from an inspection may e.g. concern a slag inclusion originating from the welding process, rather than a crack induced by fatigue loading and finally with respect to a measured pollutant the information concerning the observed concentration may relate to a fluctuation in the natural environment instead of emissions from industrial activities. In such a case the information collected has no relevance and decisions made or adapted on the basis of the collected information would be suboptimal.

The question is then – what to do to mitigate the adverse consequences of irrelevant information? The answer is simple – but only comes with considerable efforts. What is needed is to account for all possible systems leading to the information applied in support of the decision ranking. In the considered example this means that the decision analysis also must account for possible alternative systems which might be a cause for irrelevant information. Such a representation is illustrated in Figure 7.

In decision analysis the probability that the information originates from system **X** or system **X*** must be represented consistently in accordance with the best available knowledge. Indeed the information originating from system **X** and system **X*** might be similar or in some cases even identical which underlines the difficulties associated with the immediate identification of the systems. Given that the existence of the systems have been realised the decision problem is then adequately analysed on the basis of Equation (3).

The fourth principal case concerns when the information is relevant but not correct, i.e. Category 4 information. Incorrect information may be caused by gross errors, e.g. in the collection or processing of information – or by intent. If gross errors are at hand the nature of the errors may be assumed to be random. Examples of gross errors include the use of imprecise or defect equipment and misreading of data from tables.

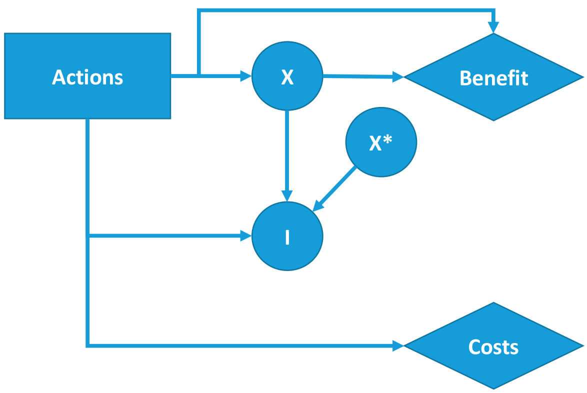

Figure 7. Illustration of principal decision analysis when Category (3) information **I** about a system subject to uncertainty represented by **X** or **X*** is collected.

Considering again the aforementioned examples, the information concerning the presence of damage to the bridge, an observed crack in the weld or the detection of particular pollutant in the groundwater might be correct but can also be incorrect. Also the opposite holds, e.g. when damages, cracks or pollutants are not observed. In statistics such gross errors are considered in hypothesis testing and denoted Type 1 and Type 2 errors, respectively. In integrity management of fatigue sensitive details these types of errors are commonly modelled through the concept of the probability of indications or the probability of detection, see also Straub (2004).

As mentioned earlier, Category 4 especially – but in principle also Category 3 information may be due to intentional manipulation (i.e. 'fake news') – in which case it might be expected that the information is tailored to achieve a specific objective. Intentional manipulation of information may concern in principle any of the information flows illustrated in Figure 2, however, most often when reference is made to 'fake news' it especially refers to the flows of information to stakeholders, with the objective to modify their perception and thereby change the premises for decision making; i.e. the set of decision alternatives available to the decision maker as well as her preferences.

The principal decision analysis to account for manipulated information in the decision analysis is illustrated in Figure 8.

In Figure 8 a decision node is added compared to Figure 7 to highlight that in addition to appreciating the possibility that the information is not correct, actions are also considered for the management of the system which is the cause of the manipulation. Clearly, the various possible causes for the occurrence of different categories of information may occur in combinations, and these must also be accounted for.

The final information condition concerns disrupted or delayed information, i.e. Category 5 information. This particular information condition is relevant to account for in decision analysis and systems modelling, whenever transmission of information may affect the system states and consequence generation. Again it is instructive to consider possible causes for disruption and delay of information as basis for the identification and inclusion of these types of events in the decision analysis. In practice, various types

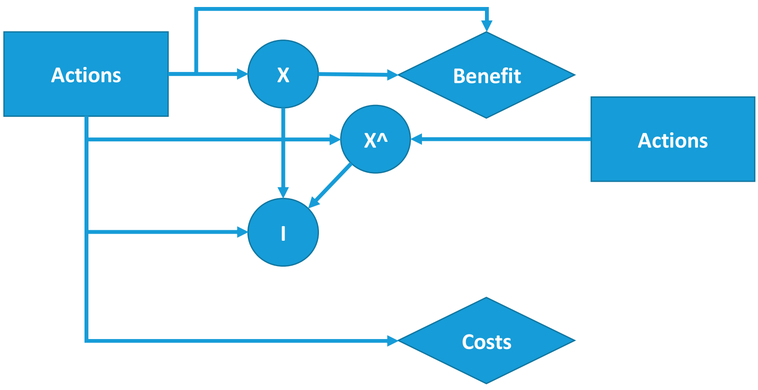

Figure 8. Illustration of principal decision analysis when manipulated Category(4) information **I** about a system subject to uncertainty represented by **X** is collected but where the information collected may originate from another system **X^**.

of technical failures play a significant role for this category of information, however, it is important to notice that information disruption and delays are often seen as immediate consequences of events of natural hazards or larger industrial accidents. Finally, also cyber attacks should be mentioned as a cause for this category of information.

As a last point – the principle of 'motive, means and opportunity' should be kept in mind. The information which is available in any decision making context should always be appreciated as the 'chosen' information, which is why cognitive biases, in addition to the availability of resources of the entity facilitating the information, might play an important role for relevance, precision and correctness of information.

From the foregoing discussion it is observed that information and its characteristics with respect to relevance, precision and correctness affect decision ranking in complex and dynamic manners – and it is evident that the management of information must be an integral part of decision support for the management of socio-technical systems.

6. Conclusions

In the present paper, we address the premises for the interpreting and representing knowledge and information in the context of societal risk-informed decision making. We find that the constructionist perspective to the representation of truth forms not only a philosophically sound but also a consistent and operational framework for this. Models developed and utilised for risk-informed decision support must be understood as propositions, there is not one correct model but rather an ensemble of possible models which all must be accounted for in the context of the decision making.

Moreover, we provide arguments supporting that the process and approach to develop risk-informed decision support does not depend on the source of hazards, nor the perceived intents of sources to do harm. Any possible underlying intent, just as any other system model assumption, represents a premise for the understanding and identification of possible efficient means for risk management. Such premises may and will also affect stakeholder perceptions of risks and have impact on the objectives for decision making as well as on the ranking of decision alternatives. However, this impact should not be presumed and included in the development of risk-informed decision support. Risk-informed decision support should rather be utilised as a vehicle to develop informed preferences of stakeholders, enhance the transparency of decision-making processes and facilitate efficient management of risks in coherency with fundamental societal values.

We emphasise that indeed any risk management problem is nothing but a problem of information management and that focus should be directed on the flow of information and causes for different classes of conditions of information. Understanding and modelling the flow of information is of crucial importance for the identification of the system which is subject to management. To address these risks we propose a framework for the classification of conditions of information. However, on this particular topic there is still substantial potential for research and improvements on methods and strategies for their management.

In support of decision making subject to possible multiple relevant system candidates, different types of hazards and classes of conditions of information we outline a scheme for decision analysis in which the system modelling is integrated into the decision optimisation. Based on this approach we describe how the robustness of decisions may be quantified to assess the significance of possible system candidates and system modelling assumptions with respect to decision rankings. Finally, a principal example is provided illustrating selected aspects concerning how the condition of information may affect and be accounted for in risk-informed decision making.

It is hoped that the present contribution will provide value in the further development of informed and preference coherent decision making in the management of societal risks, provide basis for identification of future areas of research and not least direct focus on the key concepts which must be carried into the curricula of future risk education.

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CHAPTER 5. TOWARD AN INFORMATION THEORETIC ONTOLOGY OF RISK, RESILIENCE AND SUSTAINABILITY AND A BLUEPRINT FOR EDUCATION

5.1. PART I

Nielsen, L., & Faber, M. H. (2020). Toward and Information Theoretic Ontology of Risk, Resilience and Sustainability and a Blueprint for Educations – Part I. Submitted to *Sustainable and Resilient Infrastructure* on September 13, 2020.

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Toward an information theoretic ontology of risk, resilience and sustainability and a blueprint for education – Part I

Abstract

The concept of risk as the theoretical and methodological basis for information-consistent ranking of decision alternatives is central for safe, sustainable and resilient societal developments. However, due to significant disparities in the understanding of the concept of risk in academia, and in its application in governance and industry, we argue that a new paradigm for risk must be established. In a sequence of three papers (Part I, Part II and Part III) we take up this challenge, with the leading objective of providing a coherent foundation for the further development and transfer of the general body of knowledge relevant to governance of risk, resilience and sustainability – through research and education. In Part I, the present paper, we first present our motivation and general approach to the problem. Thereafter, we provide an overview and a discussion on the state of research and education in the domain of risk, resilience and sustainability, and propose a generic, information-based hazard classification scheme, which informs the development of a domain ontology and a blueprint for education. Part II provides a logic for the structuring of the knowledge domain in terms of a domain ontology of the concepts relevant for an integrated knowledge of risk, resilience and sustainability. In Part III, based on the results of Part I and Part II, we identify educational requirements, and finally provide a blueprint for education designs. We believe that the proposed ontology and the related education blueprint may provide value both to the further evolution of research and education in risk in general and for the governance of risk, resilience and sustainability in particular.

Keywords: risk; resilience; sustainability; risk governance; domain ontology; embodied cognition; philosophy of education; learning design

1. Introduction

Population growth, urbanization, depletion of non-renewable resources, climate change, and ever-increasing demands for welfare underlie contemporary challenges society faces at global and local scales. There is a pressing need for a substantially more efficient exploitation of potentials for improving welfare in the short- to mid-terms, without jeopardizing the opportunities for welfare of future generations. The concept of risk, as the theoretical and methodological basis for information-consistent ranking of decision alternatives, stands in the middle of this challenge. However, since risk has not been established as a knowledge domain in itself until now, there is significant variability in how this concept is understood across the sciences and applied in industry and governance. The societal need for risk-informed governance of resilience and sustainability strongly mandates that a new paradigm for the knowledge domain of risk must be established.

The foundation of normative risk-informed decision analysis is provided in the seminal work of Raiffa and Schlaifer (1961), with roots going back to Bernulli (1738) and Bayes (1763), and further basis in axioms of utility theory by von Neumann and Morgenstern (1944). Since the 1970s, the discipline of psychology and its off-shoots behavioral economics and cognitive science have contributed to descriptive decision analysis with theoretical insights such as e.g., Prospect theory (Kahneman and Tversky 1979), applied and theoretical research in mental models (Craik 1943, Johnson-Laird 1983, Johnson-Laird and Byrne 1991), cognitive biases and heuristics (Tversky and Kahneman, 1973, 1981, Tversky and Kahneman, 1974, Kahneman et al., 1982, Kahneman, 2011, Gigerenzer, 2007, Gigerenzer and Gaissmaier, 2011, Heuer, 1999), and applied and theoretical research in emotional and volitional processes (Slovic et al., 1980, 1986, Slovic, 2010; Damasio, 2001). In the domain of cultural anthropology, group-grid theory has contributed to the study of risk perception, risk acceptance and behavior (Douglas, 1970, 2003) and to knowledge on political-cultural factors affecting perception and preferences (Douglas, 1978, 1992, Douglas and Wildavsky, 1983). A sociological theory of risk is outlined in Beck (1992). Hansson (1999) has provided an applied philosophical interpretation of decision theory, uncertainty and determinism in relation to risk analysis.

Despite partial methodological and theoretical advances within and across disciplines united through the notion of risk, there is no unified conceptual framework that justifies the existence of a risk science. Even though the concept of risk brings together academic disciplines from the applied engineering sciences, natural and life sciences, and the social and human sciences, no consensus on core concepts, conceptual definitions, procedural or scientific frameworks, or agreed metrics can be found among researchers and practitioners alike. The significant increase in the volume of research on risk (Nielsen and Faber, 2019), the acknowledgement of the generic aspects of risk analysis, independent of application area, and the social and political trend to treat risk-based analysis as the only legitimate form of evidence for the basis of individual and collective decisions and actions, have given reasons to view the subject matter of risk as a science in its own right rather than a specialization within established, individual disciplines.

Aven (2018) calls for "a new risk analysis science" as a unified domain of two types of knowledge: (i) applied knowledge related to particular activities in the world, where risk is of importance to a given decision context, and (ii) theoretical knowledge of concepts, frameworks and methods as a kind of meta-knowledge of risk, irrespective of application or decision context. While we share much of Aven's rationale and motivation for a new science of risk, we find a number of shortcoming with the framework he proposes. First, what is presented as conceptual knowledge does not seem to differ from procedural knowledge. The 'concepts' that are selected as relevant for this new science are presented similarly to a glossary of terms with no apparent logical justification. Moreover, the majority of the 'concepts' provided appear to refer to procedural steps in risk assessment or risk management and their definitions hardly go beyond a general dictionary definition of a term. In addition, the framework proposed by Aven does not facilitate or enhance a contextual understanding of risk and perpetuates the divide between risk assessment and risk management that exists in both practice and research. This is also evident from the lack of inclusion of resilience and sustainability considerations into the semantic domain of risk. Despite the objections outlined above, we however, strongly agree that a re-design of the framework in which these practices take place, is necessary to accommodate the continuously evolving context of the knowledge domain of risk.

In a triad of papers (Part I-III[1]) we take up this challenge by:

i) outlining an approach and a methodological basis for representing the knowledge domain of risk, resilience and sustainability science (Part I);

ii) establishing a domain ontology of concepts for an integrated risk, resilience and sustainability science (Part II) and;

iii) identifying educational requirements, and together with the results of Part I and Part II, finally providing an education blueprint for the design of educational offers (Part III). The structure of the triad is illustrated in Fig. 1.

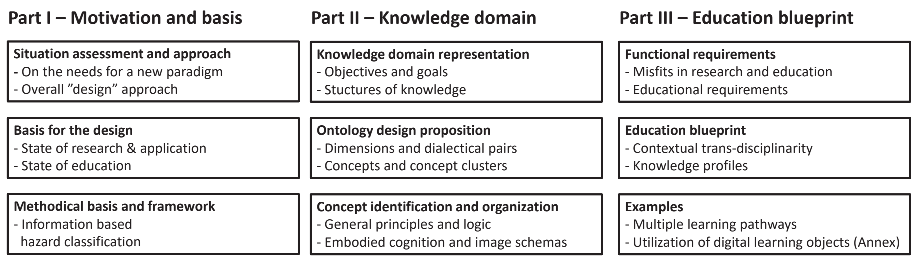

Fig. 1 Overview of the structure and contents of the three papers presenting the information theoretic ontology of risk, resilience and sustainability and a blueprint for education.

In the present contribution (Part I) in Section 2 we first provide an outline of our methodology for developing the ontology and blueprint. In Section 3, based on the bibliometric study of Nielsen and Faber (2019) of the research domain of risk, resilience and sustainability between 1990 and 2017 and a survey of risk-related master level

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[1] For ease of syntax, in the following we refer to Part II and Part III of the triad without specification of authors and year, however these are always the same and may be found in the list of references under (Nielsen and Faber, 2020).

educational programs that have sprung up over the past decade (Nielsen and Faber, 2018), we provide the system understanding – or base line context for the design. To this end, past and current practices in research and education in the domain of risk are outlined and discussed, and the multiple contexts of the integrated knowledge domain of risk, resilience and sustainability are explored. Finally, in continuation of Nielsen et al. (2019), Section 4 concludes by presenting an alternative scheme for hazard classification based on information type rather than on hazard source, which in turn provides the foundation for the novel domain ontology and education blueprint.

2. Logic and framework

Our underlying idea is that the synthetization of the knowledge domain and the design of the education blueprint, which we are pursuing, constitutes a systems design challenge, the solutions to which are to be identified through the three main constituents: "function," "form" and "matter."

- Function defines high-level objectives or requirements of the ontology, the achievement or fulfillment of which should be maximized by the design; these are addressed in terms of educational requirements.
- Form includes the basic building stones and the structural relations among them. The organization of these, facilitates that the educational requirements may be reached in a given context. Form is thus addressed through an ontology of concepts relevant for establishing a joint risk, resilience and sustainability knowledge domain.
- Matter may be understood as the contents of the form. Matter in this context is information. The concept of information is used both in the nominal sense, i.e. what is given, or data; and in the predicate verbal sense, i.e. the in-forming of data. Information can thus be thought of as the

immaterial material that is the structure that structures and the structuring process, the building of structure. As an element of the ontology and blueprint design, matter is context; the context of management and governance of risk, resilience and sustainability.

Ultimately, the task is to optimize the form and the contents of the form, i.e. matter, in such a manner that the function – i.e. given through the educational requirements, addressed in Part 3 of this study – may be efficiently achieved. As our objective is to establish a representation of the knowledge domain of governance of risk, resilience and sustainability and a corresponding blueprint for education, which might be applied in any context and for very different cohorts of students, we introduce learning pathways as possible options for navigating the ontology relevant to a problem context. These pathways define, in principal terms, (i) which parts of the ontological constituents are to be invoked in a specific context of education (ii) in what sequence, and (iii) with which weights.

An analogy to the education blueprint design challenge is systems design in structural engineering. In this context there is:

- Function: the high-level objectives of design of structural systems as related to provision of intended use, adequate safety for individuals, resilience of the community for which they serve, and finally, sustainable developments for the global population.
- Form: the natural laws of physics or the interaction of forces with matter; i.e., the fundamental equations of mechanics which make it possible to achieve functionality.

- Matter: the entire domain of possible choices of parameters, defined through geometry and characteristics of materials, which might be chosen to fill into the equations of mechanics to optimize achievement of the function.

A designer of a structural system will follow the laws of mechanics in the most ingenious manner and take advantage of his/her expertise on materials to shape these in fulfillment of purposes the building aims to serve.

In the following, humbled by the challenge, we as designers of the education blueprint, attempt to substantiate function, form and matter in a similar manner as the structural engineer, to frame and scope the design problem in, if not an unambiguous manner, then at least transparently, and in terms which are tangible and operational.

2.1. Matter – Form – Function

As mentioned earlier by the term matter we refer to the manifold context of risk, resilience and sustainability governance. Formally, matter may be seen to be comprised by a set of interrelated conditions, which together define the system subject to governance. These interrelated conditions can be thought of as events in time and space. A particular manifestation or realization of these interrelated conditions corresponds to the identity of a system. In traditional approaches to governance of risk, resilience and sustainability, the commonly applied practices focus on the control of matter, which might also be relevant and valuable; however, especially in the context of governance of resilience and sustainability, form and function play key roles.

Historically, causal dependency between form and function has been given a Darwinian explanation in relation to an organism's adaptive capacity to environmental factors or context. In Thompson's seminal work On Growth and Form (Thompson, 1961/2010), the historical aspect of natural selection is set in perspective to physical and mathematical laws such that form and function of living organisms and of inanimate artifacts alike, are said to be a result of dynamic physical forces acting upon the organism or artifact[2].

In the built environment, architect Christopher Alexander's *Notes on the Synthesis of Form* (Alexander, 1967) follows the same principle of introducing mathematical logic of order and relations to the problem context of artifact in architectural design. For Alexander a design problem consists of the synthesis of form and context (matter), which is a test of a goodness of fit[3]. But while a designer is in control of the form to be produced, the context controls the designer by imposing certain restrictions and requirements which are boundary conditions to the design problem. An engineering problem differs from a design problem in that in the former the context is fixed, i.e. assuming that a mathematical model of Thompson's 'diagram of forces' can be built that is fairly isomorphic to its target system in the real world. The problem then is reduced to computation and the goodness of fit is a test for optimization. A design problem, on the other hand, can be understood as a problem where a 'diagram of forces' describing the context of a problem is difficult to frame due to our incomplete knowledge of the context in the real world. Risk problems in the fields of engineering and economics are in present best practices

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[2] "The form…of any portion of matter, whether it be living or dead, and the changes of form which are apparent in its movements and in its growth, may in all cases alike be described as due to the action of force,.., the form of an object is a diagram of forces."

[3] "The form is the solution to the problem; the context defines the problem. In other words, when we speak of design, the real object of discussion is not form alone, but the ensemble comprising the form and its context. Good fit is a desired property of this ensemble which relates to some particular division of the ensemble into form and context."

most often framed and solved marginally, with exogenously given boundary conditions to the considered system assumed unaffected by decision alternatives. When governance of resilience and sustainability is considered, however, dependencies and dynamic couplings may prevail, and non-marginal considerations are necessary, see e.g. Nishijima (2009). In such cases the simple problem context of risk governance is essentially transformed into a complex and non-linear optimization problem - a design problem.

Disregarding whether the world as such is a manifestation of outcomes of random processes, or in principle deterministically knowable, the context for a given problem situation cannot be known with certainty, see e.g. Faber (2005). This implies that the process of finding a good fit between form and matter (context) extends beyond compiling a list of requirements, as such a list necessarily will be incomplete or even inadequate. Moreover, goodness of fit is affected by the interaction of requirements, which may render any specific set of requirements complementary or divergent, i.e. may result in a tradeoff among requirements. In the application domains of risk, the practice to compile requirements based on stated preferences for proxies of natural attributes has been found unreliable, precisely for this reason. Requirements such as e.g., the UN's Sustainable Development Goals (SDGs) or the Millennium Development Goals (MDGs) are examples of requirements, whose interactions produce competing objectives and tradeoffs, which are difficult to reconcile. Examples may include tradeoffs between resilience and sustainability or the safeguarding of individual rights vs communal interests. To deal with the problem of deriving a fitting limited set of requirements from an infinity of form-matter possible interactions, Alexander (1967) proposes a cognitive heuristic of describing requirements in their negative manifestation, which he terms 'misfits'. There is an intrinsic relation between misfits and a problem at hand as it is through the perception of misfits that the problem's essence is perceived[4].

In synthetizing the knowledge domain of risk, resilience and sustainability and designing the education blueprint, we take guidance in the design methodology of Alexander, where in a given context (matter) and subject to specified requirements (function) the form is identified such as to minimize misfits between functional affordances and functional requirements. The building stones out of which the form may be shaped are a set of concepts selected from a corpus of research papers in the Web of Science in the domain of risk, resilience and sustainability over a 30 year period and organized into a classification system (the domain ontology presented in Part II) according to the principles and logic of embodied cognition.

From an extensive bibliometric cluster analysis of the same corpus, we derive a set of misfits, which we label 'Misfits Research.' Similarly, from a desktop survey of master programs in risk, all dating back to less than a decade, we derive a set of misfits, which we label 'Misfits Education'. We combine the two sets of misfits to derive a set of functional requirements, which in the context of education are expressed through the notion of 'Educational Requirements' (presented in Part III, Nielsen and Faber (2020)).

To the best of our knowledge, these educational requirements are not achieved in present educational programs; indeed, they are not even explicitly formulated. In our design, the set of educational misfits mirrors what in Alexander (1967) is referred to as

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[4] "The incongruities in an ensemble are the primary data of experience. If we agree to treat fit as the absence of misfits, and to use a list of those potential misfits which are most likely to occur for our criterion for fit, our theory will at least have the same nature as our intuitive conviction that there is a problem to be solved."

‘functional requirements’. The design objective to minimize misfits, in the same sense as decisions might be optimized to minimize expected value of losses, implicitly and subjectively weighs the misfits.

2.2. Elements of the design process

As mentioned earlier, the ontology and education blueprint design problem may be approached as a systems design problem, where the system is represented in terms of a form-function diagram, with interacting elements as shown in Fig. 1. In the following these elements are explained and discussed in the order of the design process.

In Alexander (1967) a diagram which combines a representation of the structural elements (form) with a representation of functional properties or constraints (function) is referred to as ‘constructive diagram’.

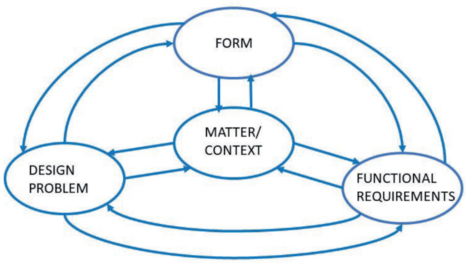

Fig. 2 Constructive diagram illustrating the (interacting) phases in establishing the domain ontology and the design of the education blueprint.

The constructive diagram shown in Fig. 2 illustrates the four phases of the design together with their interactions. As the diagram indicates, due to the mutual interactions between the phases, the design process is highly iterative. The four phases of this process may be summarized as follows:

Phase I. Defining the design problem, design objectives and desired outcomes

Phase II. Defining the context

Phase III. Defining the functional requirements

Phase IV. Designing the ontology and education blueprint

In the following, the approach taken to define the elements of the construction diagram and complete the four phases is outlined and discussed.

2.2.1. Phase I - Defining the design problem, design objectives and desired outcomes

Phase I involves defining a system boundary for the design problem. To form an overview of the scope of the problem, the overall context is sub-divided into distinct components. What seems to be intuitively problematic in this regard is that over the past half century, risk has evolved from being a specialization in traditional disciplines like engineering and economics into a discipline of its own right. Yet despite a significant increase in research and application of risk-based methods in various industries, the academic discipline of risk lacks a distinct identity and large volumes of research lie scattered across disciplinary domains with little or no coordination among the various knowledge traditions and/or application areas. We attribute this to the lack of theoretical research on risk, which is generic (in the sense of common) to all application areas and a deep division between the natural and social sciences, best summarized in the phrase and eponymous seminal article by scientist-policy-maker-writer – C.P. Snow – "The Two Cultures" (Snow 1959).

In appreciation of the significant broadening of the scope of risk governance over the past 30 years to include theoretical and operational considerations of resilience and sustainability, we therefore set-out to re-design risk education in accordance with a re-defined synthetization or conceptualization of the knowledge domain of risk. Rather than complementing or replacing the specializations of risk in the respective domains of civil and environmental engineering and economics with knowledge components related to resilience and sustainability, the challenges associated with integrating risk, resilience and sustainability in the context of governance have highlighted the need for a distinctly different type of science and a distinctly different type of education.

The specialized knowledge of engineers and economists is as necessary and as important as ever. The education of e.g. reliability engineers (the specialization of civil engineering that deals with risk) and economics specializations in operations research, welfare economics or econometrics have all high relevance but are not of our concern in re-designing risk education. The focus of our knowledge domain synthesis and education blueprint design concerns governance at local, national and supra-national scales. The target audience of the design is consequently current and future decision-makers (individuals, groups and institutions) at all societal scales and inclusive of the full spectrum of public-private-international-non-governmental-non-profit organizations. Fig. 3 provides an illustration of the different functions engineering, social and natural science disciplinary experts and risk governance specialists have in providing knowledge within an integrated risk-resilience-sustainability decision framework. In this illustration, the engineers, and the natural and social scientists contribute with distinct and in-depth subject-specific knowledge, whereas the risk governance specialist role is to ensure that the individual subject matter contributions are coherently and consistently related in a global decision framework.

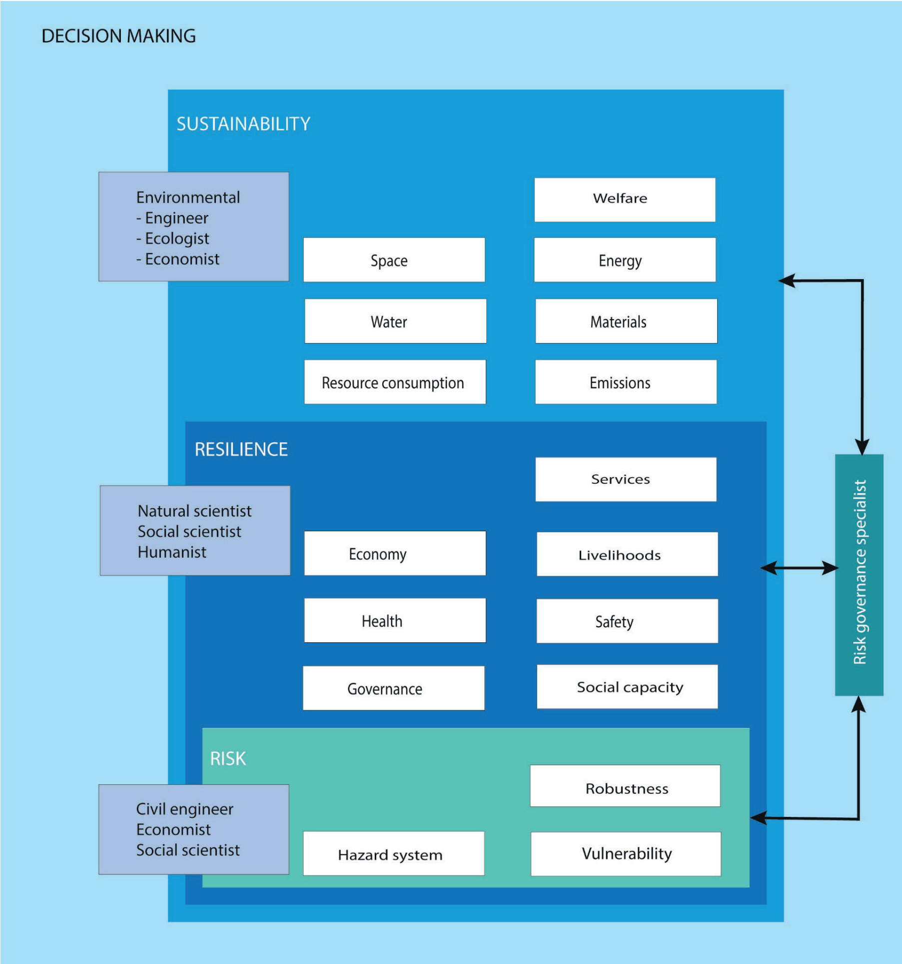

Fig. 3 Roles of disciplinary experts and risk governance specialists in governance of risk, resilience and sustainability (adapted from Faber (2018)).

In calling for a global governance of systemic risks, Faber (2011) points out that failures in the context of risk management are less of an epistemic than of axiological kind: "We generally know what should be done, but we fail to do it." We see these failures as a manifestation of the rigid division between risk assessment and risk management, and between quantitative and qualitative methodologies. They spring from incoherence and inconsistency between the epistemic domain of knowledge and the axiological domain of action. The divisions are carried over to the procedures used to model risk, where the lack of integration between the various risk modeling stages (defining spatio-temporal system boundaries, modeling exposures and consequences, weighing decision alternatives, and choosing risk treatment strategies) results in partial, highly idealized models that are at best ineffective in describing the physical world, and at worst are the source of new hazards and unintended consequences. Our chief concern is to develop a blueprint for education in integrated risk, resilience and sustainability science for societal stakeholders from the local to the global level, which is not specific to any industry or application area. This new science and education take basis in the concept of information, Bayesian probability theory and the experiential basis of embodied cognition research. This information theoretical basis can unite the diverse risk specializations and practices we find today into a consistent and coherent structure. The foundations of this structure rest on a unified method and on a shared language.

The novel hazard classification system by information type, the domain ontology and the education blueprint are all based on the principle of unity in multiplicity, which facilitates a shared language across knowledge traditions, applications and cultures. In tables 1-3 we provide a summary of the causal factors of misfits between state-of-the-art research, best practices in industry and governance, education, and the context of their interactions. The misfits here are to be understood as adverse consequences to the state of knowledge and the state of decision-making. On the basis of those considerations, in Fig. 4, we show a schematic representation of the design's logic underlying the three conceptual artifacts presented in the paper triad: the new hazard classification, the ontology and the blueprint.

Table 1 Causal factors driving misfits: (i) Hazard classification by source of origin.

Current practice generating misfits	Hazards classified by source of origin
Adverse consequences for State-of-the-Art Research	• Division among academic disciplines. • Division into technical, social and environmental/ecological systems. • Knowledge of hazards pertaining to technical and biophysical systems can be quantified using parametric models; knowledge of hazards pertaining to social systems can be quantified categorically only, i.e. using nominal and ordinal data for which uncertainties may not be quantified.
Adverse consequences for best practice in Industry and Governance	• Division of the process of risk modeling into discrete phases and respective responsibilities for assessment, evaluation, management and regulation of hazards/risks • Single sector approach to management and governance
Adverse consequences for best practice in Education	• Single discipline approach (e.g. natural hazards – Civil Engineering; biological and chemical hazards – Environmental Engineering; disasters and security risks – social sciences; operational hazards and human error – Operations Research/Management. • Division of programs into "quantitative" MSc – "qualitative" MA; since only the former are considered relevant for evidence-based management/governance, programs whose subject matter is qualitative adopt parametric models in their instruction to justify the nomination MSc.
Re-designed solution	**Hazard classification system by information type, based on the consequences instead of the causes of hazards**
Affordances of the re-design	• System boundaries are not pre-defined but emerge as a map of potential consequences in space and time. Thus context rather than a-priori disciplinarity and/or best practice define a system and categorize it as technical, environmental/ecological, social, or hybrid. • A generic, information-based approach to assessment and management of hazards provides unified basis for methodology and metrics across disciplines, sectors and application areas. • The information-based approach allows for updating models when new information becomes available in contrast to current procedural frameworks.

Table 2 Causal factors driving misfits: (ii) Multiple competing concept definitions, methods and metrics.

Current practice generating misfits	Multiple competing concept definitions, methods and metrics
Adverse consequences for State-of-	• Communication and collaboration between scientific experts from different disciplines is difficult not due to lack of a shared vocabulary (terms), but due to lack of shared conceptualization of

the-Art Research	terms. Divergent methods, procedures and metrics follow as a result of lacking a shared conceptual system. • Rigor in research is disciplinary. When using a systems approach, rigor may be extended to alliances between traditions, resulting in inter- or multi-disciplinary research, which is less rigorous (e.g. in a study of social-technical system, a branch of engineering may be combined with a branch of a social science). In the conceptual tradition of the West, the division between mind-body (conception-perception) prevents trans-disciplinarity and downgrades its rigor.
Adverse consequences for best practice in Industry and Governance	• Communication between scientific experts and decision-makers is ineffective and inefficient due to a multiplicity of conceptual definitions for a single term as well as the use of multiple terms for the same concept. • Communication between experts and the general public via decision-makers is ineffective and inefficient due to misinterpretation and distortion of information in the communication channel. Loss of trust and legitimacy of both experts and decision-makers.
Adverse consequences for best practice in Education	• Non-systematic use of both terms and concepts, reflecting disciplinary or best practice biases perpetuate the fragmentation of the conceptual domain as graduates enter faculty, industry, governance and educational posts. • Indiscriminate use of methods and metrics. Poor abilities at the level of conceptualization result in inability to critically assess the nature of data, the implications resulting from method and model choices and assumptions. Both capacities for critical and creative reasoning are diminished by the use of computational tools with no (or very limited) understanding of the grounding logic.
Re-designed solution	**A domain ontology of concepts generic to the modeling of consequences within and across technical, environmental/ecological and social systems. Instead of technical definitions of terms rooted in individual disciplines or application areas, the semantic range of a concept is given in a cluster of concepts with "family resemblance."**
Affordances of the re-design	• Trans-disciplinarity in research and education necessary for holistic understanding and modeling of systems dynamics. • Contextual understanding of concepts facilitates "shared language" across academic, professional and cultural traditions. • All hazard approach to the assessment and management of hazards and risks • Whole-of-governance approach to decision-making and regulation.

Table 3 Causal factors driving misfits: (iii) Lack of integration among risk, resilience and sustainability considerations into common theoretical and operational frameworks.

Current practice generating misfits	**Risk, resilience and sustainability not integrated in a common theoretical and operational framework**
Adverse consequences for State-of-	Partial (incomplete and/or biased) knowledge of systems dynamics. Conceptually irreconcilable tradeoffs between resilience and sustainability at local scale.

the- Art Research	
Adverse consequences for best practice in Industry and Governance	Gap between knowing and doing.
Adverse consequences for best practice in Education	No current educational offers integrate conceptual knowledge of risk, resilience and sustainability. Challenges of such integration to educational designers and planners include: • Theoretical and operational integration models of risk, resilience and sustainability are at the vanguard of research. Education systems tend to be slow and resistant to change. A better fit between education and state-of-the-art research requires research-based problem/project based learning, which is itself a recent and not widely accepted didactic approach. • The whole range of conceptual interdependencies and associated trans-disciplinarity is difficult to achieve both in terms of a learning design and its pragmatic implementation (trans-disciplinary teaching capacity and resources, acceptable acceptance criteria for the evaluation of learners, etc.). • Universities' current tendency to treat higher education degree programs as commodities. Universities become intermediaries between customers (students) and clients (the labor market). As degree programs are transformed into industrial apprenticeships, it becomes very difficult to design programs that precisely challenge industry best practices.
Re-designed solution	**A blueprint for education design that integrates risk, resilience and sustainability-related knowledge of systems dynamics for the purpose of managing and governing hybrid technical, environmental/ecological and social systems. The blueprint is based on the hazard classification by information type and the domain ontology of concepts generic to all types of systems and applications**
Affordances of the re-design	• As a dynamic template, the blueprint offers contextualized level of specialization depending on the learner's profile and preferences (broad – full degree program; narrower – individual module; problem/project specific). • Provides the conceptual basis for the information architecture of a depository of digital learning objects. The establishment of such repository makes it technically possible that trans-disciplinary state-of-the-art knowledge, which is geographically dispersed among faculties within a university as well as between universities, becomes available to learners distributed across physical and virtual university campuses. • Adaptive navigation of the repository allows for teacher controlled navigation and learner-led exploration.

Based on the three causal factors identified as the principle sources of misfits, in Fig. 4 the design problem context, objectives and purposes are outlined.

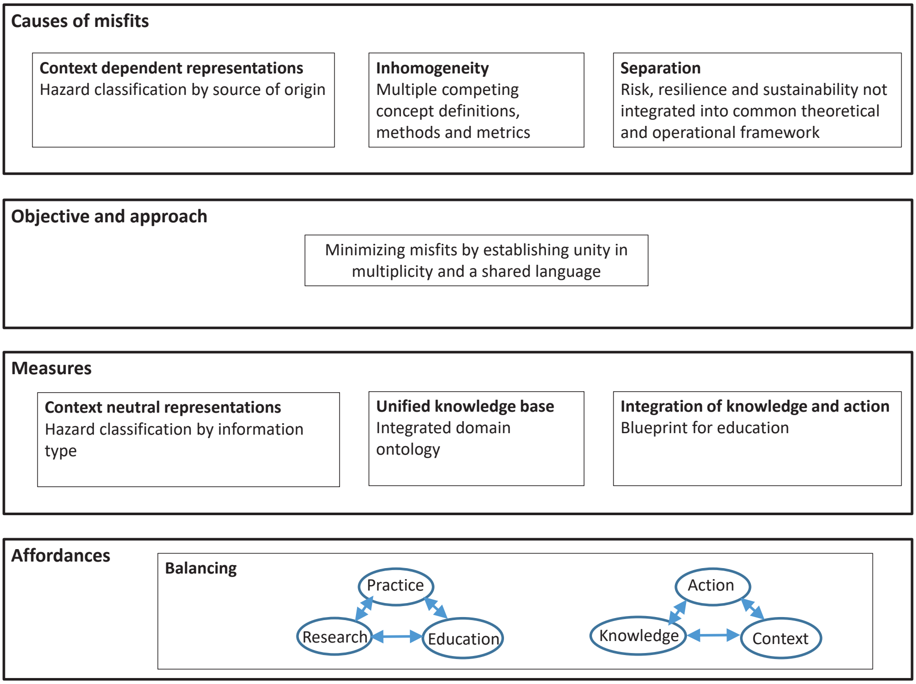

Fig. 4 Design problem context, objectives and purposes.

2.2.2. Phase II - Defining the context

The context of the design problem has two dimensions: physical and conceptual. The physical dimension is the material world of all the physical phenomena that may generate consequences, which humans desire to manage. In this sense, the context is basically the same as the sum total of all hazards and their manifested consequences. The conceptual dimension is the immaterial world of knowledge and information flows among scientific research on risk, risk education and decisions about risk governance and management from local to global scale. We can think of the former as the state of nature and the latter as the state of knowledge. In Phase II we thus break down the design context, as illustrated in Fig. 5, into four mutually interacting elements, named 'All Hazards,' 'Knowledge About,' 'Knowledge Transfer,' and 'Stakeholders'.

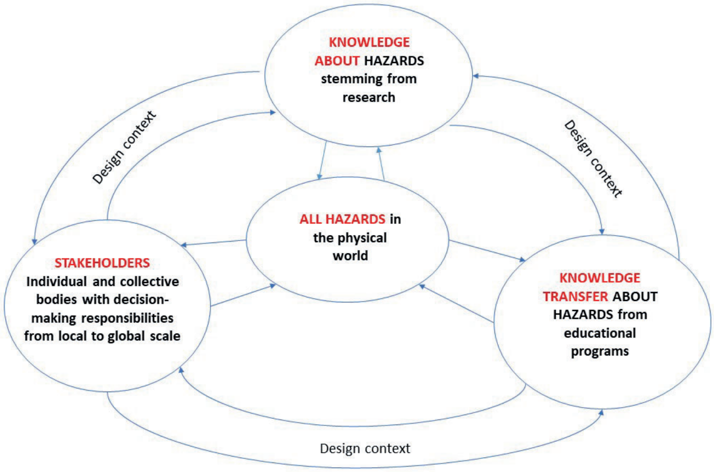

Fig. 5 Elements of the design context for the domain ontology and education blueprint.

2.2.3. Phase III - Defining the functional requirements

As shown in Fig. 6, the functional requirements consists of three overarching educational requirements. Each educational requirement is subdivided into particular learning objectives that we believe are relevant in meeting the requirements. The requirements and learning objectives are discussed in more detail in Part III. Here we briefly explain the general themes of the requirements.

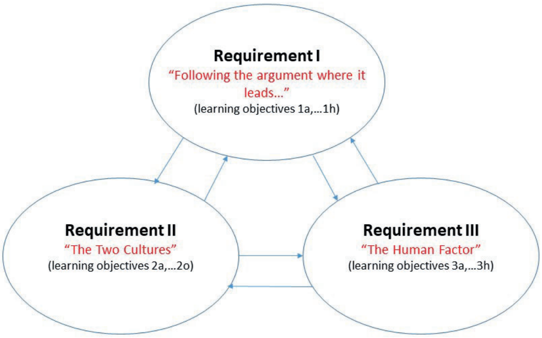

Fig. 5 Functional – educational requirements.

Educational Requirement I is about "learning to learn." It is labelled "Following the argument where it leads" with reference to Socrates' pedagogical method as it exemplifies the ability to evolve together with the context – perhaps the supreme goal of education from an evolutionary perspective. The learning objectives are grounded in Bayesian reasoning and information theory.

Educational Requirement II is an attempt to re-unite the "The Two Cultures" (Snow, 1959) – of the natural and human sciences in the pursuit of holistic systems understanding and modeling. Systems dynamics and embodied cognition are the knowledge bases for the learning goals associated with Educational Requirement II.

Educational Requirement III deals with the normative aspects of decision support in risk evaluation, risk acceptance and risk management. This requirement is labelled "The Human Factor" because fundamentally it is about putting a check on human hubris in its various forms (conceit, deception, self-deception, etc.). Central to this requirement is how the concept of 'intention' relates to thinking about the world and acting in it. Learning objectives under the umbrella of Educational Requirement III are anchored in the knowledge traditions of behavioral economics, cultural and social anthropology, ethics and political science.

Since form (ontology) and function (education blueprint) must be coherent to fulfill the purpose of fit (matter/context-form-function), a balance between different types of knowledge is necessary: descriptive, explanatory and prescriptive. The ontology may be considered descriptive to the extent that the large majority of concepts are selected on the basis of a statistical corpus analysis of term co-occurrence in state-of-the-art research. The ontology may be considered prescriptive with regard to the authors' choices of selection of relevant concepts and classification criteria. The ontology may be considered explanatory in its use of image schemas, for which embodied cognition provides empirical evidence, to structure relations among concepts into a categorical system. These choices, while inherently subjective, are not arbitrary: the image schema logic provides explanation for a-priori knowledge not based on pure reason, but a synthesis of physical perception and mental conception.

The education blueprint is perscriptive in function, but in-formed by description and explanation in a logically consistent, coherent and transparent manner. The theoretical assumptions that underlie (i) the new hazard classification, (ii) the domain ontology and (iii) the blueprint are those of pragmatism (meaning and value determined on the basis of context and consequences) and phenomenology (data-based, inferential logic).

2.2.4. Phase IV - Designing the ontology and education blueprint

In designing the domain ontology and education blueprint the input from all three previous phases is utilized. The ontology as a whole is a system representation of the knowledge domain that integrates research on risk, resilience and sustainability. The blueprint is a dynamic template for mapping the concepts from the ontology onto the lists of misfits and educational requirements, together with three possible learning pathways. The latter describe sequences for navigating the ontology with respect to the scope and modularity of learning activities. In designing the ontology our main focus is on the logical coherence of the content. We do not claim that this is an exhaustive rendering of all concepts relevant for the domain, but we do believe that it is representative of the major themes. As the knowledge domain evolves, surely revisions will be necessary to fit future research and education contexts.

Fig. 7 illustrates the structural components of the ontology, organized in a nested hierarchy of objects.

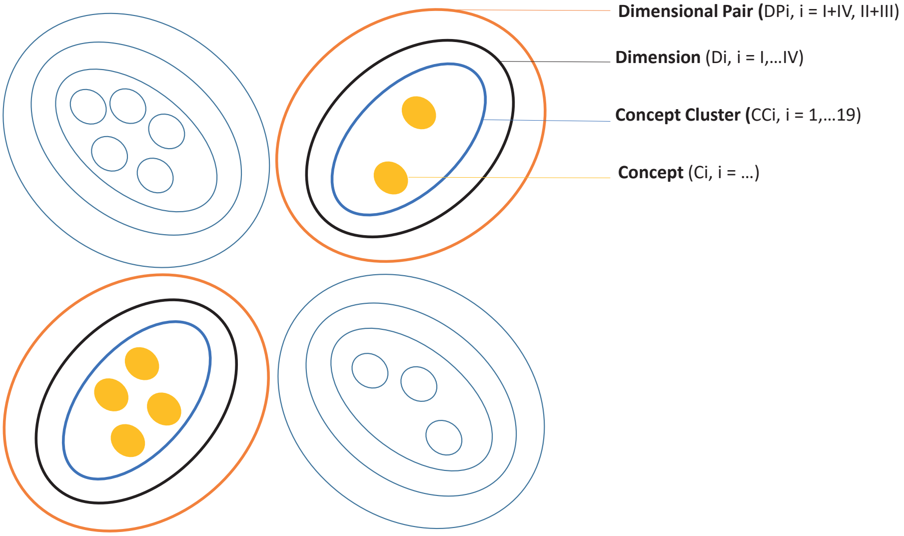

Fig. 7 Structural elements of the domain ontology.

The smallest object is an individual concept. A group of concepts we have associated to a common category is a concept cluster. The individual concepts define the semantic range of the cluster. The concept clusters are generic to the integrated domain of risk, resilience and sustainability, in the sense that they are of relevance to the domain regardless of the application area. A concept cluster is located in a dimension.

The four dimensions comprise a higher category of association based on a concept's function in the ontology. Concepts in Dimension I (D I) are associated with a taxonomic listing of objects and events - 'Things in the World'. Concepts in Dimension II (D II) express 'Ways of Structuring and Representing' things in the world. Concepts in Dimension III (D III) describe movement and change; hence it is named 'Processes Affecting Things in the World'. Concepts in Dimension IV (D IV) are about scalarity and action – 'Values Affecting Things in the World'. The four dimensions correspond to the four major branches of knowledge in accordance with a Western conceptual tradition of thought: D I – ontology/metaphysics; D II – epistemology; D III – Physics/Dynamics and D IV – Axiology.

Each dimension is part of a dimensional pair. Two complementary dimensional pairs form the ontology's upper boundary. In each dimension, an additional set of categorical pairs introduces what in the Western system are viewed as irreconcilable conceptual oppositions, e.g. material-immaterial, mind-body, rational-irrational, harm-benefit, deontological-teleological, deterministic-probabilistic, nature-culture, etc. Although those splits are mainstream positions, there are logical alternatives to either the objectivist or relativist worldviews upon which such divisions rest. One such alternative logic comes from empirical research in embodied cognition over the past 30 years; another is more than 2 millennia old and comes from China. In our design, we make explicit use of both. In a worldview based on embodied realism (see Lakoff and Johnson 1999), the elements in those categorical pairs stand in complementary rather than opposing relation. Many Eastern conceptual systems are built on the logic of complementarity. In this logic entities exist as continuous events in contrast to classical Western logic, where an entity is defined as a discrete object. The ontology we present in

Part II gives equal ontological status to objects and events in an attempt to form a basis for mutually comprehensible logic of conceptualization.

Here it is interesting to note that the function offered by the concept of image schemas from embodied cognition have a strong parallel to Bayesian reasoning which, in the context of governance of risk, most commonly forms the framework for the representation of knowledge and information, see e.g. JCSS (2008) and the basis for accounting for the influence of uncertainty in decision analysis (Raiffa and Schlaifer, 1961).

The fundamental mechanism of Bayesian reasoning is that knowledge is acquired through the combination of knowledge already available (a-priori knowledge established through accumulated information) and any new information, which becomes available over time. The significance of new information relative to already available knowledge is represented through the likelihood of the new information relative to particular instances of interest. The likelihood may be understood as a weighing of new information relative to existing knowledge, or in other words, the transformation of perception into conception (a-posteriori knowledge). In cases where in principle no prior knowledge is available, the representation of prior knowledge is generally chosen such as to weigh any possible new information equally; this may be ensured by what is referred to as non-informative priors. Extending the utilization of Bayesian probability theory to knowledge representations in the context of governance of risk, resilience and sustainability is a logical choice and also already considered, see e.g. (Gardoni, 2018) for examples. For the structuring of knowledge domains, however, Bayesian reasoning is, to the knowledge of the authors unprecedented.

Our approach to this is that the knowledge domain represented through the ontology should – to the extent possible free of bias – contain all possibly relevant concepts to be applied, in principle in any possible context. Moreover, the context of governance of risk, resilience and sustainability, whether in practical decision support or teaching/learning, should be the driver of the selection of relevant concepts to be considered in the quest of searching for or acquiring knowledge.

For this reason the ontology is chosen as a non-informative prior – a flat but structured hierarchy of concepts – from which the concepts relevant in a given context may be identified through likelihoods. The big question then, of course, is how the likelihoods should be chosen; to this end we take benefit of the concept of image schema from embodied cognition – the basic mechanism by which organisms with cognitive abilities are able to perceive contexts, and process information. The image schemas resemble likelihoods in a Bayesian updating scheme where prior knowledge is weighed through the likelihood function. Here it is the individual concepts contained in the ontology which are weighed by means of the image schemas. It is in the nature of this process, due to the subjective elements associated with cognition, the selection of relevant concepts cannot be pre-determined, and as such there is no guarantee that in the end the selected concepts are the optimal ones. However, the final selection of concepts will follow the principle of "following the argument where it leads"[5] – thus the quality of the argument will be decisive.

For coordinated action in matters related to risk, resilience and sustainability, a shared language is essential for how things and processes are conceptualized. This shared language is not only a matter of compiling glossaries of terms among different academic disciplines that contribute to the knowledge on risk, resilience and sustainability, but an

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[5] This is the label we have given to the first overarching education requirement for the blueprint discussed in Part 3 of the triad.

inter-cultural understanding of the different logical rules for structuring conceptual systems. To this end, in Part II of the triad we go at some length to find a basis for a shared language both among disciplines and between the philosophical traditions of West and East.

Finally, when choosing the concepts making up the ontology, in addition to their semantic content, also modularity is considered with a view to implications for the development of a repository of digital learning objects. Based on the concepts in the ontology a sketch for such a digital repository is provided in Annex A of Part III.

3. Context

3.1. The scientific domain of risk, resilience and sustainability

The knowledge domain of risk, resilience and sustainability is here understood to include all present publications on risk, resilience and sustainability in academic peer-reviewed journals. The large scale bibliometric study (Nielsen and Faber, 2019) conducted to map this domain rests on a sample of 0.5 million records extracted from the Web of Science for the period between 1990 and 2017. There are two distinct outputs of that study which are utilized as basis for the present design, namely: (i) extracting the form (see Section 2.2), i.e. a set of concepts as the raw building material for the ontology (addressed in Part II); and (ii) the identification of a list of misfits from the research domain to inform the educational requirements (addressed in Part III).

Statistical clustering of concepts is a straightforward method to identify which concepts have high occurrence and form stronger links. These concepts would then per default be candidates for the most important concepts in the domain. However, in the bulk of the research literature, exactly such concepts tend to be loaded with ideological content and/or disciplinary bias. Since the aim of our design is an ontology of concepts that are generic and applicable across domains, we have chosen to complement the statistical approach with a qualitative expert selection of concepts. We present here two examples to illustrate this point – the case of two concepts with high occurrences and link scores that were not chosen to include in the ontology: social-ecological systems and community resilience.

When looking at bibliometric maps of the knowledge domain of risk, resilience and sustainability from 1990s to the present, a distinct categorical demarcation is visible in the divisive labeling of "engineered," "ecological," "social" or from about 2009 onward "social-ecological-systems" (SES), see Fig. 8.

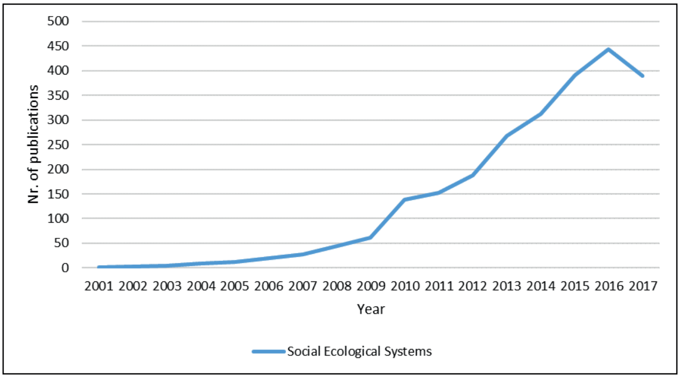

Fig. 8 Evolution timeline of SES based on data from WoS (Nielsen and Faber 2019).

This demarcation is not 'natural'. It is in, fact, engineered (at least implicitly) by researchers in the domain of environmental sciences and ecology (Fig. 9).

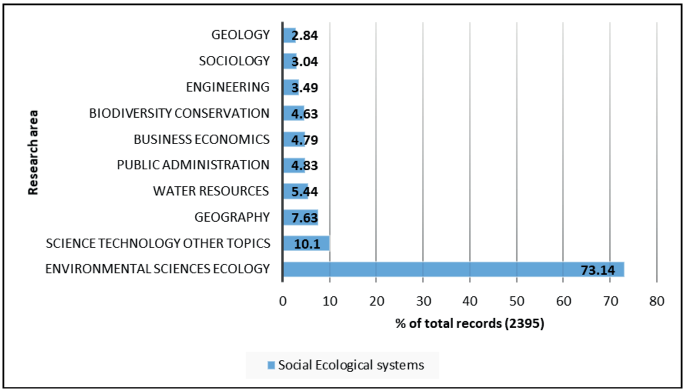

Fig. 9 Distribution of research on social-ecological systems by discipline (Nielsen and Faber 2019).

More than an ideological construct, it is also covertly deceptive as the following network visualization of the term 'community resilience' illustrates (Fig. 10). If the term SES were to live up to its definition, the state of research in the area of 'community resilience' should show at least some integration between the communities of nature and the human communities. Yet data analysis of the research shows that such integration is rather difficult to substantiate, and thus that in the established body of knowledge, the world of humans is only weakly linked to the natural world; to put it otherwise, there is an empirically observable and significant gap between intentions and actions – a gap most international organizations are dedicated to minimize. What we see in this illustration, however, is the world of thought in the red cluster of ideological rhetoric associated with the term SES, and the world of action in the green cluster, where ecologists and environmental scientists actually work – mostly disconnected at the level of science.

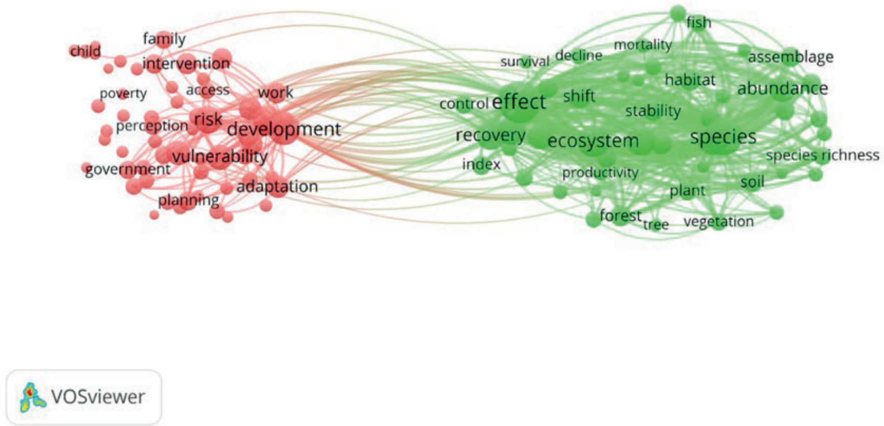

Fig. 10 Cluster term map of research on community resilience.

From the breakdown of SES and community resilience into contributing disciplines, it is also evident that not even the social sciences have much contribution to the ‘social’ of social-ecological systems (Fig. 9 and Fig. 11).

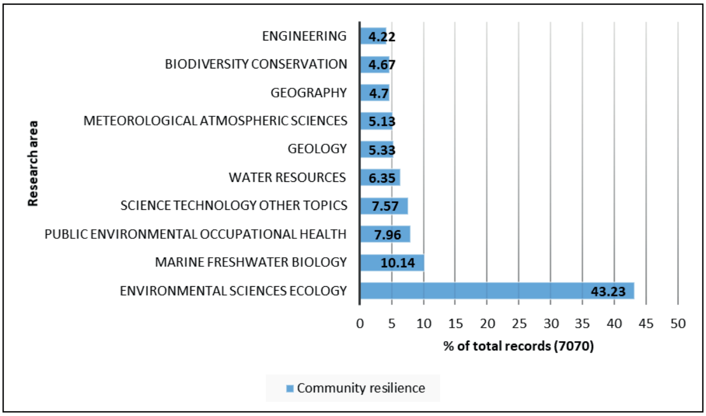

Fig. 11 Distribution of research on community resilience by discipline.

In Part II of this study, we address the past developments and the present state of the scientific domain of risk, resilience and sustainability in more detail in the light of the considerations underlying our proposed domain ontology.

3.2. The educational domain of the discipline of risk

While not yet mainstream, the integration of risk, resilience and sustainability considerations into unified operational models is at the vanguard of scientific research (Faber 2018). Risk education, in comparison, has not progressed much beyond the research and industry best practice of the 1990s. Methods such as risk matrices and FN curves, which have been discredited as ineffective and outright hazardously misleading (Anthony Cox Jr., 2008), are a staple in courses on risk methods. To the best of our knowledge, there exists no academic program, which integrates risk, resilience and sustainability in its curriculum in a logically coherent, operational manner. In a desktop survey of educational programs in risk in Europe (see, Nielsen and Nielsen, 2017), 107 postgraduate programs are identified, all of which date back less than a decade, i.e. to about 2010 or later. Though the programs differ by either the type of hazards they address or a given sector or industry they inform, they all follow the same linear structure reflected in normative or pre-normative procedural guidelines and codes. Risk education, contrary to the advertised claims of inter-, cross-, multi-, and trans-disciplinarity on programs' websites, has in reality a strong disciplinary focus. It has typically the following elements, which are taught more or less in the same sequence (Fig. 12):

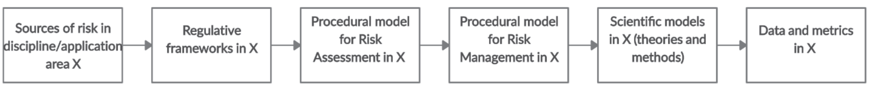

Fig. 12 Elements and sequence of risk programs curricula.

The integration of resilience and sustainability considerations into the knowledge domain of risk renders the above model inadequate to represent the reality of the complexity and non-linearity of interactions and dependencies among engineered, ecological and social systems, which as a result of such integration emerge, more often than not, as hybrid social-ecological-engineered systems. If the gap between models and reality is a main source of risk induced by cognitive errors, as highlighted in the foregoing, then the use of such a model for education, which bears the risk that students focus on procedures rather than the complexity of the subject matter, and rely overly on "scientific" models, must be discontinued. Collectively, all disciplines must focus on uniting their efforts in co-creating knowledge that is relevant and necessary for the modeling of hybrid social-ecological-engineering systems. Certainly, not all decision problems involve hybrid systems of hazards or of organization of components. At the scale where a system of consideration consists of the same type of components, disciplinary experts are essential.

The chief innovations of the proposed design are to:

(i) Model risk education as a conceptual scientific model (where scientific is based on the sole requirement of "following the argument where it leads") rather than as a procedural model for application by a particular industry or sector;

(ii) Discard the educational practice of indiscriminate study of all available methods without consideration of relevance and validity for a specific decision situation, and replace those with methods implicit in the concepts of the ontology and their relations: Bayesian probabilistic methods, systems methods, embodied cognition methods.

(iii) Replace the current practice of classifying risks according to their source of origin with a classification based on information type.

In Part III of this study, when specifically addressing the design of the education blueprint we discuss these in more detail.

4. Hazard classification based on information type

In the present best practice hazards classifications are based on their source of origin: man-made hazards, environmental hazards, biological hazards, etc. (Fig. 13). This classification may be realized as a strongly contributing factor for the division between academic disciplines whereby particular hazards only become relevant in the context of particular disciplines. For instance, the study of "structural hazards" becomes the property of civil engineering; the study of chemical and biological hazards – the property of environmental engineering; the study of human and animal safety – the property of health and life sciences; the study of malicious/intentional hazards – the property of social science disciplines.

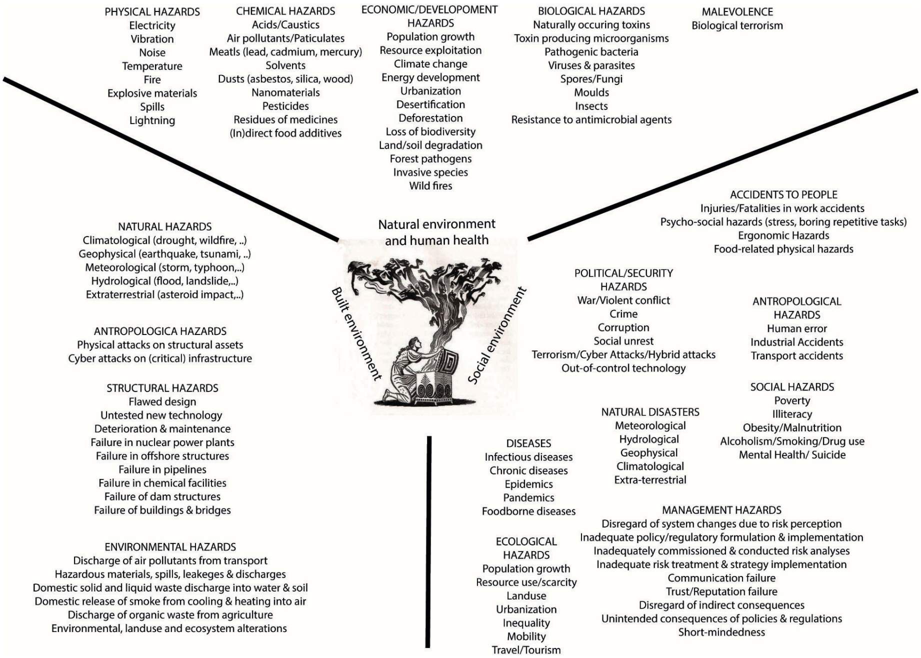

Fig. 13 Pandora's Box classification of hazards by source of origin.

Those hazards, which have manifest effects across engineered, environmental and social systems, namely hazards related to the resilience and sustainability of hybrid systems, have been adopted by the disciplines of ecology and environmental management. With the notable exception of studies aimed at quantifying the Planetary Boundaries (Rockström et al. 2009, Steffen et al. 2015) for a safe operating space for humanity, the bulk of research stemming from this knowledge domain, does not fit our understanding of "scientific" in that it does not "follow the argument where it leads," but follows instead an ideological agenda expressed through stated preference principles such as the Global Sustainability Goals, the Sendai Framework for Disaster Risk Reduction, etc. What is common to all such frameworks is that they attempt to measure progress in accordance with a palette of aggregate indices (The Environmental Sustainability Index, The Human Development Index, The Happy Planet Index, The Inclusive Wealth Index, etc.), but what they are really measuring is public opinion at policy level without verifiable basis that these stated social preferences are, or will ever be, empirically observable at behavioral level (Faber, Qin and Nielsen (2019).

In the integrated problem context of risk, resilience and sustainability, we are chiefly concerned with hybrid systems and hybrid risks. The novel classification scheme based on an informational typology of hazards' consequences (previously outlined in Faber (2018) and Nielsen et al. (2019)) enables the operationalization of trans-disciplinary research and education.

The proposed new hazard classification is based on the understanding that there are important dependencies and back-couplings between information, decision makers and stakeholders in a given decision situation (Nielsen et al. (2019)), illustrated in Fig. 14.

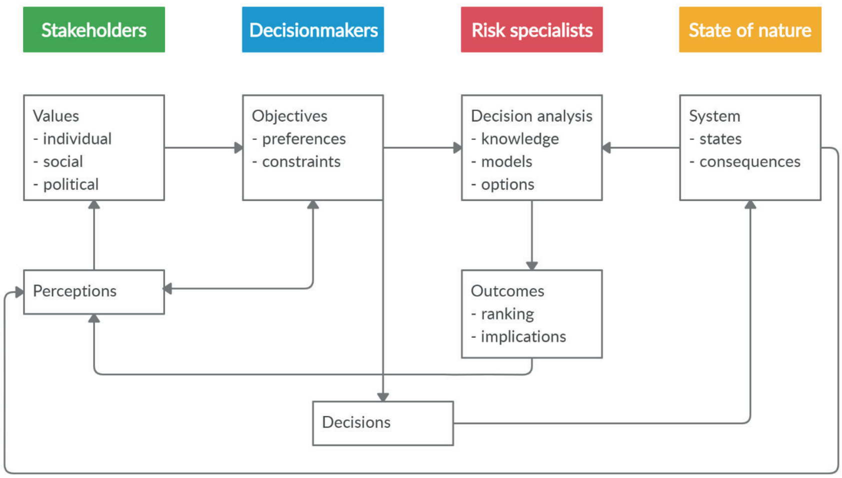

Fig. 14 Systems representation of interactions among stakeholders in the decision-making context with focus on the non-linear flow (arrows between boxes) of information affecting decision ranking and outcomes of decision making. Adapted from Nielsen et al. (2019).

Based on the systems representation in Fig. 14, five information conditions that affect the outcome of decisions are outlined in the following:

i) The information is relevant and precise

ii) The information is relevant but imprecise

iii) The information is irrelevant

iv) The information is relevant but incorrect

v) The flow of information is disrupted or delayed

Based on these conditions, Faber (2018) and Nielsen et al. (2019) develop an information-based typology that groups hazards by information properties (see Table 4).

Table 4 Hazard groups by information type.

	Information Type I	Information Type II	Information Type III	Information Type IV
Distribution in time & space	Rare occurrence in time and space	Frequent in time & space	• Extremely rare in time & space • Probability of occurrence poorly or not at all understood	Random or unknown
Consequence characteristics	• High; • Predictable due to large scale averaging effects	• Small – short-term; potentially high – long-term • Due to cognitive biases, commonly & collectively ignored	• Catastrophic/existential • Unpredictable even in large extents of time & space • Evolution of consequences poorly or not at all understood	May resemble Type I, Type II or Type III
Examples	• Geophysical hazards, e.g. flood, earthquake • Technical failures in e.g. power plants, wind parks • Infectious diseases, e.g. flu	• Emissions to the environment • Exploitation of resources • Extinction of species • Inefficient/ inadequate regulations, inadequate budgeting, human errors • Biases associated with the technological transfer of information caused by e.g., inadequate control and calibration procedures, delayed transfer of information caused by organizational inefficiency • Chronic and lifestyle illnesses; Antimicrobial resistance	• Super volcano eruptions, impacts by asteroids, high intensity solar storms, global climate change, major malevolent actions, out-of-control technologies • Solar storms shutting down electronic communication systems at large scale, malevolent disruptions of satellite communication systems, interferences of GPS navigations systems • Unknown viruses; Pandemics	Events triggered by incorrect information and knowledge: • Intentionally and unintentionally omitted or manipulated information, "fake news", • censored and/or erroneous observations • False positives and false negatives in statistical testing
Affected systems	social, engineered, ecological	social, engineered, ecological	social, engineered, ecological	social, engineered, ecological
Relation to other types	At small scale, may be the same as Type III	Accumulation over time and space, may transform Type II into Type III consequences	At small scale, e.g., region/community the same type of hazards as Type I hazards may belong to this group since no sufficient averaging effects	May play a role for Type I, Type II and Type III

The adoption of an information hazard classification goes even further than abolishing the disciplinary orientation of current practice. It also abolishes the grouping of several disciplines into what has been designated 'engineered' and 'social-ecological systems' by researchers in the knowledge domains of ecology and environmental management. As will be presented in more detail in Part II of the present paper sequence, it enables a unification of disciplines a step further, rendering the descriptors ‘engineered,’ ‘social’ and ‘ecological’ obsolete by facilitating the creation of a “flat” conceptual ontology of the knowledge domain, where concepts previously considered properties of engineering, environmental and social sciences are given equal ontological status in the event space, with the possibility to be grouped or clustered together according to the information properties of relevance for a given system, and defined on the basis of a decision situation in space and time.

The information hazard classification, together with its accompanying knowledge domain ontology, is based on combining theoretical insights from information theory, Bayesian probability theory, Bayesian decision analysis and systems theory. The concept of image schemas stemming from embodied cognition, which is used as the principle rule for the categorization of concepts into categorical containers (concept clusters, dimensions and dimensaional pairs in the ontology), is an informational concept. An image schema can be thought of as a dynamic template – a relatively stable, recurrent, but not stationary structure. Together, these theoretical insights form a transparent and less arbitrary methodology for assigning hazards and concepts to the exclusive property of any one given academic discipline, thus diminishing the ideological input of prior disciplinary beliefs and enabling an open-ended scientific inquiry of the hazards. The new classification system is thus the foundation for the ontology as well as the basis for formulating the three overarching educational requirements for risk education.

5. Conclusions

The present contribution is Part I of a triad of papers reporting on the development of an ontology and a blueprint for education design in risk, resilience and sustainability science. The present paper starts out by discussing the necessity for pursuing this research, the approach taken and the baseline for the developments in terms of what presently constitutes research and educational activities in the domain. It then articulates a view of hazards as information types which brings all risks, independent of science domain and application area, under a common denominator.

First an outline is provided of the need for a paradigm shift, away from the classical procedural, methodical and technical focus, which presently underlies research and education on risk-informed governance of societal systems. We then argue that in order to advance the body of knowledge through research and education in the risk, resilience and sustainability science, the knowledge domain as such must be reestablished in a manner which ensures that it is generically applicable across sciences and application domains, void of societal value settings, free of traditions of industrial practices, and not least, makes possible a coherent and consistent account of all existing - as well as any new - knowledge made available over time. Using systems design methodology, a design approach is then presented for the development of education in risk, resilience and sustainability science. This approach directs the focus of future efforts on closing the gaps (misfits) between what is ultimately desired and what is currently available in present practice, organization and conduct of research and education. The approach not only informs the development of the domain ontology in terms of relevant concepts and clusters of concepts, but also guides the formulation of educational requirements and identification of context specific learning pathways.

Based on previous works by the authors on past and contemporary research and teaching in the domain of risk, resilience and sustainability, concepts of relevance for the development of the ontology are then identified and high-level objectives for the educational design are formulated.

Finally, as a means for establishing a truly generic, coherent, and consistent basis for the development of the ontology, one void of past and contemporary societal value settings, a new hazard classification is presented, based on information type rather than the traditional classifications focusing on hazard sources. The information-oriented perspective to risk sheds light on the significance not only of available or achievable knowledge related to states of the world, but also of the crucial importance of the possible ways such information might be subject to distortion, misinterpretation, delays and disruption and thereby substantially contribute to risks.

In the subsequent Part II of the present triad the development of the domain ontology is discussed in some detail, together with the underlying theoretical and methodological basis. Finally, in Part III, the educational requirements are formulated, the education blueprint is completed and its application is illustrated at three different levels of modularity: full degree program, individual course and specific problem/project activity.

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5.2. PART II

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Toward an information theoretic ontology of risk, resilience and sustainability and a blueprint for education – Part II

The concept of risk as the theoretical and methodological basis for information- consistent ranking of decision alternatives is central to safe, sustainable and resilient societal developments. However, due to significant disparities in the understanding of the concept of risk in academia, and in its application in governance and industry, we argue that a new paradigm for risk must be established. In a sequence of three papers (Part I, Part II and Part III) we take up this challenge, with the leading objective of providing a coherent foundation for the further development and transfer of the general body of knowledge relevant to governance of risk, resilience and sustainability – through research and education. In Part I, we first present our motivation and general approach to the problem. Thereafter, we provide an overview and a discussion on the state of research and education in the domain of risk, resilience and sustainability, and propose a generic, information-based hazard classification scheme, which informs the development of a domain ontology and a blueprint for education. Part II (the present paper) provides a logic for the structuring of the knowledge domain in terms of a domain ontology of the concepts relevant for an integrated science of risk, resilience and sustainability. In Part III, based on the results of Part I and Part II, we identify educational requirements, and finally provide a blueprint for education designs. We believe that the proposed ontology and the related education blueprint may provide value both to the further evolution of research and education in risk in general, and for the governance of risk, resilience and sustainability in particular.

Keywords: risk; resilience; sustainability; risk governance; domain ontology; embodied cognition; philosophy of education; learning design

1 Introduction

Societies at local and global scales are facing major challenges in the pursuit of welfare, safety, security, and even existence. Global trends of population growth, urbanization, depletion of non-renewable resources, and anthropologically induced climate change severely challenge sustainable developments. These trends, together with a host of natural and anthropological hazards, well represented by the recent outbreak of the Covid19, call for a disruptive improvement in governance at all levels of societal decision making.

The concept of risk stands in the middle of this challenge. It is well appreciated that risk forms the basis for optimal decision ranking when the outcomes of decisions are associated with uncertainty. However, risk has not been established as a knowledge domain in itself until now, and for this reason, there is substantial variability in how the concept of risk is understood across sciences and application domains. Conceptual knowledge underlying the knowledge tradition of risk is unsystematic and disorganized. It stems from a spectrum of disciplines and application areas spanning engineered, social and environmental systems, but despite the generic structure of the procedures, concepts and terms are poorly, if at all, defined, and definitions are widely divergent across applications. The growing acknowledgement of the generic characteristics of the concept of risk, and risk-based analysis as the only legitimate form of evidence in support of ranking of individual and collective decision and actions, however, supports the perspective that the subject matter of risk might be seen as a science in its own right rather than a specialization within established, individual disciplines.

The integration of risk, resilience and sustainability considerations into a common conceptual and operational framework is at the vanguard of research. It is now at this early stage of integrating these knowledge traditions that a common conceptual classification system needs to be established, that is generic and captures the theoretical foundations upon which knowledge of risk, resilience and sustainability can build on.

We here endeavor to take a first step in establishing a more formal basis for the continuously evolving knowledge domain of risk in the context of societal governance for resilient and sustainable developments.

To this end, in a triad of papers (Part I – Part III[1]) we:

i) Outline an approach and a methodical basis for representing the knowledge domain of risk, resilience and sustainability science (Part I);
ii) Establish an ontology for the integrated knowledge domain of risk, resilience and sustainability (Part II) and;
iii) Identify educational requirements, and together with the results of Part I and Part II, finally provide an blueprint for the design of educational offers (Part III).

The overall structure and contents of the triad of papers is illustrated in Fig. 1.

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[1] For ease of syntax, in the following we refer to Part I and Part III of the triad without specification of authors and year, however these are always the same and may be found in the list of references under (Nielsen and Faber, 2020).

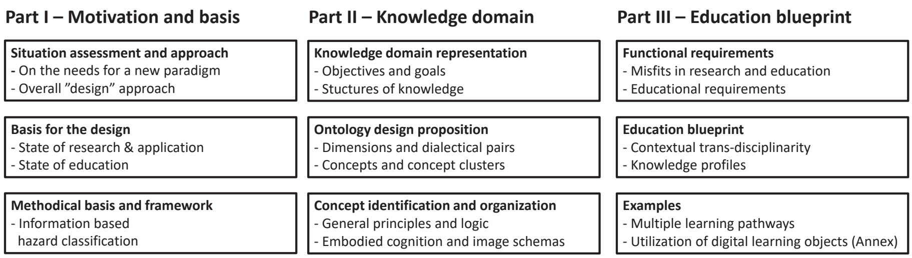

Fig. 1 Overview of the structure and contents of the triad of papers presenting the information-theoretic ontology of risk, resilience and sustainability and a blueprint for education.

The present paper, i.e. Part II, is organized as follows: In Section 2 we compare and contrast alternative structures for knowledge organization. We contrast the present best practice of compiling glossaries of terms as structured or unstructured lists with the advantages of more sophisticated structures, such as taxonomies and ontologies. We explain, in non-technical terms, differences between taxonomies and ontologies as well as genealogical, radial and mereological hierarchies. Further, we provide background on relevant theoretical concepts from embodied cognition that we use as anchors for the classification choices we have made in designing the ontology: family resemblance, prototype effects, and basic level categories. In Section 3 we present the ontology and briefly discuss the themes covered by its four dimensions. In Section 4 we give an overview of the sources and methods for selecting concepts for the ontology. In Section 5 we discuss what it means to know a concept and what a definition is. Subsequently, we provide an overview of the paradigmatic framework of embodied cognition, which we have used as a structuring principle of the ontology and key terms such as image schema and conceptual metaphor are introduced and explained. In Section 6 we discuss the image schemas and conceptual metaphors that correspond to the categorical pairs in the ontology and how selection of the source domain of metaphors affects the boundaries of concept and system definitions. Section 7 attempts to establish a basis for a shared inter-cultural language between Western and Eastern conceptual systems. Finally, Section 8 concludes with reflections on the extent to which the ontology may provide direction toward a unified theory of risk, resilience and sustainability and a shared language among disciplines and cultures. A vision of this new science as a holistic life science is outlined, together with how the ontology can be used in the design of education.

2 Alternative structures for organizing conceptual knowledge informing design choices in the ontology

A knowledge domain can be organized to form very different structures, resting on different logical foundations, such as lists, glossaries and hierarchies, of which the latter type form the basis for the design of taxonomies and ontologies. In this section, we explain briefly, and in non-technical terms, how taxonomies and ontologies differ, and how different kinds of hierarchical structures affect design choices for building domain ontologies.

When items are classified through child-parent-grandparent relations, typically the structure is called a taxonomy and it resembles a genealogical tree. The function of a taxonomy is to classify an individual entity into a category of ascending (parent/more general) or descending (child/more specific) order. From Aristotle's system of categories to Darwin's theory of evolution via the Linnaean taxonomic system, classification of biodiversity in evolutionary biology has historically been based on the hierarchical tree structure. The system is an arrangement of morphological attributes by means of which plants, animals and minerals can be classified and identified through classes, orders, families, genera, and species. More recently, classification based on advances in molecular biology, uses genetic and molecular sequencing to structure variety. The concept of 'horizontal gene transfer' (Ouzounis, 2005), which describes the process of an organism incorporating genetic material from without (i.e. from another organism) rather than inheriting it from within (an ancestor), has uprooted the genealogical tree metaphor and replaced it with another structural metaphor – the network. The vertical hierarchy, whether top-down from general to particular or bottom-up from particular to general, has over the past two decades been replaced by the phylogenetic tree, whose horizontal hierarchy has been used to theorize structural arrangements as 'flat hierarchies' in multiple domains[2]. Both the tree and the network are hierarchies in the sense that they classify relations among objects. However, while the tree has an internal structure of inherited relations, the network has a radial structure of family relations. By 'family', it should be understood any grouping, cluster or category where elements interact not on the basis of inherent shared properties but on the basis of functional relations. 'Family resemblance' is a notion introduced by mathematical philosopher Ludwig Wittgenstein to describe how concepts can be united in a common category without the pre-condition that they all share a common collection of properties; rather, in a family-like manner, some properties are shared by different members (Wittgenstein, 2009). The implication of Wittgenstein's observation is that category boundaries are not fixed but stipulated and that the only possible definition of a concept is ostensive. Both implications are of central importance to the design of the ontology presented in the present Part II and the education blueprint presented in Part III of this triad of papers. In the ontology, we choose not to provide definitions of the concepts, but to present the semantic range of a concept by means of displaying family-related concepts in a given concept cluster.

In the following, we explain how prototype theory of categorization can be used to structure categories radially by having basic level categories at the center of the

[2] Prominent examples include actor network theory (Latour, 2013) and object oriented ontology (Harman, 2018).

hierarchy, with superordinate categories branching upward and subordinate level categories – downward. We discuss implications for this arrangement in terms of the role basic level categories play in the metaphorical transfer of meaning between image schemas and our design choice to visualize the ontology as a radial structure. The notion of basic level categories is, in fact, closely connected to the notion of family resemblance. It would be impossible to differentiate levels in a category if all category members shared the same common properties. Wittgenstein's demonstration that some members of a category are better examples is the foundational basis for Rosch's (1975) prototype theory and basic level categorization in experimental psychology. According to the latter, some members of a category are perceived and judged as being more representative of a category than others, resulting in asymmetries (technically called "prototype effects") between members rated as more or less representative, with the most representative members referred to as "prototypes". These prototypes function as anchors or "cognitive reference points" of inference Rosch (1975). However, unlike Wittgenstein's radial structure of family resemblance, which has no center or core, Rosch's experiments reveal that the middle level (i.e. the level of genus) is the primary level of organizing information, which is why categories at this level are called basic level categories:

Superordinate level – ANIMAL

Basic level – BIRD

Subordinate level – SWAN

Lakoff (2008) summarizes four characteristics of the basic level of categorization based on the empirical studies of Berlin et al. (1974/2013) and Mervis and Rosch (1981):

i) Perception: Overall perceived shape; single mental image; fast identification
ii) Function: The level at which a person uses similar motor actions to interact with category members
iii) Communication: Shortest, most commonly used, contextually neutral words; first learned by children

iv) Knowledge organization: The level where most attributes of category members are stored.

Basic level categorization is applied to the structure of the ontology presented in this paper (Fig. 2).

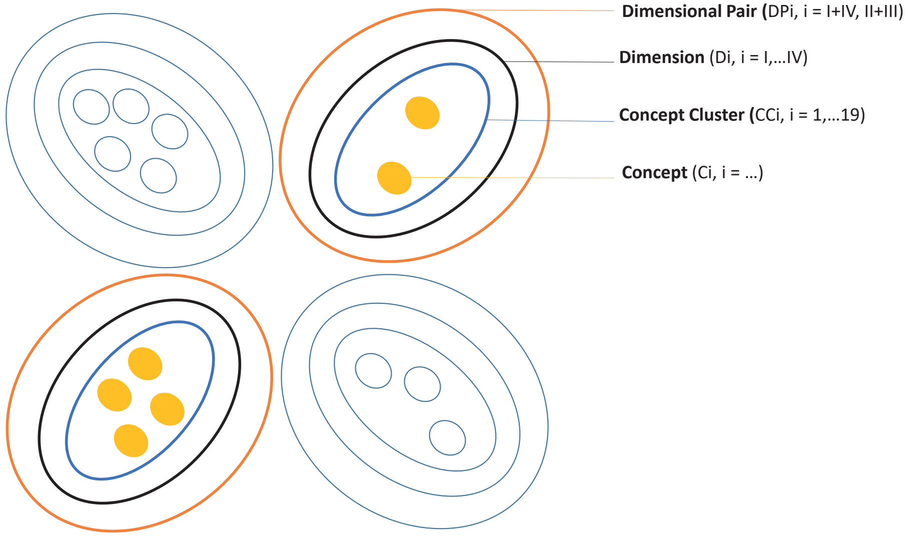

Fig. 2 Skeleton of the ontology.

The ontology's three levels: concept, concept cluster and dimension correspond to the subordinate, basic, superordinate levels from cognitive linguistics experimental and theoretical studies of Rosch, Lakoff and Johnson. This structuring enables a radial rather than genealogical hierarchy. The notion of family resemblance underlies the choice to not give prominence to any prototypical members of a concept cluster in order to avoid disciplinary bias. Prototype effects are instead treated in the context of their relation to image schemas (explained in Section 5.4), which govern the super-imposed structural level of dimensional pairs, visualized symbolically as an ouroboros that groups the four dimensions into two complementary pairs. The ouroboros layer should be seen as the interface for a shared language between theoretical and cultural traditions. The "core" of the ontology is thus the middle ring of concept clusters. The level of concreteness contracts inwards toward the subordinate scale of individual concepts, while the level of abstractness expands outwards toward the superordinate scale of dimension.

A major shortcoming of the genealogical hierarchy structure is that it cannot be used to represent a knowledge system, in which concepts may have more than one categorization. Furthermore, a category can fall into more than one branch. An ontology, in contrast with a taxonomy, is a more flexible structure in that its function, in addition to classification, is specification. In a seminal paper by Gruber (1993), an ontology is defined as "an explicit specification of a conceptualization" and a formal ontology as "the statement of a logical theory". Writing in the context of artificial intelligence, Gruber's definition of ontology intuitively touches upon a significant difference in the subject matter of a taxonomy and an ontology. A taxonomy is typically used to organize physical (material) entities, whose existence is not questioned (see discussion on natural kinds in Section 5.3) and is accepted as a given. The data of taxonomies is thus typically plants, animals, materials, and artifacts. Ontology, as a branch of philosophy, is first and foremost interested in defining what exists, how it exists and how we can know that it exists. An ontology thus starts by defining what an entity is and only subsequently, how entities are organized in relation to one another. For example, when organizing entities x, y, z, a taxonomist's assumption is that there are 3 entities. An ontologist's first consideration is to arrive at a logic that proves that given x, y, z there are 3 entities or whether the combinations of these entities, in turn form new entities (e.g. x + y, x+z, y+z, x+y+z), or in other words, when a collection of entities forms an entity. The data of ontologies are con-cepts, information clusters, which derive from the physical realm of per-cepts. Taxonomies and ontologies have a dependency relation since ultimately the question of how many entities there are or exist only makes sense after a classification or sorting scheme has been assumed. This dependency underlies the position of pragmatic realism outlined in Putnam (1981, 1990).

Pragmatically, the function of an ontology is to facilitate a shared language among a variety of users with different knowledge bases (Gruber, 1993). In the context of our design, a shared language among disciplines and culturally different conceptual systems is an explicit functional requirement. The design of the ontology is then a precondition for fulfilling this requirement. An ontology, unlike a taxonomy, is a designed structure. A taxonomy is organized data. An ontology is not the data itself but the rules that define the organization. In the present paper, the rules for the proposed ontology are qualitatively described. In Part III of the triad, we discuss the possibility for formalizing these rules for the design of a repository of digital learning objects.

One further example needs to be made with regard to the choice of hierarchical structure. When an ontology is structured as an aggregate of individual forms (things, objects), the designed system is atomistic. The individuals are so-to-speak chiseled out of the undifferentiated matter (content). Such structures tend to be visualized as horizontally or vertically branching trees. When a taxonomy or ontology is structured as an aggregate of functions, the designed system is mereological and individual instances (spatio-temporal events) are subsumed by a nested set of containers. Such structures tend to be visualized as regions of bounded space. The difference between taxonomic and mereological classification is not straightforward due to a common cognitive tendency to confuse kinds and parts. Mereology (in philosophy and mathematics) is the study of parts and wholes. Fig. 3 provides an explanatory illustration.

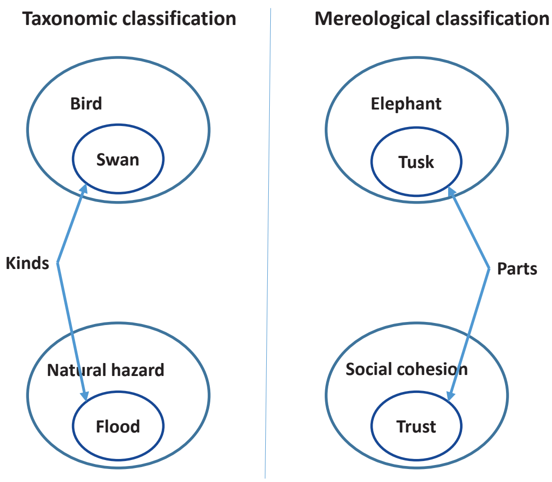

Fig. 3 Illustration of the principal differences between taxonomic and mereological classification.

A taxonomic classification has ontological commitment to objects. An instance of a category is a kind of that category. It is differentiated from other instances in the category on the basis of form and its membership in the category depends on shared attributes of form with the other instances in the category. A swan is a kind of bird, not a part of bird. A tsunami is a kind of natural hazard, not a part of natural hazard.

A mereological classification has ontological commitment to events. Here the instance of a category is not a kind, but a functional part. Hence, tusk is a part of elephant, not a kind of elephant. Trust is part of social cohesion, not a kind of social cohesion.

In embodied cognition, PART-WHOLE is a basic image schema for organization of information based on human-environment interaction that is said to occur at precisely the basic level described in Rosch's theory of basic level categories. This claim is supported by experimental evidence from Tversky and Hemenway (1984), which shows that part-whole relations structure cognitive processes both with respect to objects and to events. First, with regard to objects, part-whole structures provide understanding of functions. Lakoff (2008) points out that we learn and reason about functions based on our sensorimotor interaction with the parts of objects. In the words of Tversky and Hemenway (1984): "We sit on the *seat* of a chair and lean against the *back*, we remove the *peel* of a banana and eat the *pulp*." The same embodied cognitive process is at the core of Gibson's (1977) theory of affordances that underlies the principles of form-function design as well as the ecological concept 'niche'. Second, with regard to events, part-whole interactions with the world also capture basic level actions, static states and dynamic processes.

3 Presentation of the ontology

Fig. 4 provides a visual illustration of the ontology as a nested hierarchy, comprised of the elements concept, concept cluster, dimension, and dimensional pair. The color scheme is based on Opponent Process Theory of Color Vision (Hering 1964). This theory, in contrast to the prevailing trichromatic RGB theory (red, green and blue) based on light and the pigment of one the above colors, posits that the human visual system interprets colors based on the differences between the responses of cone cells, rather than each type of cone's individual response. This means that color is perceived from three opposing pairs: red vs green, yellow vs blue and white vs black. This underlies our choice to use blue and yellow to bring forth the dimensional pair DI – DIV and red and green for the dimensional pair DII-DIII

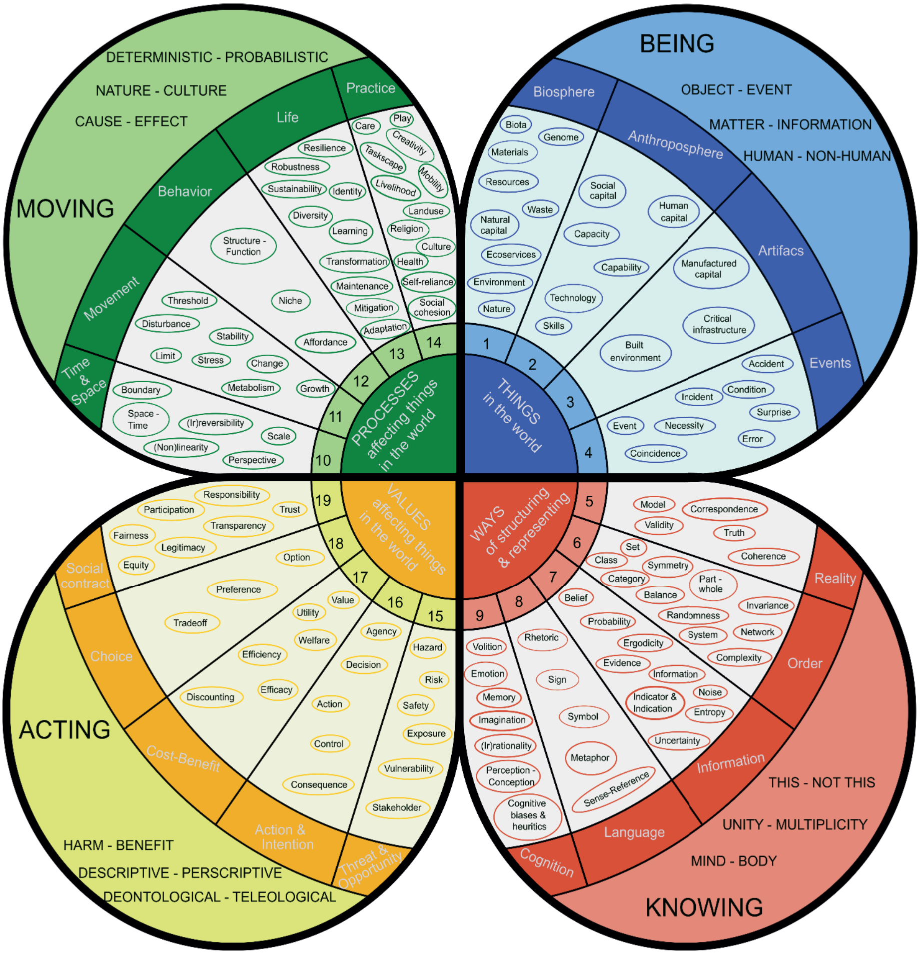

Fig. 4 Ontology of the knowledge domain of risk, resilience and sustainability.

In the remainder of this section we briefly discuss the content of each dimension, while in Section 6, we present the conceptual structuring of the dimensions in terms of embodied image schemas.

3.1 Dimension I - Things in the world

This dimension deals with the ontological question of Being, or what the integrated knowledge domain of risk, resilience and sustainability is composed of, namely concepts denoting organisms, artifacts, resources, and events. Three additional categorical pairs overlay this dimension: object – event, matter - information and human - non-human. The first pair deals with the problem of whether the concepts denoting what exists refer to objects or to events. Do objects and events have the same ontological status? Is the difference between them one of kind or one of degree? What are the implications for acting in the world if we adopt a materialist object view of reality or an immaterialist informational view? While we have chosen to give equal ontological status to objects and events, the new hazard classification system based on information type places hazards in the event category (concept cluster 4) rather than listing individual hazards as separate objects.

3.2 Dimension IV - Values affecting things in the world

This dimension deals with the axiological notion of Acting. In the context of risk analysis, action overlaps with decision. Axiology (from Gk *axios*, 'worthy') is the branch of philosophy that studies values – ethical and aesthetic.

The reason for pairing Dimension I with Dimension IV is that which hazards we select for consideration and how we define the boundaries of a system (choices made in Dimension I) has significant implications for the normative framework chosen to treat risk (choices made in Dimension IV). Three additional categorical pairs overlay Dimension IV: deontological – teleological, descriptive – prescriptive and nature - culture. In the following, we briefly explain how these relate to human actions.

Decision Theory is the inter-disciplinary science of action. Descriptive decision theory aims to describe how humans actually make decisions in reality. It has strong empirical roots in psychology and behavioral sciences. Normative decision theory is prescriptive. It is about how we ought to make decisions.

The purpose of risk management and governance is clearly normative. While descriptive decision theory can and does help to better calibrate models, the principles upon which normative decisions about risk must be made are based on considerations of utility.

3.3 Dimension II - Ways of structuring and representing

Dimension II is about order and our perception of it. Philosophically, it relates to epistemology. Mathematically, it relates to set theory, statistics, probability theory, and information theory. Linguistically, it relates to semantics and semiotics. Empirically, it relates to embodied theories of cognition and affect theories. Each of these conceptual schemes is represented in the ontology through the respective clusters 'Reality' (5), 'Order' and 'Information' (6 and 7), 'Language' (8), and 'Cognition' (9). D II is about sense making: perceiving, orienting, learning, and knowing in the world and about the world. In developing this dimension as well as the ontology as a whole, our underlining assumption is that our only access to physical reality is by means of some kind of model. The choices we make in building our models define our reality. By defining a spatial and temporal boundary around a set of elements, we define a system. The boundary we draw influences our subsequent choices of which consequences and causal relations we take in consideration of the predictions we make about the behavior of a system. There are no systems in the physical reality. Systems are the structures defined by our models[3]. The

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[3] "Can you say where the boundaries are? No. You can *draw* some; for there aren't any drawn yet…To repeat, we can draw a boundary – for a special purpose." Wittgenstein, Philosophical Investigations 68-69.

three additional categorical pairs of DII, mind - body, this – not this, unity – multiplicity underlie the choice of model free structuring and representation of reality.

3.4. Dimension III - Processes affecting things in the world

Dimension III is about change and process – the dynamics of biophysical and human systems. The three additional categorical pairs cause – effect, deterministic – probabilistic and nature – culture are based on a number of embodied image schemas for movement and interaction of forces. A fundamental goal of risk management is to distinguish between hazards with trivial and non-trivial consequences for the integrity of a given system, where integrity is to be understood through the family-related concepts identity, robustness, resilience, and sustainability (concept cluster 13). Despite best practice methods for consequence modeling and rigorous scientific frameworks for assessing indicators and metrics (e.g. Planetary Boundaries framework, LCA methods, etc.), there is no such rigor when it comes to the rather more fundamental task of distinguishing the trivial from the non-trivial and the relevant from the irrelevant information. The concepts in concept cluster 10 (time, space, boundary, scale, perspective, etc.) are precisely those that provide information for orientation in space and time for us as moving observers in an evolving environment (context).

4 Matter

4.1 Where do concepts in the ontology come from?

The material basis for the ontology is a corpus of 0.5 million peer-reviewed articles indexed in the Web of Science for the domains of risk, resilience and sustainability for the period 1990-2017. Based on statistical data mining of this corpus, a finite set of 2634 terms (concepts) clustered according to a term's co-occurrence and link strength with other terms was derived and 26 cluster maps of the knowledge domain established (Nielsen and Faber, 2019).

Using cluster analysis as an objective and transparent method of concept selection is tempting indeed. It is clear to see in a cluster map which concepts have high occurrences and form stronger links, so they would be 'natural' candidates to be selected as the most important concepts in the domain. Such concepts, however, tend to be loaded with ideological content and disciplinary bias. Since our goal is to establish a generic representation of the concepts of relevance to the study of risk, resilience and sustainability regardless the application domain of such knowledge, the statistical data mining was complemented with a qualitative hermeneutic method of text interpretation to establish criteria for the selection of a term as a concept in the ontology. The criteria are established such that the logical consistency of selection and order is also coherent with functions and purposes of the ontology. These criteria are outlined in the following:

Criteria 1: MODULARITY

i) Avoid, whenever possible compound concepts
ii) Refrain from concepts referring to particular organisms, hazards or activities, so that concepts may be applicable across systems

In complex categorization, a set theoretical treatment of adjective-noun phrases is based on the operation of intersection. The clustering procedure in our bibliometric analysis is based on the co-occurrence strength of noun-noun phrases, which is syntactically the same as adjective-noun phrases. In the linguistic domain of semantics, the inadequacy of this method is demonstrated by a plethora of examples where the complex or compound concept is not an intersection of sets. Osherson and Smith (1981) provide some clear examples – 'small galaxy', 'electrical engineer', 'past president', etc., where the intersection, or in other words, the categorically common feature, of the set of e.g. small things and galaxies, electrical things and engineers forms a logical inconsistency. In our context, compound concepts such as ‘circular economy’, ‘inclusive wealth’, ‘ecological resilience’, ‘engineering resilience’, ‘risk assessment’, ‘risk management’, ‘risk communication, etc. are excluded from the ontology even though in the statistical analysis they appear as central concepts. Typically, this means excluding noun phrases (noun + noun or adjective + noun) as they tend to particularize or instantiate a thing or phenomenon by discipline or by application area. For example, we have selected ‘growth’ but not ‘inclusive growth’, ‘population growth’. We have, however, made an exception in the case of capital, and included natural, human and social capital as separate entities. This was done in order to comply with (ii) above to stay when possible at the level of genus rather than species.

Criteria 2: SYNONYMS

When faced with synonyms, we have chosen the one that most looks like a lay term. A lay term tends to coincides with the prototype (best or salient example) of a category, according to Rosch’s prototype theory. For example, of the trio ‘consequence’, ‘impact’ and ‘effect’, we have chosen ‘consequence’ as we believe it is the term most likely to evoke association with the superordinate level concept ‘causality’, of which it is an instance. Furthermore, ‘consequence’ tends to appear in wider contexts, hence its perceived neutrality of usage in comparison with the other two terms. ‘Impact’ tends to be used in research dominated by social and political science, while ‘effect’ is the preferred term in the environmental sciences. There is also a tendency for ‘impact’ to be found in the context of human activities causing consequences while ‘effect’, in the context of natural counterforce.

Criteria 3: MISSING CONCEPTS

Given our academic and professional experience in the knowledge domain, we felt justified to introduce concepts in the ontology, which were not captured, or were not captured prominently, by the statistical analysis. In taking the freedom to include these concepts, our considerations focus on the instrumental purpose of the ontology as a basis for the subsequent development of the education blueprint.

Table 1 lists the concepts that were selected from the bibliometric study and the concepts that were added by the authors, organized in alphabetic order according to the dimension where they were allocated. Some of the selected concepts appear as members of a concept cluster; others designate a concept cluster.

Table 1 Ontology concepts derived from the bibliometric study and concepts added by the authors.

D I Things	D II Ways	D III Processes	D IV Values
Selected	Selected	Selected	Selected
Accident	Balance	Adaptation	Action
Biota	Complexity	Behavior	Agency
Capability	Evidence	Boundary	Benefit
Capacity	Indicator	Care	Choice
Condition	Information	Change	Consequence
Critical infrastructure	Language	Culture	Control
Ecosystem service	Model	Disturbance	Cost
Environment	Network	Diversity	Decision
Error	Noise	Emergence	Efficacy
Human capital	Order	Growth	Efficiency
Material	Perception	Health	Equity
Natural capital	Probability	Identity	Exposure
Nature	Sense	Land use	Hazard
Resource	System	Learning	Legitimacy
Social capital	Uncertainty	Life	Opportunity
Skills		Limit	Option
		Livelihood	Participation
		Maintenance	Preference
		Metabolism	Responsibility
		Mitigation	Risk
		Mobility	Safety
		Movement	Self-reliance
		Practice	Stakeholder
		Sustainability	Threat
		Resilience	Tradeoff
		Robustness	Transparency
		Scale	Trust
		Space	Utility
		Stability	Value
		Stress	Vulnerability
		Threshold	Welfare
		Time	
		Transformation	
Added	Added	Added	Added
Coincidence	Belief	(Ir)reversibility	Discounting
Event	Category	(Non)linearity	Fairness
Genome	Class	Perspective	Participation
Incident	Cognitive Biases & Heuristics	Structure-function relations	Self-reliance
Manufactured capital	Constants & Variables	Affordance	

Necessity	Coherence	Niche	
Surprise	Correspondence	Lifeworld	
Technology	Emotion	Play	
Waste	Embodied Cognition	Creativity	
	Ergodicity	Religion	
	Indication	Social Cohesion	
	Imagination	Taskscape	
	Invariance		
	(Ir)rationality		
	Memory		
	Metaphor		
	Part-Whole		
	Randomness		
	Reference, added to Sense as Sense-Reference		
	Relation		
	Rhetoric		
	Set		
	Sign		
	Symbol Volition		
	Symmetry		
	Truth		
	Validity		

The selection of concepts and their organization into particular clusters and dimensions has been highly iterative. Once a more or less stable form of the ontology emerged and was color-coded into the four dimensions (D I Things in the world, D II Ways of structuring and representing, D III Processes affecting things in the world, and D IV Values affecting things in the world), we applied the rules of the designed ontology to the full data set of the bibliometric study, classifying each term in the data set according to the new ontology. Fig. 5 shows the distribution of concepts in the ontology before and after terms were selected from the bibliometric study. This difference is informative of the extent to which the ontology presented in this paper is “designed” vs the taxonomic kind of classification of the cluster mapping.

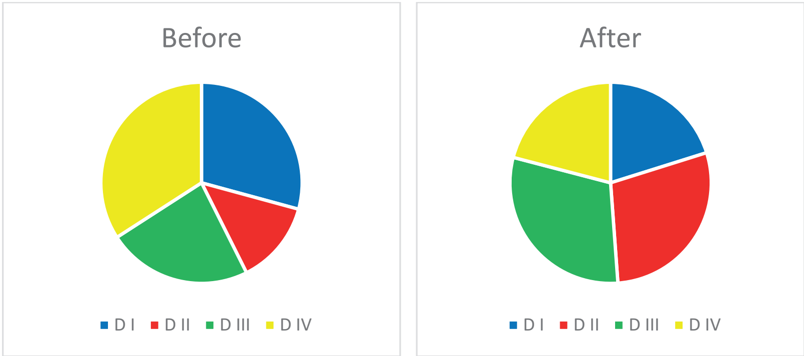

Fig. 5 State of research in risk-resilience-sustainability domain 1990-2017 according to the classification of the new ontology.

When we look at the research domain encompassing risk resilience and sustainability over the past 30 years through the lens of our ontology, we see that research focusing on conceptual schemes related to values (D IV) is double that of research on conceptual schemes related to information (D II). D I has a sizable chunk due to the fact that according to the current practice of classifying hazards by their source, concepts here are mostly instances of every possible source of hazard: fire, flood, earthquake, greenhouse gasses, terrorism, e-coli, etc. The processes dimension, D III has a fairly large representation due to the significant increase in research over the 30-year period in environmental sciences and ecology.

As in a later iteration of the design process, we decided to add the dimensional pairs, so that D I and D IV formed a pair and D II and D III formed a pair, we could see that the balance in the research domain was tipped on the side of pair D I and D IV (Fig. 6).

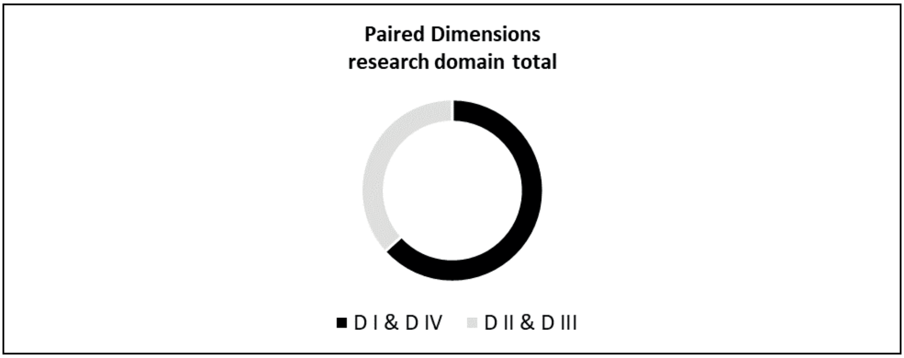

Fig. 6 State of research in risk-resilience-sustainability domain 1990-2017 according to the dialectical pairing in the new ontology.

Fig. 7 shows that much of past and current research in risk, resilience and sustainability is driven by value-related conceptual schemes, while the only area where information theoretical concepts are to be found is in the area showing research on robustness that stems exclusively from engineering disciplines. Since we argue that the concept of 'information' is the common denominator that integrates the knowledge traditions of risk, resilience and sustainability, we have designed both the ontology and the education blueprint such as to distribute the balance of forces in a way that brings 'information' out of the engineering closet.

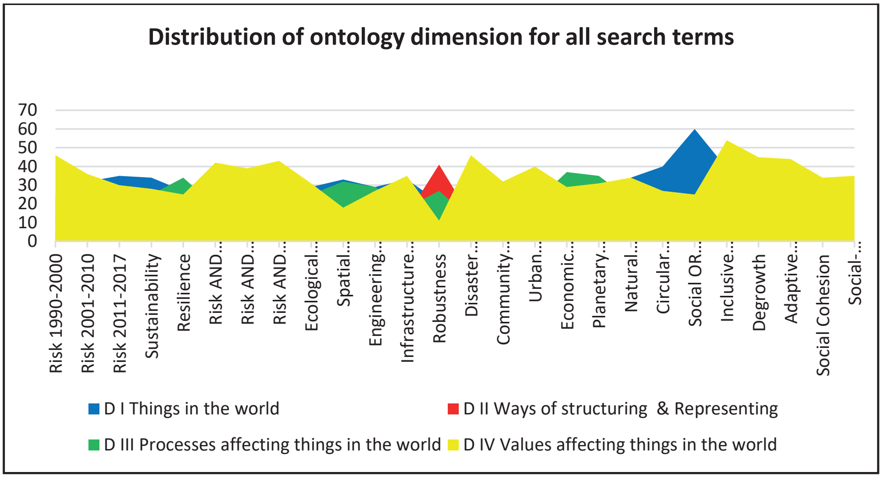

Fig. 7 Research domain dominated by value-driven conceptual schemes.

The knowledge domain of risk builds predominantly on engineering, economics and behavioral psychology disciplines. The knowledge domain of resilience builds on knowledge predominantly from ecology and environmental management as well as the newly revived discipline of ecological economics. The knowledge domain of sustainability builds on knowledge predominantly from environmental science, economics, political science, and sociology.

Of the three, risk has the longest history of research and the widest geographic distribution of produced research. Sustainability has the second longest history of research. The geographic distribution of the research in the formative period of the domain (1970-2000) is confined to Western Anglo-Saxon countries but has expanded to China over the past two decades. Resilience is the youngest of the three domains. It is limited in geographic scope of production of research to several hubs in the Commonwealth and Scandinavian countries, and the U.S. It has, however, the most articulate and cohesive conceptual structure, which it has succeeded to transfer across a large number of external domains.

An integration of the knowledge bases of the three domains requires thus more than a synchronization of terminology. It requires a common conceptual basis that is of generic application to all disciplines and practices that inform these knowledge bases. This begs the questions, what then is a concept, and where do concepts really come from if not from the statistical data mining of the corpus? We take up these questions in the remainder of this paper.

5 Form

5.1 Where do concepts really come from? Disembodied vs embodied concepts

There is a voluminous literature that deals with defining what a concept is, concept types, what counts as conceptual knowledge etc. (see e.g. Margolis and Laurence (2019) for a comprehensive overview). Despite multiple differences across the knowledge traditions of philosophy, psychology, cognitive, and learning sciences, a common function of concepts recognized across individual academic domains is that a concept is an abstraction, a compressed bundle of information that allows us to act and re-act in a context. Through the senses, information about particular instances in the physical environment enters the mind. The mind performs an operation of abstraction whereby particulars are grouped, sorted and classified into a higher-level generalization – a kind, class, type, or category. The particulars then become members of a shared property.

5.2 What does it mean to know a concept? What is a definition?

Contrary to Frege's understanding of concepts as the sense constituents of propositions, i.e. abstract objects in the mind (see e.g. (Textor, 2010)), our understanding of concepts is based on the assumption that meaning is generated in practice and evolves concurrent with practice. Concepts do not have fixed identities – neither in the Platonic realm of rational, objective scientific definitions, nor in the social conventions of codes, regulations and domain taxonomies. In our design to "know" a concept is to have knowledge of the concept's range of possible usages. To know a concept, one must therefore know many concepts; not a definition.

Ontologies, as the chief product of Western metaphysics, are logical systems aiming at the description of true reality. Methodologically, this involves the dissecting of reality into its components, which is done by cutting out categories of distinct elements. Ontologies are then assemblages of things, where definitions are paramount because for an item to be included in an ontology it must exist distinctly. Definitions are properties of logical systems, rather than physical systems, i.e. definitions are of the mind rather than the world.

5.3 Categorization principles based on embodied cognition

Embodied cognition is a theoretical and methodological framework stemming from cognitive science research on how thought processes involved in human understanding and behavior involve blending physical perception and mental conception. Instead of treating reason, perception and bodily movement as three autonomous systems (neurological, sensory and motor), the basic tenet of embodied cognition is that the body's capacity for perception and movement shapes our reasoning about what is real as well as if and how we can know it.

At the core of the embodied cognition framework is a theory of categorization based on experience and interaction with the world rather than on a logical system of analytic a-priori. As a methodology, it presents an alternative to classical empiricism (e.g. Hume, Berkeley) and logical positivism (e.g. Carnap) on the one hand and rationalism (e.g. Descartes, Kant) on the other. According to the former, because all concepts are derived from experience, those that cannot be verified based on observation are not of legitimate scientific concern. According to the latter, concepts are a-priori in the mind.

The role of perception in experience is to reveal the a-priori in our pragmatic engagement with the physical world.

In the tradition of embodied cognition, largely developed by Lakoff and Johnson through the 1980s and 1990s, perception is both biological and philosophical. A-priori conceptual structures come to be known in experience through the possibilities allowed or constrained by virtue of having a body. Categories are neither analytic nor synthetic a-priori, but structures for differentiated experiences. Similarly, concepts are not generalized abstractions but dynamic neural structures that generate our categories. Furthermore, concepts are not internal (mental) representations of external reality, but are in-formed by our sensorimotor system. This renders the distinction between percepts (external sensory input) and concepts (internally processed information), empirically invalid. In contrast to Western philosophical and scientific traditions based on the mind-body divide, embodied cognition offers a phenomenological, empirically validated framework for conceptualization and categorization that is neither based on categories of natural kinds and a correspondence theory of truth nor on purely subjective categories (see Sapir-Whorf Hypothesis of cultural relativism, (Sapir, 1929)) and a coherence view of truth.

In a position known as essentialism, there are two kinds of properties: essential and accidental. The former capture those things without which a thing would not be that kind of thing. They are, in other words, the necessary and sufficient conditions for a thing to be that kind of thing. Natural kinds then are the objective categories of the entities existing in the world. Being purely objective, they are independent of perception and linked in a system of logical relations. Truth (meaning) in correspondence theory is determined either based on Fregean sense-reference functions (Frege, 1892) or on Kripke-Putnam's causal theory of pointing and naming (Kripke (1972), Putnam (1975)), both of which depend on the assumption of correspondence between symbols in a natural or formal language and a physical world that is independent of any perception. Categorization relies on a set-theoretic methodology whereby an item is classified as a member of a set (a category) based on the inherent shared properties of members of the set and in accordance with binary logic. Everything that exists is either in the particular set or outside it.

The correspondence theory of truth relies on isomorphism between model and reality. This isomorphism is the basis for associating ‘scientific facts’ with evidence of truth. In contrast, truth in the coherence view is understood in terms of conditional beliefs about the relations between physical phenomena. Truth is then ‘justified belief’.

In the embodied cognition paradigm, the correspondence and the coherence schools form a synthesis. Embodied image schemas function as enduring structures of meaning based on experiential and interactive properties whereby items are categorized on the basis of prototypes (typical cases) and in terms of their roles in different kinds of experience. A definition is not given in terms of an isolated binary differentiation of inherent properties, but pragmatically, in a relational context, such that the function of definition is to provide a general scheme for understanding a concept and how it fits and evolves within a larger conceptual system.

5.4 Image Schemas, Conceptual metaphors, Source and Target domains of conceptual metaphors

In embodied cognition, conceptual metaphors function as conduits between perception and conception. Unlike the traditional view of metaphor as a poetic figure of speech that identifies one object or experience in terms of a set of similar properties shared with another object or experience, metaphor is a relational property of concepts, not of particular words. The relation is usually not one of similarity but of difference. The function of metaphor is foremost pragmatic understanding; its aesthetic use is secondary. Technically speaking, a metaphor is the mapping and understanding of one conceptual schema in terms of another. A minimal unit of a conceptual schema is referred to as an image schema.

In Johnson (1990/2013) an image schema is defined as a "recurrent pattern, shape, and regularity in or of…ongoing activities." These patterns are not static containers such as templates, scripts or blueprints, but dynamic – in the sense that they engender meaningful structures through interaction and manipulation of objects in moving through space. Image schemas thus partially order human experiences while at the same time are also partially ordered and modified because of their embodiment in concrete experiences. Table 2 provides a selection of the most important basic image schemas.

Table 2 Selection of basic image schemas after Johnson (1990) and Johnson (2013).

CONTAINER	BALANCE	COMPULSION
BLOCKAGE	COUNTERFORCE	RESTRAINT REMOVAL
ENABLEMENT	ATTRACTION	MASS-COUNT
PATH	LINK	CENTER-PERIPHERY
CYCLE	NEAR-FAR	SCALE
PART-WHOLE	MERGING	SPLITTING
FULL-EMPTY	MATCHING	SUPERIMPOSITION
ITERATION	CONTACT	PROCESS
SURFACE	OBJECT	COLLECTION

It can be seen from this chart that some of the image schemas refer to positioning in space, while others to the integrity of objects and events. The former are called orientational image schemas; the latter – ontological. (Kövecses (2010) uses 'orientational and ontological metaphor'.)

Orientational image schemas (Table 3) are spatially organized systems of concepts and have primarily an evaluative function (Kövecses, 2010). They are grounded in our bodily existence in the world. It is by virtue of having the bodies that we do that we distinguish 'up' from 'down', 'front' from 'back', 'on' from 'off', 'deep' from 'shallow', etc.

Table 3 Examples of basic orientational image schemas.

Space	UP-DOWN, LEFT-RIGHT, FRONT-BACK, CONTACT, CENTER-PERIPHERY, NEAR-FAR, PATH, ROTATION, SCALE
Attribute	BIG-SMALL, DARK-BRIGHT, HEAVY-LIGHT, STRAIGHT, STRONG-WEAK, WARM-COLD
Containment	CONTAINER, CONTENT, FULL-EMPTY, IN-OUT, SURFACE

Orientational schemas are based on physical and cultural experiences but are not arbitrarily determined. Which ones are chosen depends on the role of a given schema within the coherence of the overall conceptual system. If we consider, for example, UP-DOWN as a source domain for targets such as AMOUNT, VALUE or SCALE, the semantic transfer from source to target would constitute the following range of meanings, determined both physically and socially (Table 4).

Table 4 Semantic transfer range for UP-DOWN with respect to concepts AMOUNT, VALUE, SCALE (Johnson 1990/2013).

UP	DOWN
Happy	Sad
Conscious	Unconscious
Health	Sickness
Life	Death
Having control/force	Being subject to control/force
More	Less
High status	Low status
Good	Bad
Virtue	Depravity

Such semantic transfer from source to target is technically referred to as the metaphorical extension of an image schema. What image schema ends up in the definition of a target abstraction such as RISK, SAFETY, GROWTH, EQUITY, RESPONSIBILITY, RESILIENCE, SUSTAINABILITY, and so on is a product of our being in the world physically and culturally.

Ontological schemas provide the basis for distinguishing entities and substances as individual things and consequently lay the rules for qualitative classification in categories, quantification, and ultimately inductive reasoning. Ontological schemas are frames for understanding objects, events, actions, activities, and states. In Table 5 ontological metaphors are presented according to their functions to conceptualize (i) qualitative identity and (ii) quantity.

Table 5 Examples of ontological schemas by function.

Qualitative identity	OBJECT (events, actions), SUBSTANCE (activities), CONTAINER OBJECT/CONTAINER SUBSTANCE (states)
Quantity/Multiplicity	COLLECTION, COUNT-MASS, LINKAGE, MATCHING, MERGING, SPLITTING, PART-WHOLE

Because our bodies define us as discrete entities, our experience of ourselves in the world is that of a container whose boundary marks what is on the inside and on the outside (Johnson (1990/2013)). This experience is projected on objects we perceive in the visual field. When clear boundaries are not directly perceived, often we draw a mental boundary such that the perceived becomes conceived as container objects, composed of various substances. This applies not only to tangible objects but to abstract entities. We believe we recognize ‘love’, ‘altruism’, ‘happiness’, ‘social cohesion’, and so on when we see them. Once their existence has been established, we can measure them, analyze their composition, compare their attributes, and classify them into higher order abstractions. Through this metaphoric operation, the embodied mind gives birth to the concept of ‘category’. A category is a metaphoric container. It is thus by means of the CONTAINER image schema that we reason, i.e. make inferences about things in the world.

Johnson (1990/2013) argues that it is our experience with containers and bounded spaces which provides the inferential patterns for rules of classical logic such as transitivity of set membership, the logic of negation as based on the law of the ‘Excluded Middle’, and the equivalence of double negation (tautology). Following Johnson, Lakoff and Nuňez (2000) have demonstrated the metaphoric process of mapping container schema inferences onto category inferences for Boolean logic, illustrating the primacy of embodied spatial reasoning over the abstract logic of categories in set theory.

5.5 Metaphoric transfer from source to target domains

Technically, conceptual schemas from which we draw metaphors are called "source domain", while the resulting conceptual schemas that structure our understood experience are called "target domain". Structural metaphors are mappings of a source domain onto a target domain. They enable the understanding of a more abstract concept in terms of another, simpler one. The function of structural metaphors is to frame a given perception into a specific conception. Table 6 lists typical source and target domains. Typical source domains include basic entities such as physical objects and substances and their experienced qualities (shape, color, weight, positive/negative, desirable/non-desirable, etc.). The source domain is the physical domain of humans, animals, biological organisms, artefacts, and the physical forces that govern their movements. In contrast, the typical target domains include abstract mental states, collectives and processes.

Table 6 Typical Source and Target Domains (As listed in Kövecses (2010)).

Typical Source Domains	Typical Target Domains
Human body	Emotion
Health and Illness	Desire
Animals	Morality
Plants	Thought
Buildings and Construction	Society/Nation
Machines and Tools	Politics
Games and Sport	Economy
Money and Economic Transactions	Human Relationships
Cooking and Food	Communication
Heat and Cold	Time
Light and Darkness	Life and Death
Forces	Religion
Movement and Direction	Events and Actions (change, cause, purpose, means)

In the case of highly abstract concepts such as sustainability, resilience, risk, the metaphoric transfer occurs from one abstract source to another abstract target domain. In the ontology we present, we aim to get to the image schema level of how these abstract concepts are formulated.

Which source domain is mapped onto a target domain determines the contextual boundaries of the concept and the range of interactions in a conceptually coherent system. To account for the multiplicity of inputs into highly abstract target domains, Fauconnier and Turner (2002)'s theory of conceptual integration networks (also known as 'conceptual blends') provides an explanation for how new concepts "emerge" in a manner that cannot be predicted from the input of the source domain(s). Kimmel (2013) explores cultural factors as determinants for the selection of a source domain. Culture can be viewed as a collection of cognitive patterns at a collective level. In Kimmel (2013) the ethnographic view of culture is thus contrasted with embodied cultural learning. The former is comparative and phenomenological; the latter is generic and cognitive.

In the proposed ontology, the source domain corresponds principally to Dimension I. Dimension I is the phenomenal world of physical experience comprised of objects and events. The target domain corresponds principally to Dimensions III and IV. Dimension II is the conduit by means of which basic source domain entities are mapped onto abstract target domain concepts. Dimension II is the domain of mind, models and cognition, juxtaposed to the phenomenal world of Dimension I.

It might be interesting to note that the image schemas and the general concept of embodied cognition, which we take benefit from in the structuring of the ontology, have a resemblance with the concept of likelihoods from Bayesian reasoning. The image schemas offer an analogy for the mapping of our prior understanding (prior knowledge) together with what we perceive in a given context (embodied cognition) into what we conceive (posterior knowledge). As in the case of Bayesian reasoning, the strength of the image schemas (likelihoods) depends and varies with context (more discussion of this is provided in Section 2 of Part I of this trilogy).

6 Image schemas and conceptual metaphors in the domain ontology

Fig. 8 shows how the different image schemas have been allocated to the categorical pairs and the 4 dimensions of the ontology. For purposes of illustration, we present and discuss the image schemas only for Dimension I of the ontology, and refer the interested reader to Nielsen (2021 forthcoming) for a full presentation and discussion of the image schemas for all 4 Dimensions.

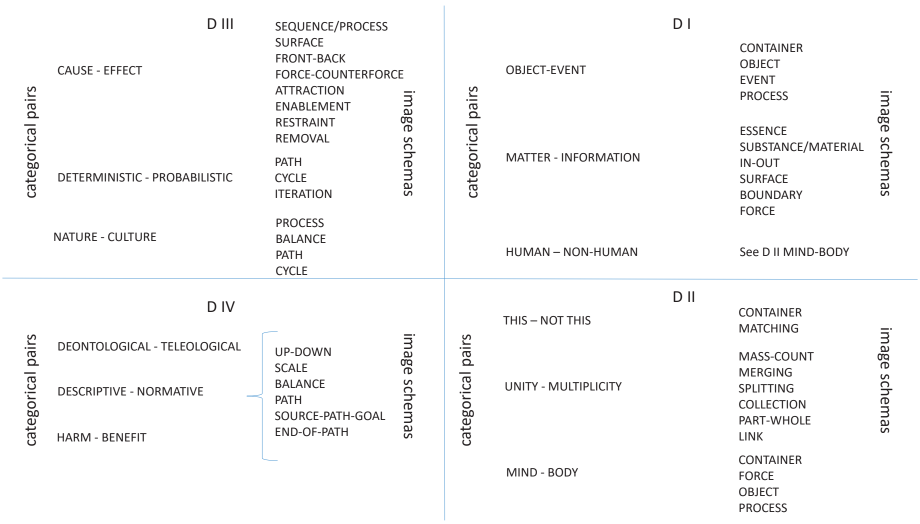

Fig. 8 Image schemas corresponding to the dialectical pairs in the ontology.

6.1 Image schemas for Dimension I

The distinction between objects and events has a very long history in the Western conceptual system, resulting in a cascade of categorical pairs such as atomistic-relational, material-immaterial, etc. In embodied cognition research, the battle between object and event continues among proponents of OBJECT as the primary building block of conception and proponents of spatio-temporal EVENT schemas as primary in cognitive development. Since our design is pragmatically oriented, we disregard the question of origin and grant objects and events equal ontological status in D I. However, objects and events do not exist equally, in that whether an object or an event schema is chosen to conceptualize an experience, the consequences of this choice are not trivial for the modeling of risk, resilience and sustainability.

In Fig. 9, it can be seen that the underlying cognitive structures for OBJECT and EVENT mirror each other, with the exception that the OBJECT schema is static, while the EVENT schema is dynamic. A possible metaphoric extension of the OBJECT schema is shown for the concept RESOURCE. It can be seen how a resource comes to be defined as an object relative to another object in terms of function. In the Western conceptual cognition system this metaphoric transfer creates a family resemblance among the concepts {resource – expenditure – scarcity – efficiency – waste – time – savings – worthiness – sustainability – efficacy – resilience} located in different dimensions of the ontology. This illustrates how although the image schemas constrain the choice of arbitrary interpretations for what a resource is, they are not universal. They are, instead, embedded in a socio-cultural context. But while there might be a widely divergent understanding across cultures and social groups about what defines a single concept such as waste, resource or time, the cluster of concepts sharing a common image schema, affords a pragmatic understanding of the context in which a given concept is used.

The CONTAINER schema is the source domain of inferences about categories. Inferential logic, which is typically considered the epitome of conceptual reasoning in mathematics is actually spatial logic, i.e. it is embodied by virtue of our perception of objects in space as the metaphor Categories Are Containers demonstrates. CONTAINER schema inferences structure the logical concepts of ‘excluded middle’, ‘modus ponens’, ‘hypothetical syllogism’, and ‘modus tollens’, which is also the basic structure of Boolean logic, set theory, and probability theory. (see Lakoff and Nuňez, 2000).

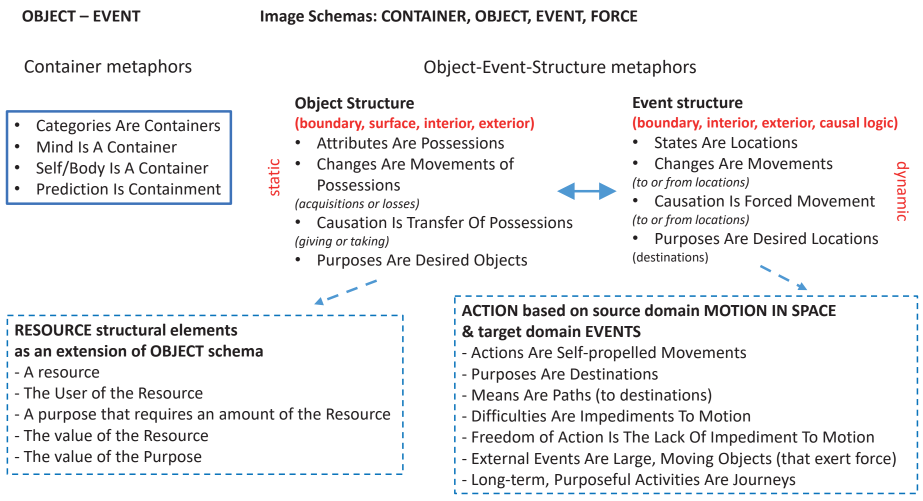

Fig. 9 Image schemas and conceptual metaphors for categorical pair OBJECT-EVENT. Image schemas and conceptual metaphors based on selection from Johnson (1990) and Johnson (2013), Lakoff and Johnson (1999) and Lakoff (2008).

The second categorical pair of Dimension I deals with the material vs informational essence of reality. Fig. 10 shows the image schemas and metaphors on which the distinction between the material and immaterial rests.

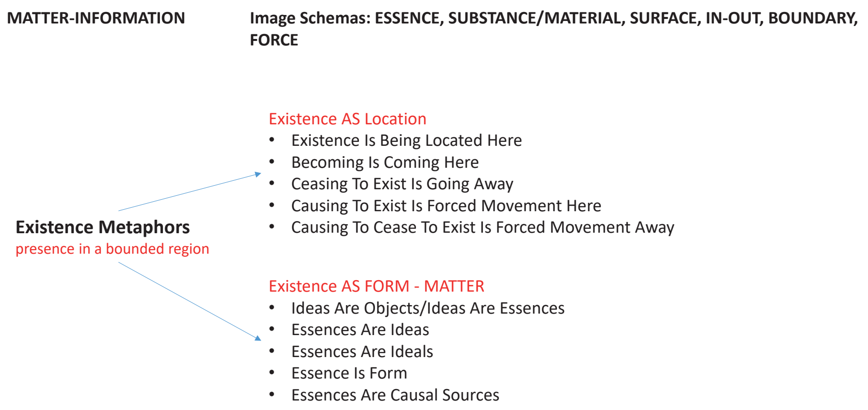

Fig. 10 Image schemas and conceptual metaphors for categorical pair MATTER – INFORMATION. Image schemas and conceptual metaphors based on selection from Johnson (1990/2013), Lakoff and Johnson (1999) and Lakoff (2008).

7 Quasi-universal shared language: image schema and *xiang*

If the knowledge domains of risk, resilience and sustainability converge at the global scale, an ontology must make sense outside the conceptual traditions of the West. Our introduction of dimensional and categorical pairs complementary to the individual dimensions and concept members is an attempt to raise awareness of this problem and is by no means a comprehensive or sufficiently systematic effort.

In Julliene (2002) the Western concept of 'category' is contrasted with the Chinese use of pairs of items that form a 'tension'. In this view, reality is not composed of metaphysical object-concepts, but rather of physical events. Contradiction, which the Western system of logic uses to validate the truth-value of propositions, is in Chinese thought not something to be avoided as a logical fallacy, but adhered to as a physical law – a creative, engendering principle upon which the processual physical reality rests.

Hansen (1985) postulates that classical Chinese thinking is structured on the basis of a mereological classification because Chinese nouns are uncountable. A conceptual system, in which number is understood as a degree of quality (a more or less of something) rather than as a distinct amount can thus be said to be a mereological ontology.

In Ma and Brakel (2016) the notion of a quasi-universal is introduced as that something by virtue of which a comparison of concepts is made possible. The context of their investigation is translation of Western – Chinese conceptual schemas, which they base on Wittgenstein's notion of 'family resemblance' and a theory of meaning grounded in pragmatic experience as opposed to symbolic sense-reference correspondence. The quasi-universal is thus part of a shared experiential mode of being in the world, which provides a meta-structure for comparing one concept with another across cultures. For example, what enables the translation of the Greek concept of ἀρετή (usually translated into English as 'excellence') with the Chinese concept of *de* 德 is a shared experience in the perceptual and conceptual systems of Greece and China of the quasi-universal experience of (moral) excellence (Ma and Brakel, 2016)).

Meaning as a shared experience is a pragmatic notion. It refers to behavior, practices and ways of acting. As such, meaning is constructed subjectively unlike the analytic notion of sense-reference, according to which meaning exists objectively, outside the realm of perception. It is important to underline that in the theory of embodied cognition and in comparative linguistics and philosophy grounded in 'family resemblance' (FR), the perceptual world of experience is not a relativistic Humpty Dumpty realm of meaning, but is constrained and structured through quasi-universal embodied cognitive gestalts. These cognitive gestalts are quasi-universal image schemas that function as cross-cultural FR concepts.

The categorical pairs we introduce in the ontology that help to define and structure the four dimensions are precisely such FR concepts based on quasi-universal image schemas (Fig. 11). The cluster of categorical pairs in D I provides a conceptual scheme for the metaphysical dimension of the ontology, which is a catalogue of the things that exist (i) in the physical world and (ii) in the conceptual domain of risk, resilience and sustainability. In D I OBJECT – EVENT is a quasi-universal pair used in both Western and Eastern traditions in consideration of metaphysical questions. Within the Western tradition Putnam (1992) points out that 'entity', 'object', 'event', 'situation', 'fact', and 'property' have not one fixed use but an expanding family of uses. Heidegger's 'thing', Russel and Whitehead's 'event', Ortega y Gasset's 'situation', Harmann's 'object' are in the context of metaphysics, FR concepts. Similarly, in the Chines tradition *wu* 物 is used to denote a thing, a kind of thing, an event, or an organism. Ma Lin (2015) explains that in classical Chinese animals are moving *wu*, i.e. *dongwu* 动物 ; humans are *renwu* 人物 ; plants are *zhiwu* 植物 ; and inorganic things (e.g., rivers, mountains, landscape) are *jingwu* 景物 .

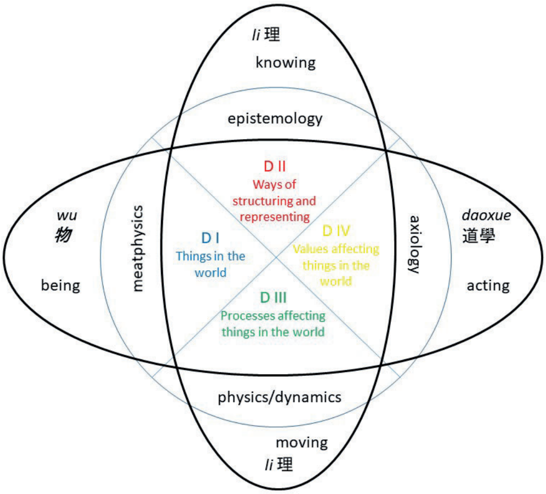

Fig. 11 Dimensional pairs with corresponding Western branches of philosophy and Chinese concepts.

In the Western tradition the semantic ranges of D I- D II form a compatible pair. The teleological end of metaphysics is epistemology. Knowledge has intrinsic value. Indeed, the instrumental use of knowledge to achieve other purposes than knowledge itself is perceived as ethically suspect. The ideal of science is objectivity that bears no relation to utilitarian purposes. D III - D IV also forms a natural pair through the FR concepts cluster 'law-regulation-choice-control' as there can be no values without the concept of change, which can simply be defined as observed invariance.

In the Chinese tradition, metaphysics is not pursued for epistemic purposes, but for the moral purpose of right living. The pairing of D I with D IV is grounded in the neo-Confucian notion of '*daoxue*' 道學. In our ontology, we have paired D I with D IV instead of D III with D IV as we wish to re-frame the deterministic perspective arising from pairing D III process – be that laws of nature or laws of culture and convention – with D IV values. In our ontology thus the taxonomic kinds of D I and the normative values of D IV do not form natural kinds or predetermined laws, but are instead the result of choice that embodied cognition enables in the process of our classification of experiences through interaction with the things in the phenomenal world. The choices made in D I to frame what exists affects what values are chosen for their measurement. What values we choose to measure affects where we draw the boundaries around what matters.

D II and D III form a further compatible pair through another classical Chinese notion – *li* 理. We understand *li* is an abstract category for information in the sense that it is used in descriptions of ordering and structuring the form and function of both organic and non-organic things in the world.

In Qiao Qingju (2006) a thesis is put forth that Western metaphysical concepts (matter, time, space) and epistemological concepts (perception, rationality, regularity, understanding) have entered the modern Chinese lexicon as neologisms that are used to describe these concepts as individual categories rather than as the all-encompassing classical Chinese FR concept of *li* 理, which is used as a descriptor for all of the above. A modern Chinese dictionary defines *li* as "Laws and regularities of matter, natural criteria, regularities pertaining to ethical categories and motion of matter, fundamental principles of the universe, the arche of the universe, the form of matter, ethics and morals, the differences in matter and so forth." The Chinese concept of *li* captures both what in the West is understood as a 'pattern' and the dynamic organizing principle that creates the pattern.

The analytic definition imports the alien to Chinese experience Western practice of pairing concepts from our ontology's D I (metaphysics) and D II (epistemology). The classical Chinese concept of *li* is made more comprehensible in the pairing of D II (epistemology) and D III (process). This latter pairing (D II-D III) enables a comprehension of *li* as the structuring principle of both perceived and conceived reality. *Li* is the matter that forms and is in-formed. The classical Chinese concept of *li* is, in other words, our concept of 'information'. It is a good approximation to the range of meanings we attach to our notion 'information-theoretic ontology'.

The Chinese concepts *wu*, *li* and *daoxue* thus offer a possibility for establishing a shared West-East ontology:

- D I - the phenomenal lifeworld of objects and events, characterized by multiplicity of forms/patterns;
- D II – the cognitive-affective ability of humans (i.e. the heart-mind/embodied mind) to discern and conjure patterns;
- D III – the unitary principle of in-formation, i.e. the ceaseless reproduction of forms/endless creativity/process;
- D IV - when D II properly actualized through the pursuit of self-cultivation and empirical inquiry leads to good governance (virtuous action) based on the unitary principle of informed-choice; a meeting point for the Socratic definition of knowledge as virtuous action and the Chinese cosmological axiology summarized in the notion of *daoxue*.

The concept of 'information' is a quasi-universal we use to establish meaningful communication between West and East also with respect to the notion of image schema. In a linguistics study of the Chinese character system Jia (2008) examines the embodied conceptual system of Chinese thought as a product of metaphorical mappings of image schemas. He demonstrates how the concept of *xiang* (image), expressed by the two cognate homophonic characters 象 and 相, underlies the process of analogical inferential logic, which structures Chinese perception, understanding and reasoning about phenomena in the world as well as acting in the world. The semantic range of *xiang* clearly shows the family resemblance between visual perception, classification of experiential input, inferential information processing, and not least, understanding as a faculty of imagination rather than disembodied pure reason.

In Fig. 12 we show a radial semantic range for the concept of *xiang*, illustrating the close correspondence between the Western notion of cognition based on embodied image schemas and the Chinese mode of visual perception-conception.

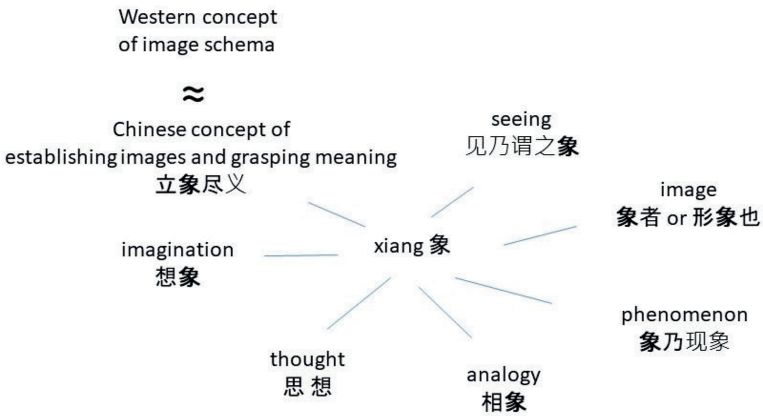

Fig. 12 semantic range of the Chinese concept *xiang* as an approximation to embodied cognition concept of image schema. Based on translation from Jia (2008).

In this context, the structure-function relation can be thought as a quasi-universal that facilitates a comparison between Western and Chinese ways of conceptualizing cognitive processes. *Xiang* 象 is a pictographic depiction of a dead elephant's bones (Jia, 2008). Far from a symbolic sense-reference representation of a ghostly natural kind, the Chinese elephant is a probabilistic statement of a degree of belief. Just as in the inferential image schematic reasoning, perception is grounded in the concrete visual experience of a form and metaphorically transferred to the abstract domain of conception. The conduit of this metaphoric transfer, which we may call learning or grasping meaning, is imagination. Knowledge priors are image structures stored in the *xin* 心 (heart-mind); on call for re-call, potentially pliant. Fig. 13 presents an illustration of this process from the Chinese perspective of how meaning (function) is generated from image (form).

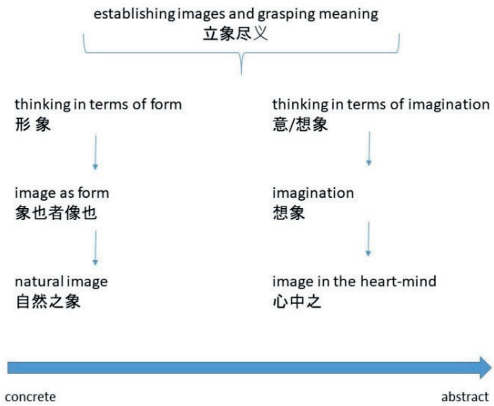

Fig. 13 Image schematic process of Chinese sense making based on structure-function relations. Examples and translation from Jia (2008).

8 Conclusions

The present paper is the second in a triad of papers in pursuit of establishing a formal basis for the representation of knowledge and for designing education in risk, resilience and sustainability science. In this paper we focus on the representation of the knowledge domain.

To this end we assess different options for structuring of conceptual knowledge in terms of different hierarchical structures: taxonomies and ontologies. On this basis, we propose a structure of the knowledge domain of risk, resilience and sustainability through what might be termed a mereological ontology (in philosophy) or a nested hierarchy (in computer science), consisting of 128 concepts, 19 concept clusters, 4 dimensions, and 2 dimensional pairs. The theoretical and methodical basis for the proposed ontology is provided only in summary. Moreover, we include a mere minimum of formalism in this presentation such as to support the readers in the domain of risk, resilience and sustainability who might not be familiar with the formal philosophical basis for structuring knowledge.

As we strive for a knowledge representation in a context of governance at in principle any geographical scale, we finally address and describe the differences and the similarities between the traditional Western and Eastern lines of logical reasoning. To this end, taking basis in the fundamental concepts *wu*, *daoxue* and *li* from classical Chinese philosophy as a representative of Eastern lines of logical reasoning, we discuss and relate the dimensions, the clusters and the categorical pairs from our proposed ontology.

We fully appreciate that our proposal might be improved, not least with respect to inclusion/exclusion of concepts – the choices of which underlie significant subjectivity and which, moreover as such will change meaning in the course of time. However, our proposition for the structuring of the knowledge domain of risk, resilience and sustainability offers a new paradigm for education and governance that integrates risk, resilience and sustainability considerations into a single theoretical and methodological framework. It establishes thus for the first time a conceptual baseline for the synthesis of the three knowledge traditions of risk, resilience and sustainability, which until present have evolved and been pursued independently. The baseline is the common domain ontology that allows their further development as a new life science. A unique strong point of our proposition is that it holistically and neutrally integrates relevant concepts from both the natural, social, human and technical sciences and across cultures, in a manner that is balanced in the context. Using the metaphor of construction as we have been applying this to illustrate and explain the design of the ontology – our ontology may be seen as a building, a container and organization of relevant knowledge – profiling the fallacies of present developments in Western societies where the “space” for the human and social sciences rhetorically and financially is shrinking.

In the last part of this triad - Part III - we use the developed knowledge representation to establish a blueprint for the design of education offers in risk, resilience and sustainability science as an instrument for achieving informed preferences, decisions and actions across scales .

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5.3. PART III

Nielsen, L., & Faber, M. H. (2020). Toward and Information Theoretic Ontology of Risk, Resilience and Sustainability and a Blueprint for Educations – Part III. Submitted to *Sustainable and Resilient Infrastructure* on September 13, 2020.

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Toward an information theoretic ontology of risk, resilience and sustainability and a blueprint for education – Part III

The concept of risk as the theoretical and methodological basis for information- consistent ranking of decision alternatives is central for safe, sustainable and resilient societal developments. However, due to significant disparities in the understanding of the concept of risk in academia, and in its application in governance and industry, we argue that a new paradigm for risk must be established. In a sequence of three papers (Part I, Part II and Part III) we take up this challenge, with the leading objective of providing a coherent foundation for the further development and transfer of the general body of knowledge relevant for governance of risk, resilience and sustainability – through research and education. In Part I, we first present our motivation and general approach to the problem. Thereafter, we provide an overview and a discussion on the state of research and education in the domain of risk, resilience and sustainability, and propose a generic, information-based hazard classification scheme, which informs the development of a domain ontology and a blueprint for education. In Part II, we provide the logic for the structuring of the knowledge domain in terms of a domain ontology of the concepts relevant for an integrated science of risk, resilience and sustainability. In the present paper - Part III - we finally identify educational requirements, and provide a blueprint for education designs. We believe that the proposed ontology and the related education blueprint may provide value both to the further evolution of research and education in risk in general and for the governance of risk, resilience and sustainability in particular.

Keywords: risk; resilience; sustainability; risk governance; domain ontology; embodied cognition; philosophy of education; learning design.

1 Introduction

Fostered by the evolution and dissemination of knowledge and technological advances, societies at both local and global scales have experienced significant improvements in welfare, health, safety, and security. However, global trends such as increasing global population, urbanization, diminishing natural resources, and beyond clear indications that human activities are posing a threat for sustained existence of civilization as we know it today, underlines the need for establishing the very best basis for societal decision making obtainable. As the consequences of decisions – especially long-term consequences - are associated with substantial uncertainties, such a decision basis must be able to account not only for the best available knowledge but also the lack of knowledge and natural variability, in terms of epistemic and aleatory uncertainties.

To this end risk informed decision making, facilitated by Bayesian decision analysis (Raiffa and Schlaifer, 1961) and the axioms of utility theory (von Neumann and Morgenstern, 1944) provides the theoretical basis. Fundamentally, this theoretical basis is generic and applies to any context of societal decision making, whether addressing design of infrastructures, recovery or preparedness planning in the event of earthquakes, or identification of strategies for reduction of CO2 emissions.

Ultimately, any decision may be considered equivalent to the commitment of resources. The committed resources may include direct upfront investments and use of natural resources. Committed resources may however, also relate to implications for life safety, health and welfare to individuals, potential damages to the qualities of the environment and existential discontinuity – distributed over time and space. In principle, the committed resources envelop this full spectrum of consequences, and risk-informed decision making must be able to account for this.

The present best practices of research, dissemination and application of risk-informed decision making, however, may be said to have evolved out of the numerous different contexts of societal decision making. This has resulted in incoherent application area and discipline-specific developments that do not cater for, or reflect, the generic and trans-disciplinary characteristics of risk-informed decision making, thus leading to a critical gap between what is collectively known and what is contextually decided and done. The present best practice in this manner seriously impedes the vast potential risk-informed decision making offers as a means for supporting societal development towards welfare, resilience and sustainability.

In order to enable the realization of the full potential risk-informed decision making offers in the manifold contexts of supporting societal developments, our objective with the present contribution, Part III in a triad of papers, is to establish the knowledge domain of risk-informed decision making in integration with the knowledge domains of resilience and sustainability as a generic science free of context (application areas/scientific disciplines). As outlined in Part I, we pursue this objective from the perspective that this integrated knowledge domain must provide the scientific basis for the analysis of consequences and decision making based on informed preferences. This basis is unemotional, unbiased and void of concurrent societal value settings. Moreover, the structuring of the knowledge domain should take basis in the processes generating consequences, namely those related to information: information change, perception, conception, decision, and action.

Risk-informed decision making, in the broad scope of governance of risk, resilience and sustainability, is subject to the effects of epistemic uncertainty; knowledge is simply limited. In recognition of this, we follow a Bayesian approach, appreciating that information should not only be utilized to update prior beliefs but, moreover, form the basis for assessing the relevance of prior beliefs.

In the present paper, Part III of a triad of papers[1], we build on the knowledge basis and framework established in Part I and the ontology for the integral knowledge domain outlined in Part

[1] For ease of syntax, in the following we refer to Part I and Part II of the triad without specification of authors and year, however these are always the same and may be found in the list of references under (Nielsen and Faber, 2020).

II, with the purpose of establishing a blueprint for the design of education offers in risk, resilience and sustainability science. The structure of the triad is illustrated in Figure 1.

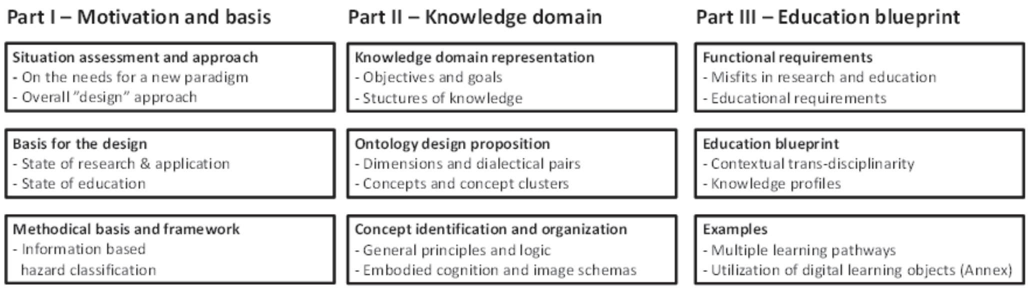

Fig. 1 Overview of the structure and contents of the three papers presenting the information theoretic ontology of risk, resilience and sustainability and a blueprint for education.

The present paper, Part III, is organized as follows: After presenting the vision for a unified science of risk, resilience and sustainability and its application for governance in the introductory Section 1, we focus on the scope and target audience of the education blueprint in Section 2. In Section 3 we present the elements of the blueprint, together with how the logic of their interactions can be used as a measure for context-sensitive goodness of fit between problem and solution. Section 4 proposes a scheme for contextual trans-disciplinarity based on the logic of the domain ontology presented in Part II of the triad. Following this logic, we show how the multiplicity of methods, used indiscriminately in present educational practices, can be unified through three systemically related methodologies: Bayesian reasoning, General Systems Theory and Embodied Cognition theory. Section 5 presents three examples for structuring educational activities based on the proposed ontology and blueprint. Each example charts a learning pathway at different levels of modularity: (i) a long-term degree program, (ii) an individual module as part of a degree program or as a stand-alone unit for professional education, and (iii) an individual problem case. Whereas the blueprint for educational activities may be readily applied as it is presented, its modular structure lends itself to the further development of digital learning technology such as a repository of learning objects. We do not provide a detailed design for such a digital platform but do suggest a sketch (Appendix A) for such an implementation to illustrate the general idea. Finally, in Section 6 we conclude the paper with a summary of the affordances offered by the blueprint, the challenges and needs for further research and developments.

2 Scope and target audience of the education blueprint

The underlying idea of the blueprint is not to develop a template for a curriculum, but rather to provide a logical basis and a generic framework - in the form of general principles - for identifying which parts of the knowledge domain of risk, resilience and sustainability are relevant in a given context of learning. These principles may then inform the planning of educational activities at any level (module, lecture and project). The blueprint is generic as it applies to any application context related to governance of risk, resilience and sustainability, which includes any combination of engineered, social and ecological systems such as encountered in e.g. food safety, health management and infrastructure development, and at any scale; local-global and individual-collective.

Ultimately, the blueprint aims to serve the dissemination and creation of knowledge of central importance for and to the benefit of all stakeholders in society, see Fig. 2.

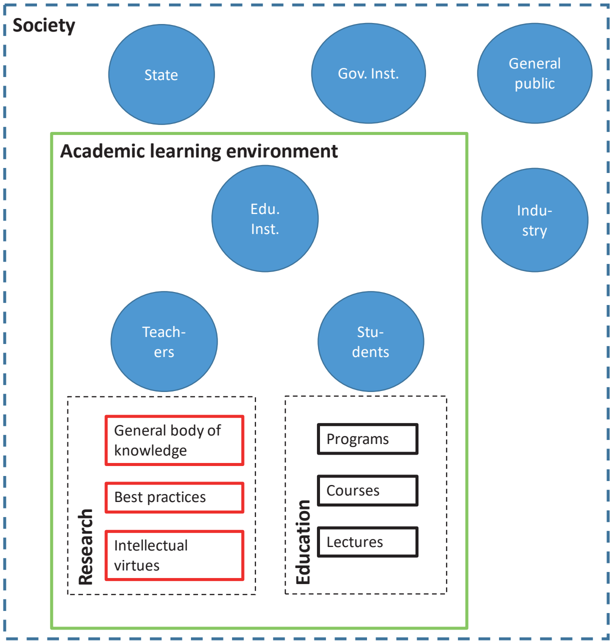

Fig. 2 Illustration of main stakeholders (blue circles), assets (red frames) and instruments (black frames) in education. From Faber and Nielsen (2017).

In Fig. 2 it is seen that education and research comprise a dynamic systems. The general body of knowledge has to be developed continuously and new insights and discoveries must find their way into best practices and educational activities. In this context it is important to appreciate that even in areas of education where the research front is only moving incrementally or even has stopped, there is a rather significant task for the educational institutions in preserving the already established knowledge. Adequate governance of risk, resilience and sustainability might be considered a public good, to the benefits of which all individuals in society should have equal access. In the transfer of and further development of knowledge, however, the affordances of the blueprint for teachers and students are key.

For teachers the education blueprint offers an aid to structure educational activities so as to achieve an adequate balance between preserving and creating knowledge. By preserving knowledge, we here refer to the task of bringing forward existing theoretical and methodological knowledge; by creating knowledge, we refer to the inclusion of new knowledge from the frontiers of research. The context should be the driver for this balancing and implicitly defines which concepts are relevant to address, and in which order. In the blueprint, concept clusters from the ontology are assigned relative to key characteristics of the concepts applications to aid the teacher in this regard.

The blueprint further facilitates the planning of educational activities by groups of teachers. Since the knowledge area is so intrinsically trans-disciplinary, often the faculty in risk programs come from different disciplinary backgrounds. A teacher with a background in civil engineering teaching a module on probability theory, and a teacher with a background in social science teaching a module on risk communication might then use the blueprint to jointly navigate through the learning objectives and concept clusters to develop learning plans and activities that feature complementary conceptual aspects of a given problem.

Most risk programs attract an inhomogeneous body of students with widely different academic backgrounds and large amounts of rather diverse a-priori knowledge and expectations. For students, the education blueprint and the ontology provide an insight into the rationale for structuring educational activities in a given learning context (program, module or project) by making the black box of education planning and curricula explicit. This means, in system engineering terms, offering students a view of the causal input-output relation between learning objectives and learning outcomes. A logical and transparent rationale for the transfer of knowledge enhances information symmetry, which is known to form a key factor for success in collaborative activities – such as education.

The blueprint, together with the ontology, is also envisaged as a compass for the students, with the primary purpose of supporting their own wayfinding rather than relying on pre-determined sequences of teacher-led navigation. To this end, the blueprint for educational activities supports the students in directing their own self-learning efforts, in a manner complying with and supporting problem based learning (PBL).

3 Elements of the blueprint and their interaction

In this section we explain how adapting Alexander's (1967) semiformal algorithmic method as a basis for design, we develop a blueprint for education in integrated risk, resilience and sustainability science. The blueprint (Fig. 3) is a functional diagram of the interaction between form (the representation of the knowledge domain in terms of an ontology of concepts) and function (the input of the ontological concept clusters into the fulfillment of the educational requirements). It is a synthesis of the extensionally-described constraints and the intrinsic, value-laden requirements. In what follows, we use Alexander's (1967) term "misfits" to refer to the constraints. The blueprint is a graphical representation of the interaction among (i) two sets of misfits stemming from best practice in research and education; (ii) a set of three educational requirements, each composed of a sub-set of learning objectives; and (iii) a set of concept clusters encompassing the relevant conceptual knowledge necessary for minimizing the misfits. The value of the blueprint is that it provides an internally coherent and externally contextual structure for the design of multiple learning pathways. In Section 5, three such exemplary pathways are outlined.

3.1 Misfits

In Alexander (1967) a misfit is described as "any state of affairs in the ensemble which derives from the interaction between form and context, and causes stress in the ensemble". Meeting a requirement in this sense is analogous to avoiding a misfit. It is important at the outset to be explicit about what a misfit and a requirement can and cannot describe. Alexander (1967) takes a misfit as a binary variable x, which assumes the value of 0 when the requirement is met and the value of 1 when it is not. The designer's goal of achieving a good fit is to bring all x's in the set of misfits to 0. For most problems in engineering design this operation is done through setting objective performance standards for each x. They are objective in the sense that they can be meaningfully measured as a "continuous variation along a well-defined scale" such as monetary cost, bearing capacity, width, temperature, etc. But they are also relative to a context, e.g. cost-benefit. In architectural design, misfits can be measured both with regard to objectively measurable standards such as the above but also subjective ones such as comfort, ease of use, atmosphere, style, etc. In the case of variables which are not objectively quantifiable so that the optimal solution, through the process of optimization, is captured in a performance standard, the process of subjectively dividing misfit variables into categories of 0's and 1's is nevertheless useful because it provides transparency of the choices made by the designer as well as a logical structuring principle.

Similarly, in the context of designing and/or evaluating education programs, some misfits can be objectively quantified, e.g. loss of government funding, loss of students due to failing exams, loss of students due to diminishing demand of subject expertise, loss of teachers, unemployed graduates, insufficient infrastructure (physical or virtual), etc. Others, such as incompetent teachers, inadequate research quality, insufficient qualification of students, irrelevant educational programs, loss of motivation (teachers and students), insufficient quality of graduates, inadequate learning environments, etc. are not quantifiable according to objectively measurable variables, but can still be identified as misfits. The set of all these "qualitative" misfits will always be incomplete just as our knowledge of physical reality is. Good fit in the context of educational design is to be understood as an evolving list of misfits. The designer in this case makes no claim to objectivity or exhaustiveness of the variables in the design problem context, but provides a transparent view of how the different misfits can be weighed relative to the context.

As the process of deriving the misfits is described in Part I of this paper triad, here only the final sets of misfits stemming from research (Table 1) and education (Table 2) best practices are given. Each misfit is given a notational number and letter and is accompanied by a short and long description as well as the educational requirements and learning objectives it has a relation to. The latter are described in Section 3.2, tables 3-5.

Table 1 Misfits stemming from the domain of research.

		MISFITS RESEARCH	
Notation	**Short Name**	**Description**	**Related Learning Goals**
M1r	Lack of structure and cohesion of the knowledge domain	Vast body of knowledge with little or no coordination among the contributing disciplines	1b, 1c, 1d, 1e, 1f, 2o, 3a, 3c, 3d, 3f, 3g
M2r	Lack of consensus on concept definitions	No agreed definition of concepts leading to ambiguous communication between: - researchers and decision-makers - researchers and the public - researchers from contributing disciplines Ambiguity over who has ownership and responsibility over various phases of the risk analysis process	1a, 1g, 2a, 2e, 2k, 2l, 2m, 2n, 2o, 3h
M3r	Lack of knowledge on constraints shaping preferences	Low awareness of the constraints shaping decision-makers' preferences	1b, 1e, 1f, 2h, 2k, 3a, 3b, 3c, 3d, 3e, 3g, 3h
M4r	Inability of procedural frameworks to apply updated information	Procedural frameworks for risk analysis do not facilitate the potential for utilizing indicators of evidence for the updating of new knowledge	1a, 1h, 2f, 2j, 2o, 3d, 3f, 3h
M5r	Lack of integrated operational scientific frameworks	Scientific frameworks integrating risk, sustainability and resilience considerations are almost purely descriptive, not operational	1a, 1b, 1e, 2f, 2g, 2h, 2i, 2j, 2o, 3b, 3h
M6r	Lack of non-Western epistemic and axiological values	Research dominated by highly developed Western countries: - overt/covert use of ideology rather than scientific epistemic values - questionable completeness/accuracy of scientific knowledge - actions based on scientific results often do not fit well into non-Western/under-developed contexts	1a, 1f, 2n, 2o, 3d
M7r	Rigid disciplinary boundaries	Stated preference for trans-disciplinary research in risk, resilience and sustainability is unrealized in practice	1b, 1c, 1d, 1f, 2j, 2k, 2l, 2m, 2n, 20, 3d, 3g
M8r	Paucity of methods for analysis of social systems dynamics	Methodologies are better developed and more comprehensive for engineered and ecological systems. Methodologies for social systems are underdeveloped and highly biased by the fields of Economics and Behavioral Sciences	1c, 1d, 2e, 2n, 3b, 3d, 3e, 3h

Table 2 Misfits stemming from the domain of education.

		MISFITS EDUCATION	
Notation	**Short name**	**Description**	**Related Learning Goals**
M1e	Lack of academic rigor	Quantity over Quality: - Popularity of risk master programs based on fashion, not academic rigor - Reputation of academic institution does not equate with the quality of a program - Programs with "risk" in the title target foreign students. Programs where "risk" is not explicit in the title but described as a specialization within a traditional discipline, e.g. Engineering, Economics, target domestic students	1a, 1b, 1c, 1d, 1e, 1f, 1g, 1h, 2a, 2b, 2c, 2d, 2e, 2f, 2g, 2h, 2i, 2j, 2k, 2l, 2m, 2n, 2o, 3a, 3b, 3c, 3d, 3e, 3f, 3g, 3h
M2e	Quantitative - qualitative divide	Strong division between quantitative programs focusing on risk assessment and qualitative programs focusing on risk management	1a, 1g, 2a, 2b, 2c, 2d, 2e, 2f, 2g, 2h, 2i, 2j, 2k, 2l, 2m, 2n, 2o, 3h
M3e	Lack of integrated approach to hazards and application areas	Curricula of different programs is based either on particular hazards or on a particular industrial or public sector	1c, 1d, 1e, 2o, 3c, 3f
M4e	Rigid disciplinary boundaries	No evidence in the curricula or didactic practice for programs claiming to be multi-/inter- disciplinary	1c, 1d, 1g, 2f, 2g, 2h, 2i, 2j, 2k, 2l, 2m, 2n, 2o, 3d, 3g
M5e	No explicit logic of content and structure	Many programs lack transparency in curriculum structure; there is little cohesion in content and methodology	1a, 1b, 1d, 1e, 2a, 2o, 3c, 3d, 3e
M6e	Outdated methods & lack of transparency in choice of methods	- Many outdated methods are taught by inertia, ignoring or not being aware of methods in state-of-the-art research - Methods are taught in a Methods class/module, out of particular context. Students are expected to learn a list of methods, all in equal degrees - Particular method(s) might be selected as relevant in given curriculum, but no justification is provided for the choice of method(s). Usually applies in programs focused on particular industrial application (e.g. oil and gas sector), where the method(s) selected are based on industry best practice	1a, 1d, 1f, 1h, 2b, 2c, 2d, 2e, 2f, 2g, 2h, 2i, 2j, 2k, 2l, 2m, 2n, 2o, 3b, 3c, 3d, 3e, 3f, 3g, 3h
M7e	Lack of decision analysis	Most programs lack decision analysis component	1b, 1e, 1f, 2h, 2k, 2m, 3b, 3c, 3e, 3f, 3h
M8e	Lack of consequence analysis	Most programs lack consequence modeling component	1b, 1d, 1f, 1h, 2g, 2h, 2i, 2j, 2k, 2l, 2m, 3b, 3c, 3e, 3f, 3h
M9e	Risk, resilience and sustainability not integrated	No programs integrate risk with resilience and sustainability considerations	2j, 3c, 3d, 3f
M10e	Misbalanced procedural - conceptual knowledge	No programs incorporate a contextual, epistemic, and/or historical understanding of concepts and methods as might be presented from the perspective of Philosophy of Science: - Master number crunchers incapable of understanding/describing model assumptions; relevance of assumptions in a given context, implications of erroneous assumptions; or ability to see relations among conceptual schemes from multiple domains - Master ideologists incapable of understanding either the relevance or the quality of a quantitative risk assessment	1a, 1h, 2f, 2o, 3b, 3c, 3d, 3h
M11e	Lack of rigor in risk communication	Risk Communication: - Usually offered as an elective if offered at all. - Focus on procedural checklists and emergency communication to the public - No consideration given to communication as a factor in generating system changes through indirect consequences related to perception and behavior. Communication thus left out of the model building, potentially resulting in (adverse) strategic surprise	1a, 1d, 1g, 1h, 2a, 2b, 2c, 2d, 2i, 2o, 3d, 3h
M12e	Little/No cover of cognitive, emotional and cultural aspects of risk perception	Risk perception as studied by cognitive science, psychology and anthropology is almost entirely absent from the curricula	2k, 2n, 3d, 3e

3.2 Requirements

Functional requirements in the context of the education blueprint are referred to as Educational Requirements (ERs). While requirements, goals and preferences belong to the subjective realm of axiology that deals with inherently subjective values, the process of identifying context-relevant requirements need not be value-driven or arbitrary. In what follows we present a transparent logic for the identification of educational requirements and explain how this logical structure provides a conceptual scheme for the theories and methods that comprise an integrated risk, resilience and sustainability science.

Three overarching ERs are identified which include a number of learning objectives (tables 3 – 5). Each ER forms a knowledge cluster of inter-related theories and methods. The first cluster includes theories and methods unified through the concept of 'information' (e.g., Bayesian probability theory, Bayesian decision analysis, Heisenberg's uncertainty principle, Shannon's mathematical theory of communication, etc.). The second cluster unifies theoretical and methodological perspectives through the concept of 'systems' (e.g., General Systems Theory, Planetary Boundaries framework, Gibson's affordance theory, Lakoff and Johnson's empirical studies in embodied cognition, Ingold's conceptualization of taskscape, etc.). The third cluster unifies theoretical and methodological perspectives through the related concepts 'action', 'agency' and 'care' that deal with attempts to theorize human nature (e.g., Western and Eastern virtue epistemologies).

In the following we first list the three ERs with their constitutive learning objectives; thereafter, we discuss how the ERs have been identified and the inter-dependencies among them.

Table 3 Functional requirements ER 1 disaggregated into specific learning objectives.

	ER 1 FOLLOWING THE ARGUMENT WHERE IT LEADS **Ability to identify ideology and convert it into open-ended scientific inquiry**
Notation	**Description**
1a	Have theoretical understanding of prior, pre-posterior and posterior knowledge and how these notions relate to truth, reality, model assumptions, and model building. Ability to "strip" metaphors to their literal phenomena. Have theoretical understanding of how this can be modeled using Bayesian probability theory
1b	Ability to identify and formulate a relevant decision problem for risk analysis
1c	Ability to identify the hazards for a particular system in a given interval of time
1d	Ability to formulate a systems representation hierarchically, generically and by the use of indicators, incl. systems components, their interactions and the direct and indirect consequences that the exposures might possibly generate for the system
1e	Ability to assess and represent decision-makers' and societal preferences with respect to investment in risk reduction, resilience and sustainability
1f	Ability to carry out a stakeholder analysis, identifying the preferences and constraints of multiple stakeholders
1g	Ability to judge the quality and reliability of data, information and analysis provided by experts
1h	Ability to develop probabilistic Bayesian decision model to quantitatively express the notions of indicator, warning, type I and II errors

Table 4 Functional requirements ER 2 disaggregated into specific learning objectives.

	ER 2 THE TWO CULTURES **Ability to express complex natural and social science concepts with clarity, precision and effectiveness**
Notation	**Description**
2a	Ability to write in grammatically correct English, using minimum jargon and a style relevant for different audiences (decision-makers, scientific peers, public)
2b	Ability to use various communication formats (reports, briefings, social media, GIS, hazard maps, visualization) and communicate with a style appropriate for different stakeholders and contexts
2c	Ability to collect and manipulate statistical and spatial data
2d	Ability to use databases of academic publications (Web of Science, Scopus) both as a search tool and for the generation of bibliometric analyses
2e	Have overview of available quantitative and qualitative methods for risk analysis, including their strengths and limitations in particular contexts
2f	Ability to establish a probabilistic model to represent uncertainties concerning time invariant and variant phenomena
2g	Ability to establish a risk model and calculate the risk of a hazard(s) at a particular site or for a particular system
2h	Ability to establish a Bayesian decision model, demonstrating transparently the choice for a given decision alternative
2i	Ability to differentiate between direct and indirect consequences in a given problem context and formulate consequence models for damages
2j	Ability to incorporate operational methods for resilience and sustainability assessment into risk assessment, analysis and management
2k	Have theoretical understanding of the behavioral, cognitive and affective models used to study risk perception and ability to apply this knowledge when formulating a system representation and in model building
2l	Have theoretical understanding of the methods for environmental risk assessment (ERA and EIA) and quantitative sustainability assessment (ELCA, SLCA) and ability to apply this knowledge when formulating a system representation and in model building
2m	Have theoretical understanding and ability to apply econometric models for the quantification of (i) damages/costs and benefits; (ii) risk acceptance; and (iii) discounting
2n	Have theoretical understanding of methods and models used in anthropology, human geography and sociology to study individual and group practices and behavior of relevance to risk perception and social dynamics and ability to apply this knowledge when formulating a system representation and in model building
2o	Ability to classify hazards according to information type in addition to classification by source

Table 5 Functional requirements ER 3 disaggregated into specific learning objectives.

	ER 3 THE HUMAN FACTOR **Develop and demonstrate personal and civic sense for care and duty**
Notation	**Description**
3a	Have an overview of different societal institutions, governance systems, national and international codes, standards, policies, regulations and legal frameworks in the context of risk, resilience and sustainability
3b	Understand the difference between normative and descriptive decision analysis. Understand the difference between utilitarian consequentialist and deontological ethics, their historical application in the context of risk, and how the inclusion of resilience and sustainability considerations into risk assessment might pose problems for the consequentialist approach
3c	Understand how risk, sustainability and resilience are related at different scales (local, national, federal, region, international, landscape, global) and the trade-offs among them at different scales. Ability to apply this knowledge when formulating a system representation and in model building
3d	Ability to explain the history and multiple definitions of compound conceptual categories (nature, environment, built environment, human/social/natural/manufactured capital, land, world, etc.) and how they influence the process of defining a system spatially and temporally. Understand that these notions are not universal but arising out of Western tradition of philosophy and science and how this might affect particular decision contexts
3e	Have theoretical understanding of the trade-offs between systems of governance aiming to satisfy individual and group needs/rights/preferences and apply this knowledge when formulating a system representation, generating decision alternatives and model building
3f	Have theoretical understanding of the concept of Planet Boundaries and how the joint assessment of risk, resilience and sustainability might be used to operationalize it
3g	Have overview of different categories of structural and non-structural protection and prevention measures for different types of hazards, including land-use planning, social cohesion and traditional knowledge
3h	Ability to understand and describe qualitatively the relations between sign, sense, reference, indicator, warning, type I and II errors, strategic/operational/tactical surprise, reality, truth, and deception. Ability to apply Bayesian probability theory to express the same notions formally. Ability to incorporate qualitatively and quantitatively these considerations into the system representation and model building

In Part II of this paper triad we showed how the bibliometric mapping of the knowledge domains of risk, resilience and sustainability revealed that the large majority of conceptual knowledge derives from value and object image schemas, which in our ontology we associate with the dimensional pair D I – IV[2]. A major flaw from having a risk, resilience and sustainability science that rests on the conceptual foundation of value and object schemas is that the identification of systems boundaries and subsequent system modeling become partial in both senses of the word: incomplete and biased. The purpose of risk, resilience and sustainability science is to provide decision support for the design, management, governance, and maintenance of systems. When value schemas play a

[2] In the ontology presented in Part II, dimension D I is named Things in the World and relates to metaphysics; D II – Ways of Structuring and Representing - relates to epistemology; D III – Processes Affecting Things in the World – relates to physics (dynamics); and D IV – Values Affecting Things and Processes in the World – relates to axiology.

foundational role, objectives are set such as to optimize particular values, thus excluding or diminishing other values a-priori rather than in accordance with unfolding events (context). In the first case, governance proceeds along stated preferences; in the second – along revealed and informed preferences. Decision support based on revealed and informed preferences necessitates a flat ontology. Since ours is a domain ontology of concepts, what this means is that no concept is more or less relevant than another concept. All concepts are a-priori equally relevant for the knowledge domain. However, when a concept is considered in relation to a context, not all concepts are equally relevant because they are differentiated conditionally. The flat plane is the formal plane where there is no context and concepts are like generic category containers into which any content can be poured. The content is the semantic plane of matter or differentiated meaning. To illustrate this, consider for example the concept 'expected utility'. On the formal plane, expected utility is nothing but a generic organizing structure for information. On the semantic plane, 'expected utility' is expected utility of something. What the something is that gets into the container structure, acquires meaning in value and significance in comparison to other potential somethings that may enter the container. The formal plane unifies differences; the semantic plane creates them.

In the blueprint, knowledge associated with the first overarching education requirement (ER 1) relates to the formal plane, whereas knowledge associated with ER 3 relates to the semantic plane. Furthermore, the relation between ER 1 and ER 3 is analogous to the relation between knowledge and action, hence in the following ER 1 and ER 3 are discussed as a pair. If risk, resilience and sustainability science is to provide decision-makers with informed rather than ideological decision-support, such science education must provide the basis for a conceptual understanding of information on both the formal and the semantic planes. In the present blueprint, this is the function of the first overarching educational requirement, which we have named after the Western tradition's most famous pursuer of knowledge – Socrates. The Socratic doctrine of "following the argument where it leads" is a requirement for updating a-priori knowledge. The Socratic method, also known as dialectics, is inquiry-based; it focuses on questions rather than answers (authoritatively transmitted knowledge). It resonates well with the method of inquiry problem based learning. In the context of risk-informed governance specifically "following the argument where it leads" can be seen as a procedure for a series of iterative steps through which prior knowledge is updated, logical errors are identified, assumptions are made explicit and/or re-classified, and alternative options are evaluated in the context of the problem formulation. Rather than focusing on a right-wrong solution, the dialectic method focuses attention on whether the question asked is right or wrong in a given context.

Yet, the closest Socrates comes to a definition of knowledge is to identify it with the pragmatic notion of 'virtuous action'. The teleological goal of Socratic education is the conditioning of the character, the molding of a disposition, the in-forming of attitude. The Socratic doctrine of knowledge as virtue relates to the blueprint's third educational requirement (ER 3). In the Apology[3], Socrates explicitly names clear thinking as the most important requirement for right living. In the proposed education blueprint, the Socratic inquiry-based method (ER 1) is the means to the goal of virtuous living, whose final purpose is good governance both at the individual and the collective scales (ER 3). Good governance is then the pursuit for "improving the soul" of individuals and collectives such that actions follow best available knowledge[4].

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[3] ὁ δὲ ἀνεξέταστος βίος οὐ βιωτὸς ἀνθρώπῳ (Plato, Apology: 38a, Loeb 1960) may be translated as For men life without inquiry is not worth living. Unlike the Aristotelean account of human welfare, which seeks to define the concept epistemologically, Socrates does not seek or provide a scientific definition. Like the Neo-Confucian *daoxue*, Socratic knowledge is a quest for self-improvement, culminating in the limitations of what is knowable to humans. Knowledge of one's ignorance is the prerequisite for ethical action.

[4] "I shall never cease from the practice and teaching of philosophy, exhorting anyone whom I meet after my manner, and convincing him, saying: O my friend, why do you who are a citizen of the great and mighty and wise city of Athens, care so much about laying up the greatest amount of money and honor and reputation, and so little about wisdom and truth and the greatest improvement of the soul, which you never regard or heed at all? Are you not ashamed of this? And if the person with whom I am arguing says: Yes, but I do care: I do not depart or let him go at once; I interrogate and examine and cross-examine him, and if I think that he has no virtue, but only says that he has, I reproach him with overvaluing the greater, and undervaluing the less." (Plato, Apology: 29b in Hamilton, E. et al. 1961)

Governance based on the coupling of informed and revealed preferences can thus be traced back to the Hellenic conceptual tradition of the West. This practice has similarly deep roots in the Chinese classical tradition. Here the Neo-Confucian notion of *daoxue* resonates particularly well with the idea of forming a synergy between informed and revealed preferences. The second overarching educational requirement (ER 2) contributes to realizing such synergy. Briefly, we provide the reader with some context for choosing to unite ER 1 and ER 3 in the manner of the Socratic doctrine of knowledge as virtue and the Neo-Confucian notion of *daoxue* 道學. *Daoxue* (learning of the way) is a conceptual system for learning and governance. The *daoxue* academies were established to promote individual self-cultivation in contrast to the state academies that trained future civil servants for their governance tasks (Lagerway 1987/2010). The *daoxue* scholars and teachers perceived the accumulation of knowledge by rota and the memorization of facts in the state schools as an unfitting model for training in governance. To them, the fundamental cause of societal problems lay with an individual's lack of self-knowledge and knowledge of the self's relations with its environment.

Central to the *daoxue* school is a metaphysics based on the coherence principle of *li* 理, which in the ontology we present in Part II is associated with the umbrella term 'information'. Since this is a dynamic principle, i.e. information is both the form of something and the process by which something is formed, there is no information out there that can be grasped and put into use. An education conceptual system based on the idea that knowledge is acquired prior to putting this knowledge into practice is what creates the divide between knowledge and action as well as the possibility that one acts wrongly despite of one's knowledge. In contrast, the Neo-Confucianist's Wang Yangmin notion *zhixing heyi* 知行合一 (unity of knowledge and action) is the foundation for a system of learning, in which knowledge and action are simultaneously manifest in an individual's situational awareness (Wei-Ming 1976). Thus cognition is not the process of acquiring a-priori existing information, but a process of recognizing perceptual input, while action is the orderly classification of perceptual input. Knowing and doing, according to *daoxue* as well as embodied cognition theory (discussed in Part II) is the mutual and simultaneous interaction between perception and conception in dynamically unfolding circumstances. The logic that underlies this type of learning is Bayesian inferential reasoning.

ER 2 is about developing the ability for inferential reasoning in a dynamically evolving context. This ability involves mereological knowledge about parts and wholes and functional knowledge about the interactions among them. Central to the set of skills ER 2 focuses on is the training of the embodied mind (the blend of affective-cognitive reasoning) to make distinctions.

The ability to distinguish, when seen as a function of the embodied mind, is an *evaluative* activity. In the classical Chinese tradition of philosophy, *xin* 心 (heart-mind) guides actions in the world by indexing, naming or picking out things through assigning to them the binary categories *shi* 是 (this/right) and *fei* 非 (not this/wrong) (Hansen 1989). In the Western tradition the truth-falsity of a proposition rests on first establishing mental models (beliefs) and, only after, distinguishing true from false beliefs in accordance with their "correspondence" to observations in the phenomenal world. Body and mind are seen as having separate functions. The Chinese heart-mind as a unitary faculty of cognition and perception is, by contrast, integrated with the phenomenal world *wu* 物 (things-events).

The distinctions that follow from the mind-body polarity forms the set of misfits that inform ER 2: the division between quantitative-qualitative, objective-subjective, descriptive-normative, risk assessment-risk management. The formulation of ER 2 is an attempt to reunite the mind with the body. In practical terms, the logic of the proposed ontology in Part II allows us to expand the quantitative domain to include knowledge not only relevant to calculation but also to mereological and functional ordering in the context of systems representation and modeling. Similarly, the qualitative domain could be expanded to include not only semantics (the relationship between sign and meaning) and rhetoric (the framing and styling of meaning), but also quantitatively oriented binary logic, which forms the basis for information, probability, decision, and game theories.

The inclusion in the ontology of the concept cluster Language (8) is primarily theoretically motivated due to the relation between information as an ordering principle of reality and language as the means by which we have natural or symbolic means to describe reality. The theoretical motivation has, however, practical strategic and operational implications for ER 2. On the practical side, we consider those misfits, which arise from the incorrect, imprecise and inappropriate use of language. These misfits are shared by research, practice and education alike, e.g., endless trivial disputes over glossary definitions of risk-resilience-sustainability-related terms from various application domains, inappropriate use of metonymy, metaphor and analogy, poor use of syntax and lexical choices that obscure meaning. These problems are relevant not only to research in that they lead to erroneous logic, but are also relevant to the efficacy and efficiency of communication among researchers, among teachers and students, among researchers-practitioners and decision-makers, and not least experts and the general public. Terminology in the knowledge domain of risk-resilience-sustainability is at present a Humpty-Dumpty playground where everything means what individuals want it to mean. This applies to individual researchers, individual disciplines, individual practice areas, and individual normative-regulative bodies alike. It is a highly unfavorable situation for coordinated action even among countries with a shared Western conceptual tradition. The issue of how these terms are translated, understood and used in places that have other conceptual traditions has not yet even been asked.

Unlike the Western epistemic obsession with language, the Chinese tradition has a pragmatic approach to language. A central notion of Confucian thought is that of 'rectifying names' as *the* principle of good governance[5].

Rectifying names is not only about the ritual exercises of social norms, it is also the cognitive process of making distinctions expressed through the evaluative judgment *shi-fei* (this-not this). In the Chinese sense-making of the world, this method integrates the descriptive-prescriptive distinction (Hansen 1989). *Shi-fei* is used for both type of judgments: to distinguish one *wu* (thing-event) in the world from another *and* to select the appropriate *xing* (action, behavior). As Hansen (1989) has pointed out, to rectify a name is not to produce a definition, as is the practice of Western researchers, but rather, to use the term correctly as a model[6].

The operational focus of ER 2 on language is the correct use of terms by means of which a concept can be knowingly applied. This implies sufficient qualitative knowledge of the discipline where the concept is used and its cluster of semantic relations within that discipline. The strategic focus of EG 2 on language is precisely the opposite, namely, to engender an ability to un-learn or ignore the conventions of a given discipline with regard to the correct use of the term in order to

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[5] *Zilu said, The ruler of Wei awaits your taking on administration. What would be the master's priority? The master replied, Certainly – rectifying names!...*

If names are not rectified, language will not flow;
If language does not flow, social affairs will not be realized;
If social affairs are not realized, ritual and music will not flourish;
If ritual and music do not flourish,…
People will not know how to move hand and foot.
(The Analects 13 Attributed to Confucius [Kongfuzi], 551-479 BCE by Lao-Tse [Lao Zi], (Ames 2010))

[6] Thus concludes the passage on rectifying names in the Analects:
Thus when an exemplary person uses a name, it
Can surely be spoken, and when spoken it can
Surely be acted upon. There is nothing careless
In the attitude of the exemplary person to what is said.

enable a situation, where trans-disciplinary, context-situated knowledge creation and exchange can occur.

3.3 Blueprint

Fig. 3 is an illustration of the proposed blueprint for education in risk-resilience-sustainability governance. A full description of the misfits and requirements is provided in sections 3.1 and 3.2. For a view of the content of the supporting concept clusters, the reader is directed to Fig. 4 (ontology of the knowledge domain of risk, resilience and sustainability) in Part II of the paper triad. The purple shaded middle concentric circle represents the three educational requirements, together with the particular learning objectives associated with each. The misfits occupy the space inside; the supporting concept clusters from the ontology are arranged on the outside. The visualization affords a radically compressed overview of the design's components and interactions. It makes apparent at first sight, our design choice to put emphasis on information-theoretic concepts (red) in sharp contrast to their negligible representation in current research practices in the domain of risk-resilience-sustainability.

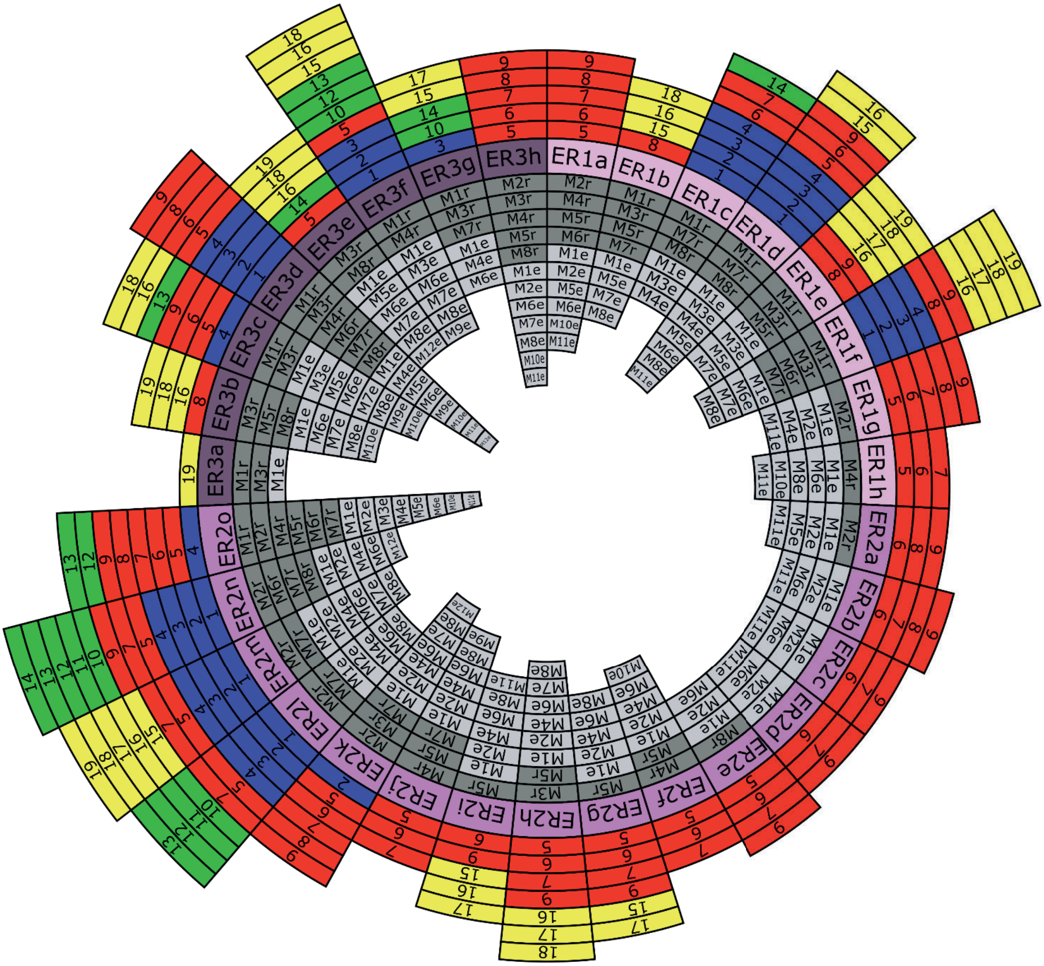

Fig. 3 Blueprint for education in risk, resilience and sustainability science.

4 The blueprint as an operational model for contextual trans-disciplinarity

In Section 3 of the present paper, trans-disciplinarity was associated with misfit M7r, namely that although agreed upon as a desirable objective by the research community, it is not an observed practice either in research or in education. We postulate that trans-disciplinarity is presently not observed because the scientific and operational frameworks that inform best practice in research and education are not context-oriented. This means that methodologically these frameworks make no use of Bayesian methods for updating information. Trans-disciplinarity is implicit in the logic of generic theories and methods. When such methods are used, trans-disciplinarity ceases to be an ideologically-driven stated preference and becomes the revealed preference of practitioners using such methods. In other words, when a scientific discipline is defined by subject matter, the result is a multiplicity of narrowly defined disciplines, technical definitions of concepts, and methods that are only applicable within those technical definitions. If, on the other hand, we let a scientific discipline be defined by method of investigation, the multiple subject matters can be seen as variables in an inherently trans-disciplinary method. In this section we illustrate how the education blueprint, with basis in the flat domain ontology presented in Part II, provides an operational model for contextual trans-disciplinarity to researchers, education planners, education practitioners, and students.

How trans-disciplinary the educational design must be for a successful learning outcome of a given target will depend on the range of selected source domains judged relevant to a particular decision context. While clearly most decision contexts in the world outside the classroom will require a limited selection of source domains because of practical consideration of resources, it is important to be aware of the full or extensive range of possible source domains and means. Knowing which source domains and means have been omitted in a given context facilitates the identification and transparent documentation of the assumptions made in the decision modeling process.

To illustrate the importance of the choice of source domain on the contextual boundaries of a given concept, we take the concept 'resilience' as an example. As discussed in Nielsen and Faber (2019), there are at least 9 distinct uses of 'resilience' in the scientific literature between 1990 and 2017: ecological resilience, spatial resilience, engineering resilience, infrastructure resilience, robustness, disaster resilience, community resilience, urban resilience, and economic development resilience. Each of these definitions of resilience selects image schemas and conceptual metaphors from different conceptual source domains. The selection of source domains determines the disciplinary boundaries, methods and metrics for the further scientific inquiry into the concept.

When resilience is framed and understood through the metaphor Body Is A Machine, the concept of engineering resilience emerges in sharp contrast to the concept of ecological resilience, which is framed through the metaphor Body Is A Homeostatic Organism. Body, of course, can be taken as the metaphoric source domain for any system. In both situations, resilience is a response to stress. But how stress is experienced differs significantly. In Johnson (1990/2013) implications of selecting Machine or Homeostatic Organism as alternative source domains for understanding the target domain concept BODY are discussed with respect to scientific advances in the history of medical practice. Here we use the same example to illustrate how the two source domain alternatives result in divergent understanding, framing and measurement of RESILIENCE.

In the case of engineering resilience, stress is experienced as an aggregation of symptoms. A breakdown or a failure (analogous to disease or injury) is experienced as the failure of a specific part. This implies that every failure (disease) has a specific and unique set of essential characteristics (symptoms). Within this image schema, it is not possible to conceptualize or model a non-specific reaction to stress because specific responses correspond to specific damages, located in specific places (organs). The solution (intervention) is control-oriented (offensive). A specific control mechanism corresponds to a specific damage potential in the same way that a specific medicine is prescribed for a specific diagnosis. Just as disease and health have clearly defined boundaries, structural health is clearly delineated from structural failure. Finally, the machine metaphor is not teleological since machines don't have a "purpose".

In the case of ecological resilience, stress is experienced as a syndrome of response, which has a general function. It does not point to any particular damage part or area. The homeostasis metaphor explains why a general response "makes sense" in maintaining a balance. The solution (intervention) is defensive. Rather than eliminating a specific symptom, it is aimed at keeping the symptoms from developing. In contrast to the machine metaphor, the difference between illness and health, functionality and dysfunctionality is not binary but a matter of degree. Finally, the homeostasis metaphor has a clear teleological explanation of health, namely the purpose of homeostasis is the maintenance of balance.

Fig. 4 shows a distribution of the predominant academic disciplines associated with each concept cluster of the ontology, when the concepts contained in a given cluster are the target of knowledge.

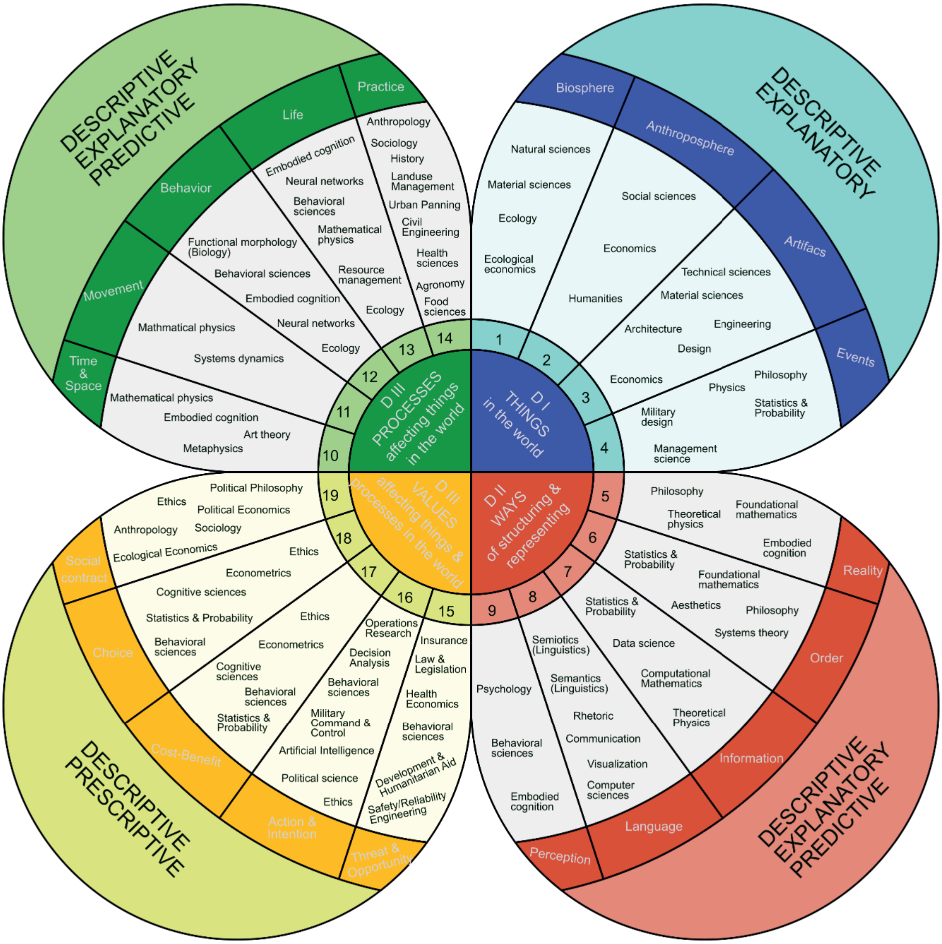

Fig. 4 A trans-disciplinary ontology of risk, resilience and sustainability science.

4.1 Knowledge profiles of the ontology's dimensions as aids for contextually trans-disciplinary education designs

When concepts belonging to Dimensions I and II of the ontology are the target domain of knowledge, we associate this knowledge with basic research, which tends to be more theoretical than applied, and descriptive rather than normative. In designing the blueprint for education this type of knowledge is not the intended learning outcome of a program or a course of study, rather it is knowledge that facilitates the successful learning outcomes for knowledge associated with the target domain of knowledge of Dimensions III and IV. Since the purpose of risk, resilience and sustainability education is pragmatic, i.e. its teleological end is governance, focus in the blueprint is directed on knowledge that is primarily associated with applied science, for which basic science provides calibrating input.

In the following we develop a knowledge profile for each dimension of the ontology, which we believe could help education designers, practicing teachers and students to formulate the disciplinary scope of teaching-learning activities in accordance with the context of the target knowledge pursued in a given problem situation. Each knowledge profile has the following elements:

(i) **Source – Target of knowledge**: provides the context of knowledge in terms of input-output of source-target among the four dimensions;

(ii) **Knowledge application**: provides information on which stage in the process of systems based risk analysis the knowledge can be utilized;

(iii) **Knowledge function**: distinguishes among four purposes for pursuing an inquiry: descriptive, explanatory, predictive, and prescriptive;

(iv) **Level of generality**: distinguishes between the extent to which the knowledge is specific to a particular context or can be utilized generically across multiple contexts; and

(v) **Disciplinary input**: provides an orientation for which disciplinary source domains might be considered relevant to the context (i).

Following each knowledge profile, a visualization is provided of the relations among likely sources for concepts when the target of knowledge are concepts from D I, D II, D III, and D IV respectively. These visualizations have aided us – the authors - in developing the three examples of possible alternative learning pathways described in Section 5. Since the context is composed of a potentially infinite number of problems, these examples should not be considered as templates but rather as structuring principles for setting boundaries for the range of conceptual source domains for a given target domain. Stated differently, this is a practical guide for planning contextually trans-disciplinary education activities.

D I (Table 6 and Fig. 5) is the metaphysical dimension, titled Things in the World. Included in this dimension is a taxonomic listing of what exists and how it exists - the rules for what is and is not an entity as well as the categorization logic. In the proposed ontology, both objects and events equally exist, i.e. no causal priority is given to an entity or to a relation among entities.

Table 6 Knowledge profile of D I.

Source-Target of knowledge	Knowledge application	Knowledge function	Level of generality	Disciplinary input
D I as input for D II	• Structure-function relations of system components (focus on structure) • Hazard classification by source of origin	Descriptive	Specific	Natural & material sciences Human & social sciences Engineering and Design
D I as input for D III	• Structure-function relations of system components (focus on function) • Process dynamics (physical & social) underlying individual hazards	Descriptive Explanatory	Specific	Natural & material sciences Human & social sciences Engineering and Design
D I as input for D IV	Selection of relevant metrics	Descriptive Explanatory Prescriptive	Specific	Natural & material sciences Human & social sciences Engineering and Design
D I as target of knowledge	• Structure-function relations of system components (when components are of the same kind) • Classification	Descriptive Explanatory	Specific	Natural & material sciences Human & social sciences Engineering and Design

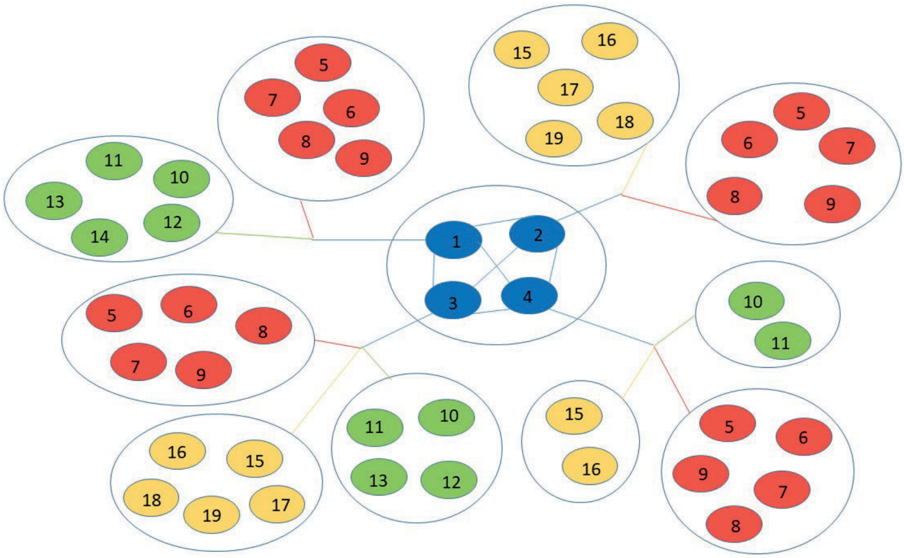

Fig. 5 when the target of knowledge are concepts from D I. (The color scheme follows the color scheme of the ontology presented in Part II (Nielsen and Faber, 2020) where blue corresponds to concepts in D I , red corresponds to concepts in D II, green corresponds to concepts in D III and yellow corresponds to concepts in D IV).

D II (Table 7 and Fig. 6) is the epistemological dimension, titled Ways of Structuring and Representing Things in the World. D II is about knowledge: what is possible to know and how we come to know it. D II provides a structure for perceptual input toward conception.

Table 7 Knowledge profile of D II.

Source-Target of knowledge	Knowledge application	Knowledge function	Level of generality	Disciplinary input
D II as input for D I	• System boundaries • Mereological system representation (static, part-whole representation of system and its components)	Descriptive	Generic	Philosophy Mathematics Embodied cognition
D II as input for D III	• Inter-dependencies among systems components; • Causal dynamic modeling of system's behavior in space and time; • Probabilistic realization of hazard events	Descriptive Explanatory Predictive	Generic	Philosophy Mathematics
D II as input for D IV	Consequence modeling alternative choices and actions	Descriptive Explanatory Predictive	Generic	Philosophy Mathematics
D II as target of knowledge	• Theory, methodology, model, and experiment building • Verification and validation	Descriptive Explanatory Predictive	Generic	Philosophy Mathematics

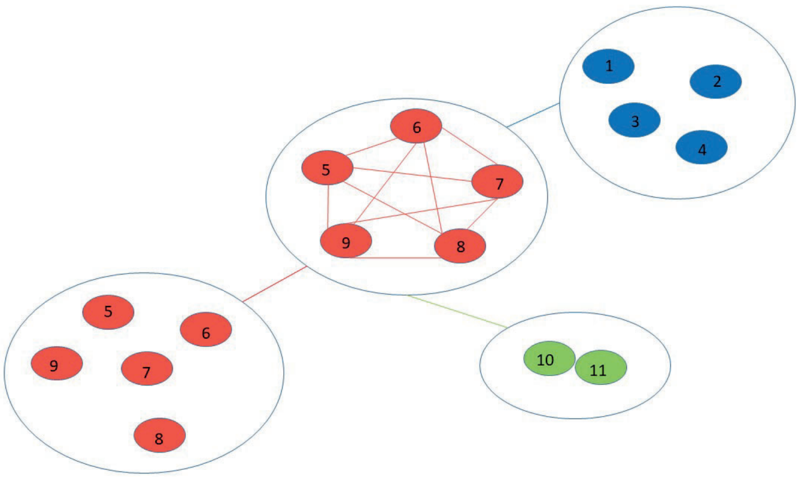

Fig. 6 when the target of knowledge are concepts from D II. (The color scheme follows the color scheme of the ontology presented in Part II (Nielsen and Faber, 2020) where blue corresponds to concepts in D I , red corresponds to concepts in D II, green corresponds to concepts in D III and yellow corresponds to concepts in D IV).

D III (Table 8 and Fig. 7), titled Processes Affecting Things in the World, is about movement, change and interaction. In the ontology it functions as the conceptual structure for a causal logic based on the postulate that this is only knowable by means of some kind of model (D II).

Table 8 Knowledge profile of D III.

Source-Target of knowledge	Knowledge application	Knowledge function	Level of generality	Disciplinary input
D III as input for D I	• Identity, integrity, transformation of a system and its components in space and time • Establishing time-space limits of system and of decision problem • Estimating system health state at a given time	Descriptive Explanatory	Generic	Physics Mathematical Physics
D III as input for D II	• Empirical observations	Descriptive Predictive	Specific Generic	Any natural, material, life, social, or human science discipline relative to the system context; Data science Statistics & Probability
D III as input for D IV	Empirical observations enabling the measurement of differences between stated and revealed preferences, thus forming the basis for establishing informed preferences	Descriptive Prescriptive	Specific Generic	Any natural, material, life, social, or human science discipline relative to the system context; Data science Statistics & Probability
D III as target of knowledge	Interaction of matter-form-force	Descriptive Explanatory Predictive	Specific Generic	Physics Mathematical Physics Metaphysics

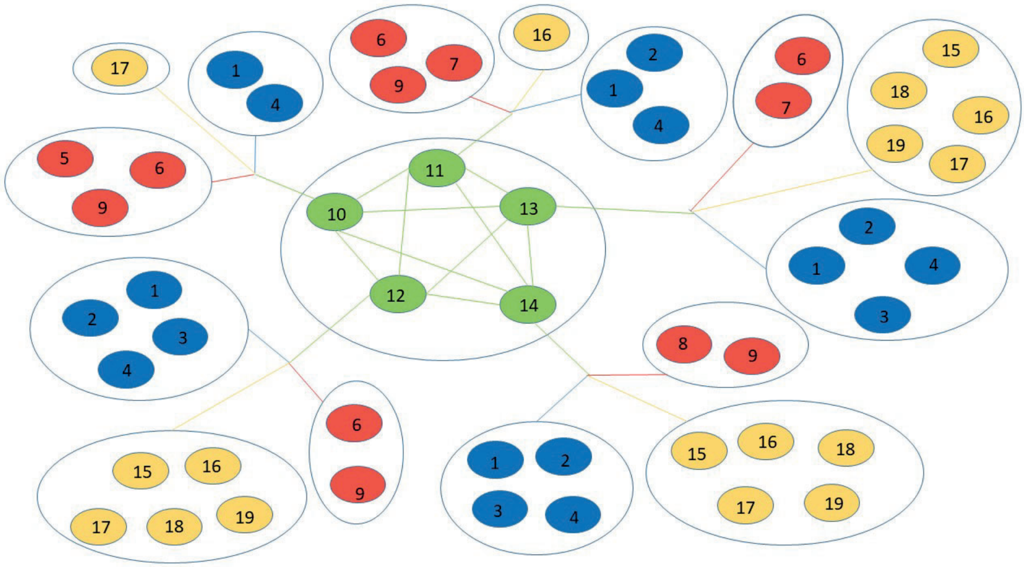

Fig. 7 when the target of knowledge are concepts of D III. (The color scheme follows the color scheme of the ontology presented in Part II (Nielsen and Faber, 2020) where blue corresponds to concepts in D I , red corresponds to concepts in D II, green corresponds to concepts in D III and yellow corresponds to concepts in D IV).

D IV (Table 9 and Fig. 8), the dimension titled Values Affecting Things and Processes in the World, deals with criteria for measuring. What is to be measured is determined with input from D I and D II. How something is to be measured is determined with input from D III and D II.

Table 9 Knowledge profile of D IV.

Source-Target of knowledge	Knowledge application	Knowledge function	Level of generality	Disciplinary input
D IV as input for D I	• Sensitivity/Factor analysis of the identified hazard scenarios for a given system which enables the formulation of a decision problem	Descriptive Explanatory	Specific Generic	Any natural, material, life, social, or human science discipline relative to the system context; Applied Mathematics
D IV as input for D II	• Identification of natural, constructed or proxy attributes of decision outcomes, aka. decision criteria • Conversion of attributes into a utility function weighing value tradeoffs of decision alternatives	Descriptive Prescriptive	Specific Generic	• Any natural, material, life, social, or human science discipline relative to the system context; • Applied Mathematics
D IV as input for D III	• Identifying appropriate discounting rate for decisions impacting future generations • Consideration of resilience-sustainability tradeoffs as a multi-attribute value problem	Prescriptive	Generic	Applied Mathematics
D IV as target of knowledge	• Knowledge about variance, its measurement and its control	Descriptive Prescriptive	Generic	• Applied Mathematics • Ethics

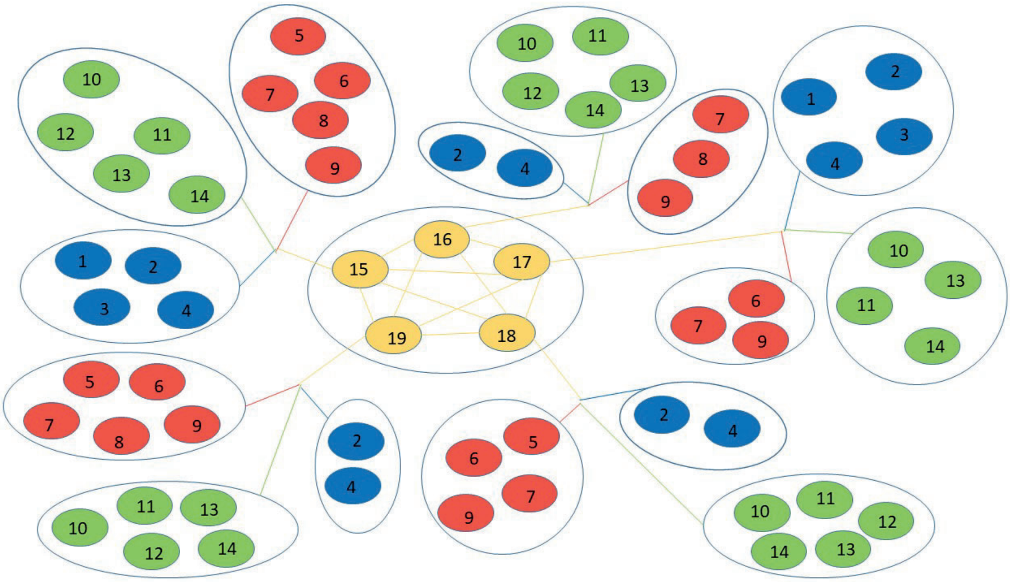

Fig. 8 when the target of knowledge are concepts from D IV (The color scheme follows the color scheme of the ontology presented in Part II (Nielsen and Faber, 2020) where blue corresponds to concepts in D I , red corresponds to concepts in D II, green corresponds to concepts in D III and yellow corresponds to concepts in D IV).

5 Multiple learning pathways

Because of the non-linear causal inter-dependencies between risk, resilience and sustainability in the phenomenal world and our incomplete knowledge of both causes and consequences, a primary goal for education is not the transmission of best practice but the enabling of cognitive flexibility that allows students to come up with solutions to novel problem-situations. As such, we take basis in Cognitive Flexibility Theory from instructional design and in Ingold's (2000/2011) concept of 'wayfinding' as embodied and situated learning.

Cognitive Flexibility Theory (CFT) developed by Spiro et al. (1987) in the context of advanced knowledge acquisition and transfer in ill-structured knowledge domains has the following five tenets:

- Use of multiple knowledge representations (e.g., multiple themes, analogies, lines of argument
- Explicit link between theory and practice whereby conceptual knowledge is situated in practical application contexts
- Introduction of complex concepts and conceptual schemes in small, cognitively manageable units
- Focus on inter-related knowledge components rather than isolated and compartmentalized knowledge
- Assembly of appropriate knowledge from different conceptual and application areas instead of retrieval of memorized information

A design based on CFT affords a context-driven, non-linear learning, which results in a multi-modal and flexible conceptual understanding rather than an algorithmic sequence for achieving a pre-defined goal. In a Bayesian framework the conceptual understanding (a-posteriori knowledge) is built up – supported by address of different contexts - through perception of concepts, which play the role of likelihoods, in conjunction with the student-dependent (a-priori) knowledge.

In addition to CFT, our design of multiple learning pathways is informed by the anthropological study of Tim Ingold (2000/2011), in which he elaborates two modes of human movement in the world: wayfinding and navigation. These two modes afford different perceptions of the environment, which result in the conception of place as a temporally situated meshwork of history, forming a "region" and a coordinate grid of lines, forming a location on a map[7]. The distinction between navigation and wayfinding is significant in terms of the temporal sequence of actions. With a map, one has knowledge before one acts. Wayfinding does not rely on prior knowledge; rather, knowledge is generated simultaneously with one's movement – what Ingold calls "ambulatory knowing or knowledgeable ambulating" (Ingold 2011). In keeping with Gibson's ecological affordance theory of visual perception, Ingold sees knowledge as embodied practice that unfolds along lines of interactions. These lines are not connectors in a network, where we can define the start

[7] "Bound together by the itineraries of their inhabitants, places exist not in space but as nodes in a matrix of movement. I shall call this matrix a 'region'…To use a map is to navigate by means of it: that is to plot a course from one location to another in space. Wayfinding, by contrast, is a matter of moving from one place to another in a region." (Ingold 2000/2011)

and end points, but are progressively revealed in movement attuned to phenomena or the movements of others (human and non-human) in the world. The logic of wayfinding is the same as the logic of image schemas in Lakoff and Johnson's (1999) embodied cognition theory, which is furthermore, the logic of Bayesian reasoning. Together these theoretical and methodological perspectives converge in the three overarching educational requirements of the blueprint presented in this paper. "Following the argument where it leads" is real-time wayfinding and learning in context. It is a radically different type of learning design in comparison with the present learning designs that focus on optimized linear sequences that transport students from one partial perspective to another in the fastest time possible. Having thus arrived at some pre-defined destination, the motivation and ability to go beyond is no longer there. We hope that the design we present here affords the possibility for non-linear movement, exploration, and creativity so that paths can be traced, re-traced, and new paths made, where no one has gone before.

In what follows, we develop three exemplary pathways for structuring learning activities based on the ontology and education blueprint presented in Part II and Part III of the triad of papers. The three pathways correspond to three modular levels of learning activities:

- Learning Pathway I (hereafter LP I) describes a possible structure at the level of a full master degree program;
- Learning Pathway II (hereafter LP II) describes a possible structure for a single course, taught either as a part of a full master level program or independently, such as a professional life-long learning (LLL) course, targeting working professionals; and
- Learning Pathway III (hereafter LP III) describes a possible structure for an individual problem based learning (PBL) activity such as a project that may be undertaken by students enrolled at either a full degree program or a professional LLL course.

While the level of teacher-led navigation is different for the different LPs, what they all share is the possibility to approach the content in a non-linear way, which is in direct opposition to most current educational practices that rely on linear procedural frameworks. Non-linearity is a specific feature of the design not only because the problem context of risk-resilience-sustainability exhibits inherently non-linear relations but also because of the heterogeneous body of students that programs, courses and professional LLL attracts. The design thus aims to structure the learning process such that it closely resembles research and practice in this knowledge domain *as it is done* rather than simply learning *about how it is done*. The design further allows for planning learning activities for audiences with different academic backgrounds, different prior knowledge and experience, and different learning styles and expectations. The non-linear navigation afforded by the design may be supported by digital learning objects (LOs) that allow both structured teacher-led navigation and explorative student-led wayfinding (See Annex A).

We wish to emphasize that the multiple learning pathways presented here are not suggested curricula for programs, modules or project-based learning activities, but structures for organizing content. This content may evolve and change because scientific knowledge has evolved and can be adapted to fit particular problem contexts or application areas. In the present design, we have only considered content which is generic to risk-resilience-sustainability decision modeling and decision-making. We believe that this generic content and structure is applicable to all human practices and at all scales where decisions about risk-resilience-sustainability must be made. In this sense we classify the proposed new science as a life science.

5.1 LP I Program Level

LP I is an example of a directed but non-linear teacher-led navigation, using concept clusters from the ontology. LP I is designed at the level of a full master program, corresponding to two years of full-time studies or 120 ECTS. It is assumed that students enter the program with some preliminary partial knowledge of risk, resilience and sustainability from a particular disciplinary domain, e.g. civil/environmental engineering, economics, sociology, political science, etc. at the bachelor level, but with little understanding of the causal feedbacks among risk, resilience and sustainability. LP I thus spans all procedural stages of risk analysis from system definition to evaluation of decision alternatives, encompassing thus descriptive, explanatory, predictive and normative knowledge.

The pathway is designed to cover four procedural steps in a generic risk analysis process: (Step 1) System Definition; (Step 2) System Modeling; (Step 3) Decision Modeling; and (Step 4) Management, Monitoring and Maintenance. At the same time a distinction is made among strategic, operational and tactical decision support situations. In a typical two-year full time program, consisting of four semesters, we have assigned the 1st semester to strategic considerations (Fig. 9), the 2nd – to operational considerations (Fig. 10), and the 3rd – to tactical considerations (Fig. 11). The 4th semester typically involves individual master projects and is therefore not dealt with here.

The semester structure of 3 theoretical modules and a problem based module is based on Aalborg University's Problem/Project Based Learning (PBL) structure, whereby the three theoretical modules equip the students with the concepts and methods they need to apply in a given decision problem and in a project-group setting. In each of figures 9-11, the inner circle identifies the temporal sequence in the program and the orientation (strategic, operational, tactical). For each module in a semester, the following are identified in every additional concentric circle:

- Module number
- Module name
- Suggested pedagogical approach, assessment and number of credits
- Relevant concept clusters from the ontology supporting the module's theme/subject matter
- Relevant theories and methods
- Corresponding educational requirements and learning objectives

As with the diagram of the blueprint (Fig. 3), we see these semester diagrams as both teacher and student navigation aids through vastly distributed conceptual, methodological and disciplinary knowledge. The color scheme used for the concept clusters is identical to that of the ontology. It allows an instant comprehension of the knowledge profile of a given semester. For example, one can immediately see that the value dimension, D IV, is more extensively represented than the process dimension, D II, in the strategic semester I, while the reverse is the case in the operational semester II.

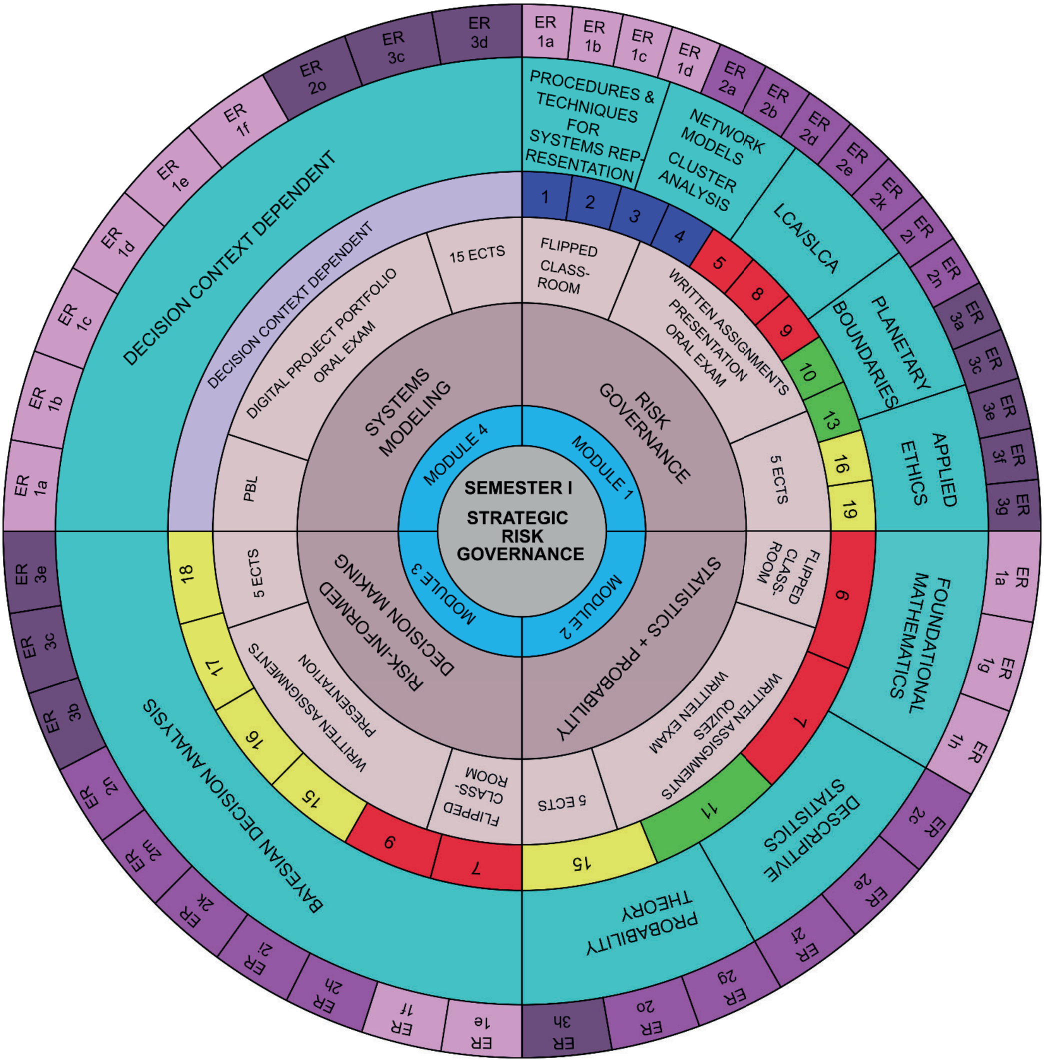

Fig. 9 Learning Pathway I – supporting conceptual knowledge during a first, strategically-oriented semester of a full master level program.

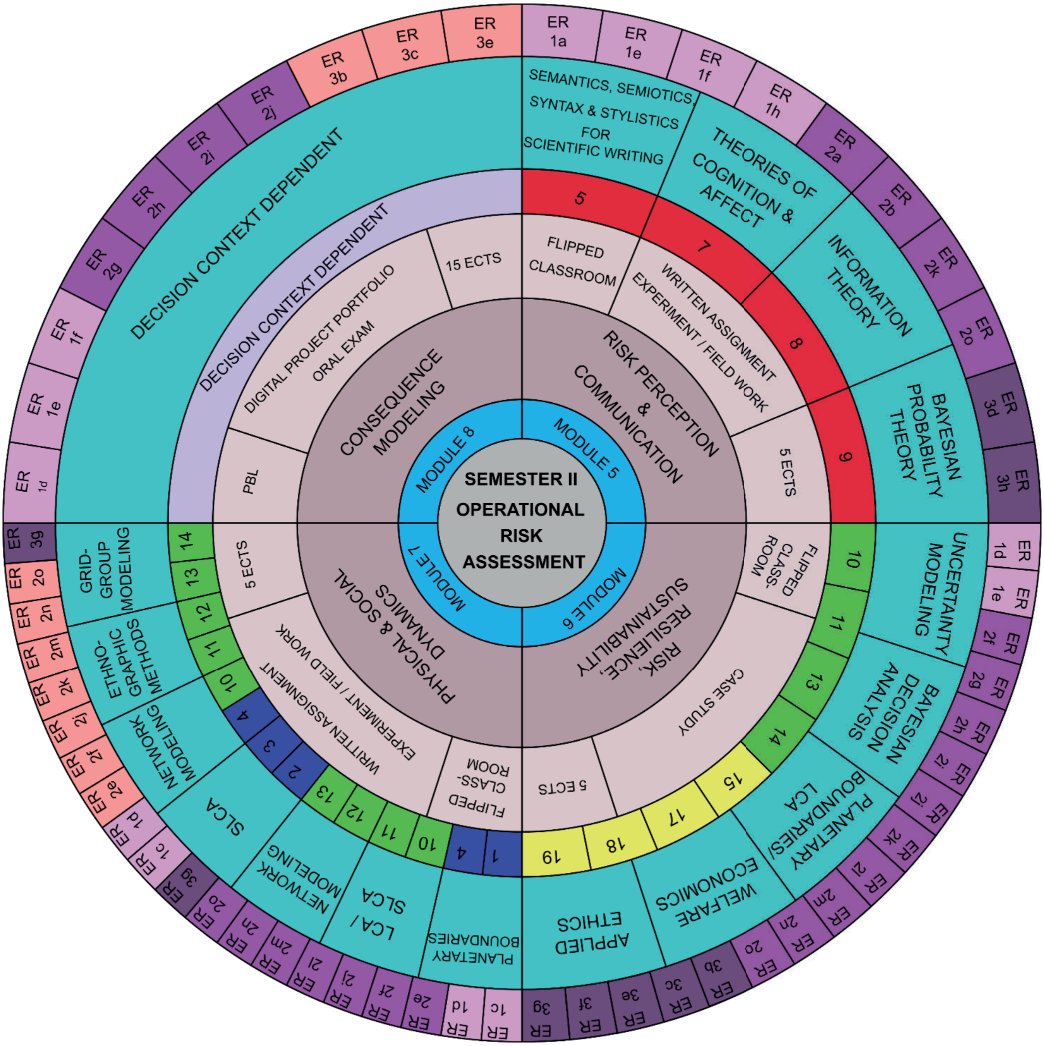

Fig. 10 Learning Pathway I – supporting conceptual knowledge during a second, operationally-oriented semester of a full master level program.

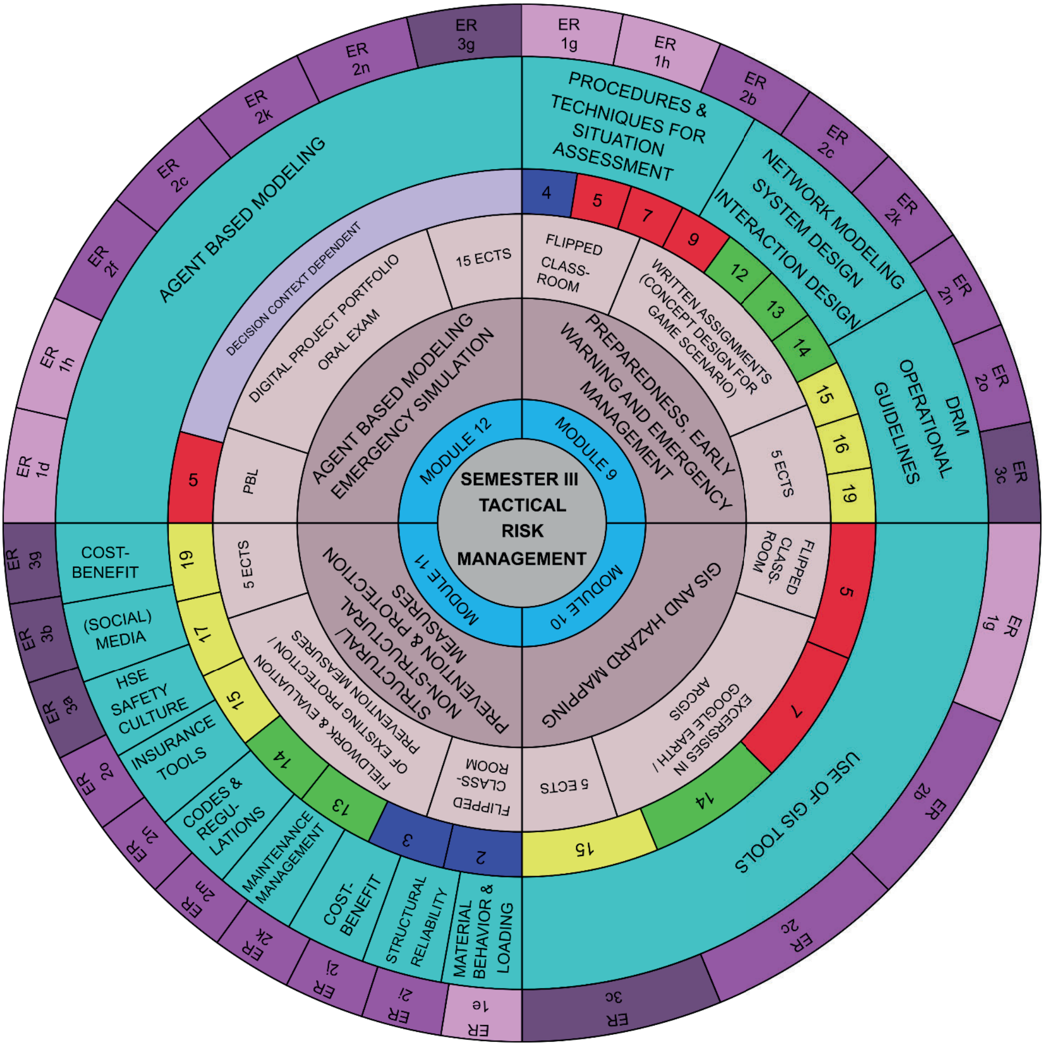

Fig. 11 Learning Pathway I– supporting conceptual knowledge during a third, tactically-oriented semester of a full master level program.

5.2 LP II Module Level

LP II is envisaged as a shorter term learning activity at the modular level of a module or course (5-15 ECTS) relevant for graduate students, professionals and researchers with prior disciplinary knowledge of risk from any knowledge domain, where risk, resilience and sustainability are a concern (Fig. 12)

LP II follows a specific scientific methodological framework for the combined assessment of risk, resilience and sustainability in a given decision situation, as originally developed by Faber (2018).

In Fig. 12 we have visualized a possible navigation of the ontology based on this particular scientific framework.

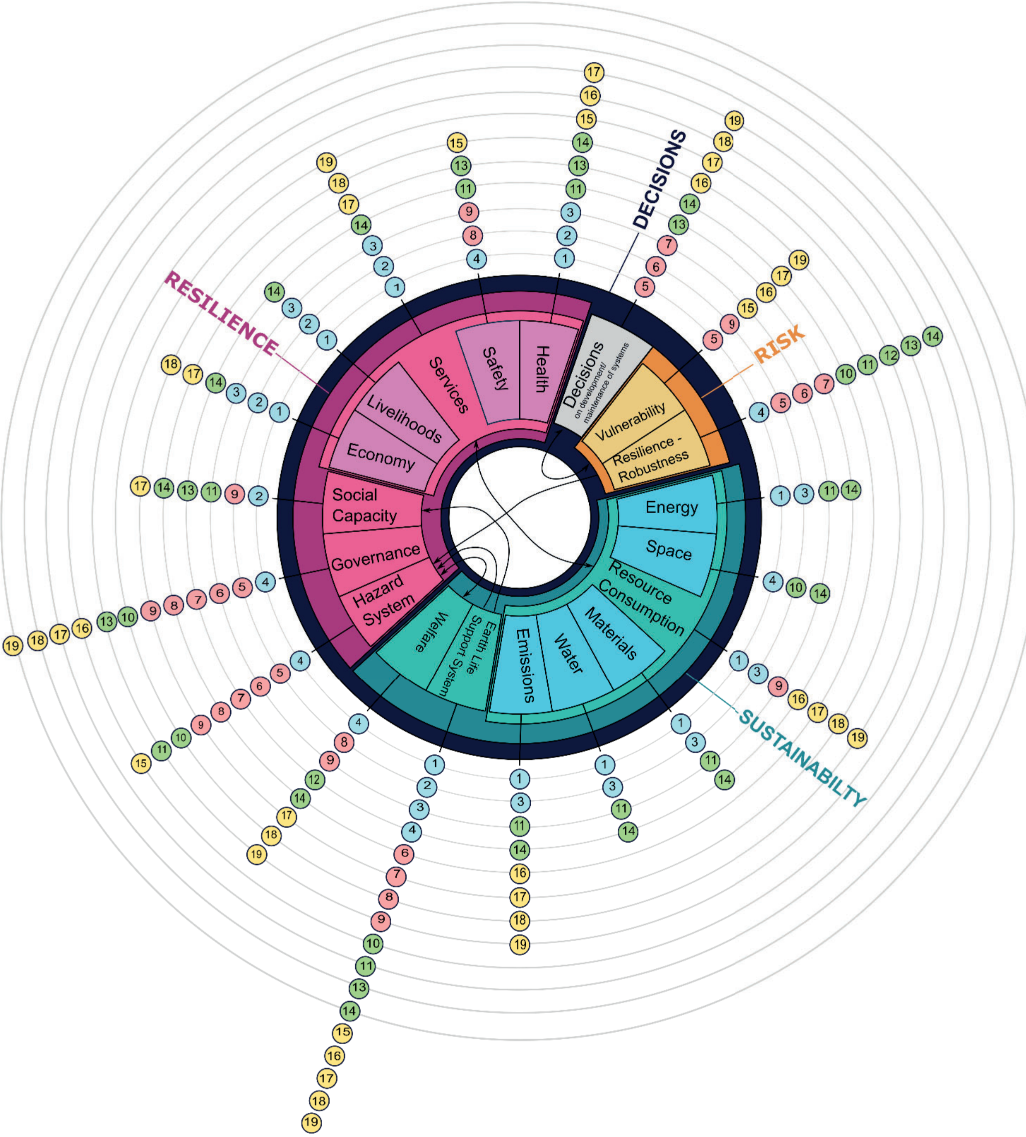

Fig. 12 Learning Pathway II supporting ontology navigation based on a specific scientific framework. The nodes outside the perimeter indicate the supporting concepts for this module-length learning activity. The lines in the inner circle correspond to the relations among the elements of the scientific framework outlined in Faber (2018) and illustrated in Fig. 13.

LP II is a directed, non-linear pathway, which may be initiated from any component, but must follow the indicated causal relations among components. Two types of relations are integrated in the visualization. The nested components indicate relations within a given frame. The decision frame is at the top of this nested hierarchy, followed by sustainability, resilience, and risk (Fig. 13).

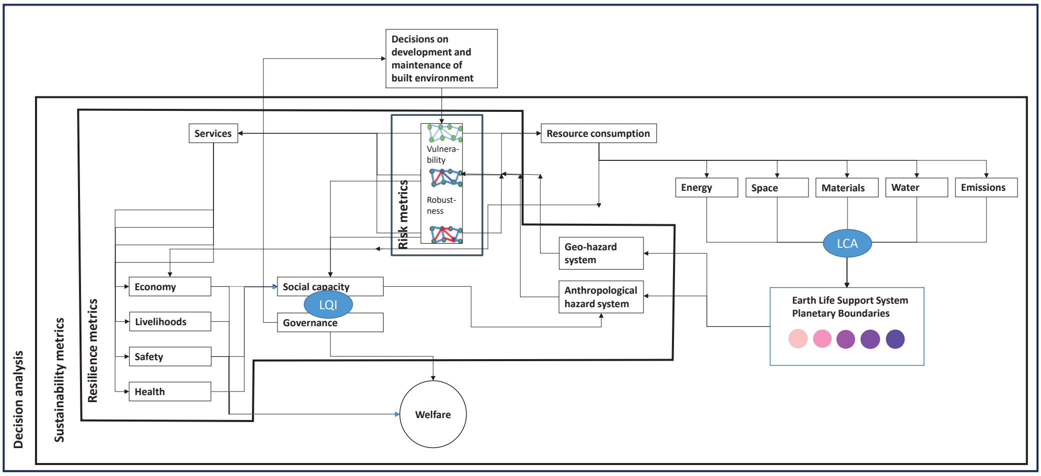

Fig. 13 Illustration of the convoluted realm of governance of risk, resilience and sustainability (adapted from Faber, 2018).

To appreciate the complexity of the causal relations between risk, resilience and sustainability not only in the physical world, but also in the mental world of concept acquisition, we zoom in for example on the component 'Vulnerability' from LP II. In risk analysis, the vulnerability of a system is measured as the sum of all possible direct consequences integrated over all possible hazard events. Knowing the vulnerability of a system is a prerequisite for measuring its resilience conditionally. This necessitates knowledge about (i) the statistical characteristics of hazards (stress or loading conditions), (ii) the capacity characteristics (direct damages) of the individual components of the system, and (iii) the systems reliability characteristics (indirect damages) of the system's structure. In the design of LP II, there are 6 concept clusters and a total of 36 concepts that provide the conceptual knowledge basis necessary to perform the analytical task of measuring resilience conditionally. In principle, a student has 720 possible ways to navigate between the 6 supporting *clusters* (6! = 720) and a rather extensive number of combinations of navigating among the concepts (Fig. 14).

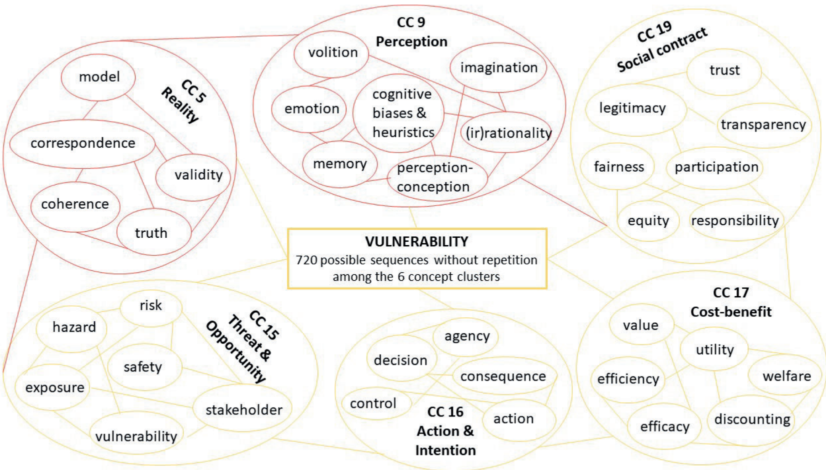

Fig. 14 Dependencies between 6 concept clusters from the ontology as part of non-linear navigation of LOs in support of a single module-course.

In Annex A of the present paper, we sketch and discuss how a repository of digital learning objects based on the structure of the proposed ontology will enable learners to explore the entire conceptual domain and find their way based on individual considerations. At the same time, such a repository might enable education designers and teachers to plan specific learning activities based on teacher-defined sequencing, thus providing learners an optional “red thread”.

5.3 LP III Problem-Based Level

LP III is designed as an example of adaptive wayfinding for a given problem context, where each student or project group chooses their own path along all possible concepts/LOs, i.e. over the entire domain ontology. Following PBL philosophy, the pedagogical goal is to enable independent inquiry on the part of the students. Therefore in LP III, learners define the sequence along the path while the teacher’s role is to monitor movement along the path and suggest possible alternatives should the path appear to lead to a dead end.

Since each problem path is the choice of an individual or a project group, we cannot provide an example of LP III. Instead, we provide a sample. We illustrate this LP III sample on the basis of an actual PBL learning case, involving a master student, a PhD student, an assistant, and a full professor working as a project team. The results of the PBL study are given in Nielsen et al. 2018. At the time of the study the ontology had not been designed, so the illustration here shows how it hypothetically could have been used for this problem case.

Fig. 15 shows the selection and sequence of concept clusters to support a problem case that could be approached from either a theoretical (Learning context 1: basic research) or pragmatic (Learning context 2: applied decision support) perspective. The division between basic and applied research need not lead to an opposition between the descriptive and the prescriptive aspects of research, leading to a "two cultures" split, but a complementarity of two different initial conditions in the model building process. The steps in the PBL process are shown, together with the knowledge output for each stage and the concept clusters that support the conceptual understanding of theories and methods used in the process.

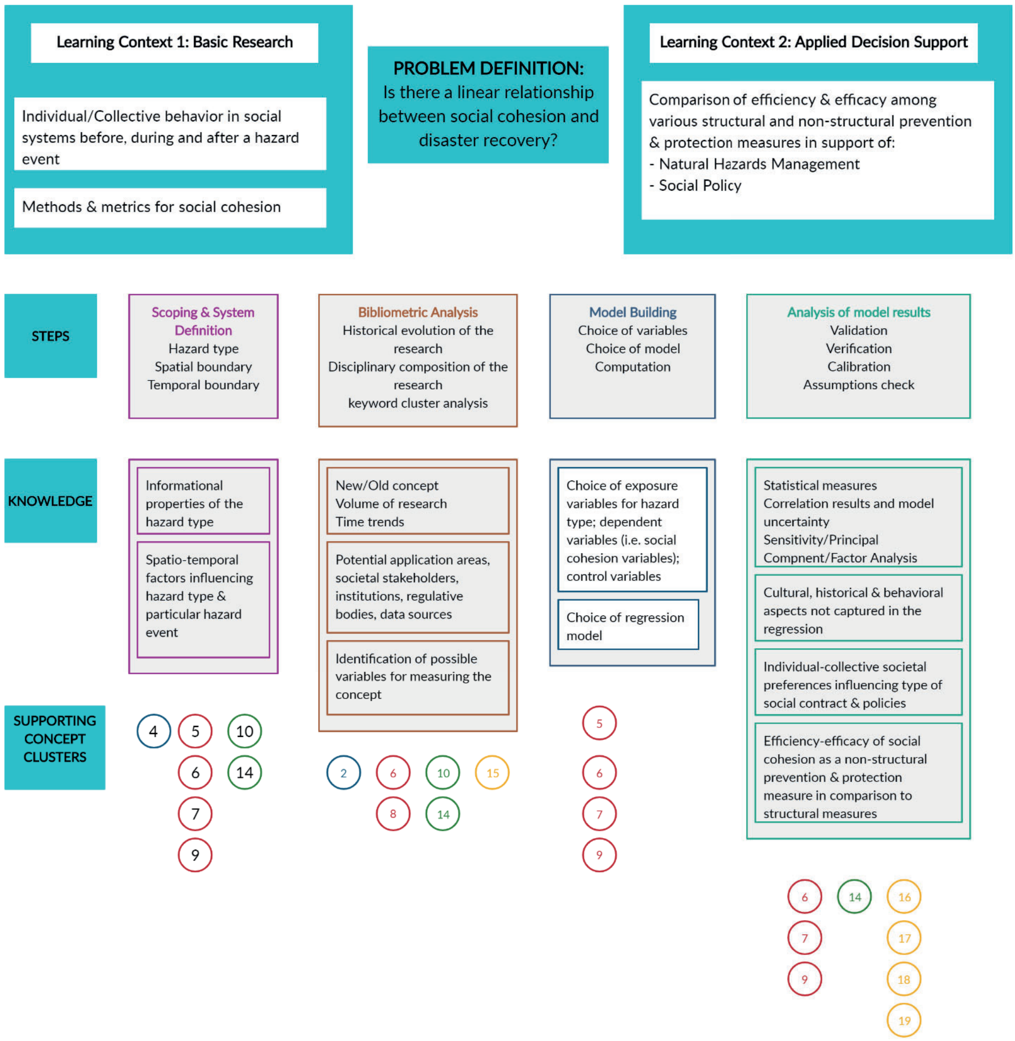

Fig. 15 Learning Pathway III supporting adaptive wayfinding for a specific problem context.

The developed blueprint can be applied directly as presented in support of the planning and operation of educational activities. However, the blueprint for educational activities in conjunction with the ontology logically lend themselves for implementation supported by information technology and artificial intelligence. This task is however outside the technical realm of the authors, which is why we here refrain from providing more than general ideas on how this might be facilitated through the concept of learning objects and object oriented programming (OOP). In Annex A we give an introduction to OOP and correspondingly provide a sketch for how a repository of digital learning objects might be structured in support of LP I – LP III.

6 Conclusions

In a sequence of three papers we have: i) assessed the need for developing the knowledge domain enveloping risk, resilience and sustainability as a unified scientific discipline in itself; ii) identified a knowledge basis for doing so through a large-scale bibliometric mapping of the state-of-the-art research; iii) established an information-theoretical basis facilitating this – and on this basis devised iv) a domain ontology; v) derived educational requirements; and finally vi) proposed a blueprint for the planning of educational activities.

The motivation underlying our endeavors is the observation that risk-informed decision making across the range of societal contexts fails to exploit its potential. There is a substantial gap between the aggregated collective knowledge available within different application domains, natural, social, human and technical sciences - and decision making in practice.

With the development of risk, resilience and sustainability as a science in itself – spanned by the conceptual system forming the ontology – we believe that the basis for societal decision making, which ultimately supports management of risks, resilience and sustainability, may be substantially enhanced – and the gap between knowledge and action significantly reduced.

The present paper, Part III of the triad, provides the philosophical background, the logic and the methodology behind the design of the blueprint, the identification of educational requirements and the blueprint itself. Moreover, in the present paper we also illustrate how the blueprint may be utilized for the principal design of educational activities at the level of programs, modules and individual PBL projects.

The blueprint is designed such that it may be applied generically, i.e. in principle in any context of governance of risk, resilience and sustainability. However, depending on the context of the decision problem, the ontology and the blueprint support the identification of which concepts should be the focus of the educational activities such as to achieve fulfillment of the educational requirements. This identification is informed by utilization of the concept of misfits, i.e. discrepancies between present best practices in different contexts of applications and science domains and the knowledge, which is generally available across these.

Naturally, a blueprint for educational activities should ideally be universal. However, since fundamental differences prevail among the cultures comprising the global population, this ambition is associated with significant challenges. In the design of the ontology and the blueprint however, we have made a serious attempt to address such differences with a view to especially the dualities, which are explicitly addressed in Chinese philosophy and culture. To this end, dualities are represented in terms of categorical pairs, introduced and utilized explicitly to direct the attention towards the stress fields that span within or between concepts.

In opposition to traditional approaches, it should be underlined that the proposed ontology and blueprint support wayfinding rather than navigation – which within the framework of Bayesian reasoning has an equivalent to adaptive decision making in pursuit of maximizing the value of information. Moreover, wayfinding as an objective – learning how to learn – underlies modern concepts and approaches to e.g. Problem Based Learning and Conceive Design, Implement and Operate (CDIO).

Whereas the developed ontology and blueprint can be applied as they stand – as support for the planning and operation of educational activities – they further lend themselves for supporting the design and implementation of digital learning tools and platforms. This task is however beyond the technical expertise of the authors, which is why we here refrain from providing more than general ideas on how this might be facilitated. To this end, digital learning objects technology supported by object oriented programming appears to offer a rather interesting avenue for further developments. In Annex A to this paper a sketch on how such a digital platform might be structured is provided.

Finally, it is with humbleness that we hereby close the triad of papers. We truly appreciate that our pursuit to establish the knowledge domain of risk, resilience and sustainability as a unified scientific discipline in support of governance and for the development and preservation of the associated body of knowledge is indeed very ambitious – and also rather non-trivial. The material presented in the triad should thus be considered only a first attempt, which surely deserves further detailing, amendments and clarifications. However, we do believe and hope that the present novel contribution in this direction will provide a solid foothold in the quest of achieving informed preferences in the manifold contexts of societal decision making in the face of uncertainty.

Acknowledgements

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ANNEX A – On the development of a digital repository of learning objects

Learning Objects (LOs) are rooted in the epistemological framework of constructivist educational philosophy, which according to Duffy and Cunningham (1996), is based on two fundamental principles: (i) learning as an active process of constructing knowledge instead of passive acquisition of knowledge and (ii) the role of a teacher as a moderator, supporting knowledge construction instead of transferring (in the sense of communicating) established knowledge.

The idea of using LOs as elements of instructional design dates to the late 1990s, when digitally supported learning rapidly developed as an application area for digital technologies. However, the concept of LOs as self-contained units of data and functions can be traced to the birth of object-oriented programming in the 1960s. In Dahl and Nygaard (1966) these units are called 'objects' comprised of clusters of properties (data) and behavior, logics, functions, and methods (code). The salient feature of these objects is that they are sealed-off from any particular relational context and thus afford the possibility to be reused in multiple contexts.

In the knowledge domain of learning design, there are a number of definitions of a LO, most of which differ with regard to scale. In Wiley (2000) a broad definition of LO is given as: "any digital resource that can be reused to support learning". LOs have been compared to LEGO building blocks because of their potential to be assembled and recombined in infinite number of forms. Wiley (2000) challenges the LEGO metaphor by substituting it with an atom metaphor, pointing out that not every atom is compatible with any other atom. The role of a teacher-designer to guide the choice and assembly of knowledge bits is therefore seen as essential.

We see no necessary conflict between the LO as a LEGO block and the LO as an atom metaphors. In our view they have complimentary affordances: wayfinding and navigation as befitting the context. Where our knowledge maps consist of large terra incognitas, a wayfinding strategy of free play LEGO may be more appropriate. Beginner students might be more comfortable to put their trust in an expert-guided knowledge acquisition. Advanced students might be more comfortable with explorative and independent learning. Whether the users (teachers and students) decide on a wayfinding or navigation strategy is not controllable directly by the design.

Technical specifications and standards for LOs are developed within the working groups of the Advanced Distributed Learning Network (ADLNet), IMS and IEEE LTSC P1484.12. These standards relate to the durability, inter-operability, accessibility, reusability, discoverability, extensibility, affordability, and manageability of LOs. Since our design is at the stage of concept rather than product development, we limit the discussion of technical specifications to those aspects that affect the content of LOs. This is captured in the relationship between granularity (the size of an LO) and its potential for reuse. At the small end of the spectrum, an LO is simply raw media such as an image, a graph, an audio/video file; at the large end of the spectrum, an LO could encapsulate a whole lesson, course, indeed an entire curriculum. Clearly, reusability of the LO is highest for small LOs and becomes progressively lower for larger LOs. Since our objective is to provide a cohesive structuring for the knowledge domain of risk-resilience-sustainability (no matter how wide this domain may be), our LOs must be of a size that is meaningfully attached to the context of the domain and not just an assemblage of decontextualized media files. We are also not interested in creating a fully digitalized curriculum for distance learning, but rather a *digitally-supported* hybrid learning environment. In this hybrid environment our digital LOs function as supporting resources to, e.g. teachers who want to replace the traditional lecture format of instruction with a "flipped classroom" approach, whereby the communication of knowledge is digitally supported through the LOs and not bound to a physical classroom location. The benefit of a "flipped classroom" approach is that it frees face time for teacher-student physical or virtual interaction, which can be used for the more creative aspects of knowledge construction such as dialogue, group and project work. Knowledge acquisition of concepts, theories and methods is in contrast declarative knowledge, which is typically presented in lectures, where learners are passively present.

As a supporting resource for students, a repository of LOs provides a compressed structure of foundational information on concepts and their possible relations relevant for the knowledge domain. For novices, they also provide a short-cut in the weeding of irrelevant information available on general search engines (e.g. google) or outdated vs state-of-the-art information contained in vast digital libraries (e.g. Web of Science, Scopus, etc.). As will be shown, the use of bibliometric techniques is a design feature of the proposed digital repository, enabling searching, retrieving, storing, verifying, and visualizing information – an essential skill in the pragmatic set of skills we associate with a specialization in risk-resilience-sustainability governance.

We suggest that the size of a LO should correspond to the smallest element in the ontology, namely the concept. In Section 4 of the present paper we have illustrated the diversity of disciplinary knowledge required to have an understanding of even a single concept in the ontology and how to have knowledge of the range of uses of a concept, one must be aware of the multiple source domains that compete for entering a concept's definition.

The inter-dependencies among concepts and their source and target domains points to a potential for high reusability of the LOs in inter-contextual problem/project settings, i.e. for different decision contexts within the full range of the knowledge domain. For example, if we look at Fig. 12 which shows a possible learning pathway for a full module, we see that concept cluster 5 appears in relation to the notion of 'Vulnerability', situated in the frame associated with theories, methods and metrics for risk analysis. Concept cluster 5 appears also twice in the resilience assessment frame under 'Governance' and under 'Hazard System'; and it appears in the enveloping frame of decision analysis. Given the breadth of knowledge necessary to cover all these areas, it is likely that different teachers, with different backgrounds will have to be involved in coordinating the structure and content of a syllabus for such a module. The LOs of concept cluster 5 will therefore come to be reused for different problem settings, providing efficiency in planning educational activities and efficacy in understanding a concept's broad range of meanings.

In Fig. 1A an interface for a LO is proposed, based on the concept 'Social cohesion'. Each LO has 7 component parts listed and described in Table 1A.

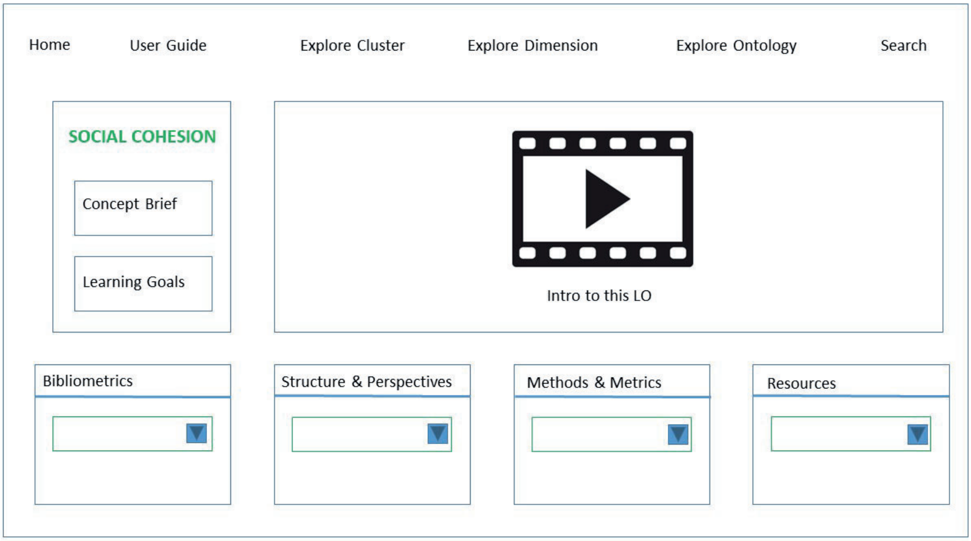

Fig. 1A Proposed interface for a Learning Object (LO).

Table 1A Generic components of a learning object (LO).

LO component	Description of content	Media
Intro to this LO	Short introduction to LOs content	Video
Concept Brief	An encyclopedic summary of the concept	Text file
Learning Goals	The relation of concept cluster where the LO appears to research and education misfits and educational requirements	Hyperbolic graph
Bibliometrics	3 drop down sub-components: (i) 3 interactive bibliometric maps of the concept in network, overlay and density modes of visualization which the student can explore alone (ii) Video presentation by the teacher or content author of the LO, explaining the above maps' topography (iii) Bibliometric visualization exercise focusing on updating the presented maps or using different filters for the search and clustering to generate different scales	(i) interactive image (can be scaled to show particular regions of the map in detail) (ii) video and transcript text file (iii)text files with instructions for data extractions from database and use of particular software for bibliometric visualization
Structure & Perspectives	3 drop down sub-components: (i) Evolution of the concept from an etymological, historical and philosophy of science perspectives (ii) Concept structure: presentation of the concept through its constituent components and a semantic-pragmatic mapping of the concepts family relations (iii) Explanation of why and how the concept relates to the risk-resilience-sustainability knowledge domain	Animated PPT/Video with transcript
Methods & Metrics	Catalog of methods and metrics used to analyze/measure the concept	Animated PPT
Resources	Links to relevant scientific articles, conference papers, books, textbooks, audio-video files, image files, etc.	Multi-media

Fig. 2A shows how a learner following LP III described in Section 5 will hypothetically have navigated the LO repository in his or hers particular problem setting.

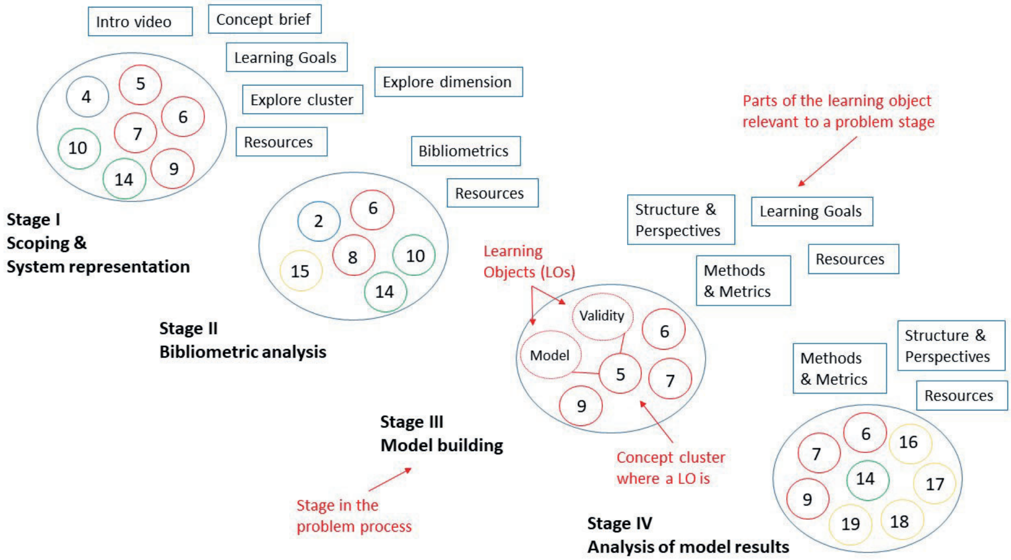

Fig. 2A LP III supported by a repository of digital learning objects.

Navigation of the repository could be designed as a hyperbolic graph that shows the student where he or she is presently located in relation to LOs in the immediate cluster as well as to the larger compounds of dimension and whole domain (Fig. 3A).

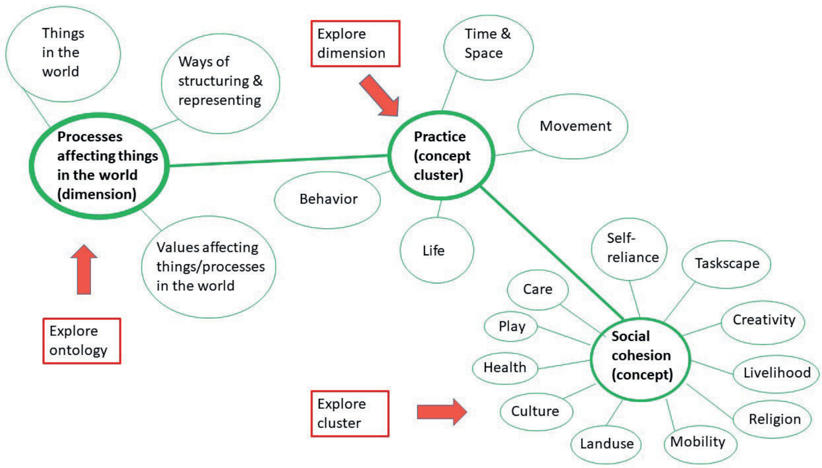

Fig. 3A Inter-LOs navigation options.

The search navigation necessitates that each LO is tagged with a set of keywords other than the concept name itself, so that the LO repository can be searched in accordance to specific problem situations. For example, if a learning activity is centered on e.g. the Life Quality Index – a quantitative measure of welfare, a student who wants to explore the conceptual schema and the family relations of the LQI, by searching LQI in the repository should be able to derive a set of relevant concepts-LOs to support his/her understanding of the LQI. Hence, all LOs, where LQI is mentioned, must be indexed accordingly by means of keywords.

We envisage the development of this repository as a trans-disciplinary and international endeavor, whereby the leading researchers are identified to co-produce the content for a given concept cluster according to state-of-the-art theoretical knowledge and practical application.

CHAPTER 6. FLOOD RISK AND INDICATORS OF SOCIAL COHESION IN THE WESTERN BALKANS

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FLOOD RISK AND INDICATORS OF SOCIAL COHESION IN THE WESTERN BALKANS

Abstract: The study investigates a hypothetical relation between social cohesion and a major flood event affecting parts of the Western Balkans region. Using state-of-the-art bibliometric techniques, we show the historical evolution of research on social cohesion and disasters, its multi-disciplinary composition resulting in competing definitions of what constitutes social cohesion as well as the relations among the different knowledge domains in the form of network cluster maps. We use the maps as the basis for objectively selecting variables representing social cohesion constituents and relevant control variables. We find that despite the high uncertainties associated with the quantity and quality of the data set, a linear relationship between social cohesion and disaster response does indeed exist as an empirical phenomenon. We discuss implications of the results with regard to a possible trade-off between the individual and collective dimensions of social cohesion and how complementing the model results with a cultural analysis based on grid-group theory could facilitate policies on social cohesion, which are in tune with cultural preferences for systems of governance.

Key words: community resilience, disaster risk management, social cohesion

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1. INTRODUCTION

The present research is conducted as part of the EU Erasmus project Knowledge for Resilient Society (K-FORCE) wherein a consortium of universities from the Western Balkans, two central European universities and three Scandinavian universities are working together to exchange and build new knowledge in the area of resilience and disaster risk management, with particular focus on educational activities. The Western Balkan countries have a leading role in the project as they are the primary beneficiaries of the outcomes. The role of Aalborg University as a partner is to faciliatate the knowledge exchange process and build awareness of frameworks, methodologies and best practice as well as provide learning-teaching materials, relevant learning strategies and platforms to deliver them. In what foolows the preliminary results are presented on a hypothetical correlation between flood disaster response and social cohesion. The primary aim of the study is to enhance awareness of the concept of social cohesion and its relation to natural hazards among disaster management academic audiences of students, teachers and researchers.

At the onset of the K-FORCE project, it became evident that many of the Western Balkan partners perceive resilience to natural hazards from two main perspectives: disaster insurance and structural protection measures. Both education and practical work related to disaster risk management thus comes mainly from the knowledge domains of Civil Engineering and partly from Economics and actuary practice. A concept such as social cohesion and how it might relate disaster response is poorly understood. We take our study as the starting point in building educational material around this hypothetical relationship by looking at the historical evolution of research on social cohesion, competing definitions and perspectives from the different knowledge fields where it has been applied, and ways to measure the effect of social cohesion on disaster recovery.

From a research point of view a study of the dynamics of social cohesion and natural hazards in the Western Balkans is both theoretically and methodologically challenging and complex. In terms of physical exposure, the region as a whole is exposed to a number of natural hazards from floods to landslides and mass movements to earthquakes. One hazard can trigger other ones (e.g. floods and earthquakes can trigger landslides and other mass movements). Upstream and downstream consequences often transcend the national boundaries of these very small nation states. In addition, due to regional climate change predictions, the Western Balkans are expected to become increasingly vulnerable to both extreme temperatures and floods (IPCC 2014).

In terms of societaly related challenges, the Western Balkans‘ coping capacities are influenced by the success of transitioning from planned to market economies and from totalitarian to democratic systems of governance. The social complexity as a result of historical, political and cultural dynamics, including a series of violent conflicts, has given birth to the term „balkanized“ to describe systems or processes that are disjointed or disunited – in effect, the very opposite of social cohesion. Yet at the same time, the region and its individual constituents can be characterized by many of the ingredients considered necessary for social cohesion as expressed in terms of informal individual relations or social capital, e.g. strong informal relations among family and friends, largely homogeneous cultures and shared values. These contradictory dynamics between individual-individual relations and individual-group relations make the Western Balkans a uniquely intersting case study in defining, measuring and analyzing social cohesion.

Following the introduction in section one, section two outlines the methodology and decsribes the data used to populate the subsequent linear multiple regression model. In section three the results of a bibliometric analysis of the scientific literature on social cohesion are presented, including the historical evolution of research, the multi-disciplinary composition of the research and the relations among the different knowledge domains in the form of a keyword co-occurrence analysis. In section four we take basis in the network representation of the co-occurrence analysis to justify the selection of variables chosen to measure the correlation between social cohesion and disaster response. In section five the results of the regression analysis for four Western Balkan countries, together with a sensitivity analysis for each individual country are presented and discussed. Section six draws preliminary conclusions about the model’s validity and some implications for future research.

2. METHODOLOGY AND DATA

The present study uses mixed methods research design, combining state-of-the-art bibliometric techniques and linear multiple regression analysis.

While the phenomenon of social cohesion is so old as to be considered part of human nature by thinkers as early as Aristotle[1], the term social cohesion itself has only in the past three decades been used by a small number of academics and a somewhat larger body of policy analysts to describe the ephemeral quality of social systems that keeps a system's integrity, preventing its physical tendency toward disintegration, chaos and collapse. Social cohesion and resilience of social systems are intimately related concepts. Both have been subject to much academic speculation on how to define them, what constitutes them, what causes them, what consequences ensue as a result of their presence or absence, and what indicators best capture their dynamics.

A comprehensive literature review is provided by Schiefer and van der Noll (2016) who trace the conceptual development of social cohesion from liberal political philosophy in 17th century Britain, which saw social cohesion as a natural result of collective willingness to cooperate and exchange goods in order to satisfy individual interests to French 19th century functionalism, particularly Durkheim's idea of solidarity based on shared loyalty and mutual interests, to late 18th century German romanticism, based on biological metaphors of organicism, where individuals and society form one holistic organic body, to contemporary formulations stemming from the social policy domain, addressing social cohesion from a plethora of applied policy areas such as security, integration, welfare, etc. As the purpose of this study is to quantitatively assess a possible correlation between social cohesion and disaster response, we do not strive to provide a comprehensive definition of social cohesion nor to explain how it relates to semantically similar concepts such as social capital or solidarity. Instead, we focus on providing an experimental operational definition, which we base on a selection of variables we derive from a bibliometric cluster analysis.

In Schiefer and van der Noll (2016) no mention is made of grid-group cultural theory developed by anthropologist Mary Douglas (1970, 1978), which we consider a serious omission in the body of research on social cohesion over the past 30 years. The only direct reference to Douglas' cultural theory in the context of social cohesion we found in Melton (2003) who tests the validity of selected questions from the World Values Survey as indicators of the grid-group. An operational definition of social cohesion developed by Chan et al. (2006), however, bears a strong indirect reference to Douglas' functionalist methodology as a whole and to her grid-group model in particular. There social cohesion is defined as "a state of affairs concerning both the vertical and the horizontal interactions among members of society as characterized by a set of attitudes and norms that includes trust, a sense of belonging and the willingness to participate and help, as well as their behavioural manifestations."

In our study, we come close to the operational definition of Chan et al. (2006) whereby we distinguish between perceived and observed elements of social cohesion, which apply to both relations between individuals in society and relations between individuals and institutions (what Chan et al. label 'horizontal' and 'vertical' respectively). Like Chan et al. we exclude a number of socio-economic conditions from our definition as we see those as causes and consequences, not essences of social cohesion. However, we argue for their inclusion as control variables as we believe they provide an opportunity for a more nuanced analysis, where situational factors may significantly impact the model results. In section 6 we suggest that Douglas' group-grid scheme might be an appropriate complement to the regression model as a way to achieve a culturally nuanced comparison of the four countries under consideration, wich would in turn facilitate social cohesion policy tailored to the preferences for social organization of individual countries.

Our selection of social cohesion variables is further aided by a keyword co-occurrence analysis of the literature on social cohesion. A keyword co-occurrence analysis is a statistical datamining method. The relatedness of items is determined based on the number of documents in which they occur together. We used the VOSviewer software to construct keyword maps of the 6000+ records we extracted from the Web of Science on the topic of social cohesion. The methodology is described in detail in Van Eck and Waltman (2017).

To analyze the correlation between the selected social cohesion variables and a major flood event affecting the Balkans region in 2014, we adapted a multiple linear regression model from a study by Calo-Blanco et al. (2017) on social cohesion and earthquake disaster response in Chile, which is the only other study we are aware of that attempts to quantify the dynamics between social cohesion and disaster response, using at least partially objective indicators.

Data for the model was collected from sources listed in Table 2. The availability, quantity and quality of the data differs considerably among the countries as well as among the different variables. Most of the data pertains to perceived elements of social cohesion, collected through stated preference type of surveys. Observed elements of social cohesion could be found in data of the revealed preference type, of which only data on marriage, divorce and reported intentional homicide could be collected. A significant omission in our model is therefore data related to observed social-institutional relations

[1] For a discussion of Aristotle's designation of man as social/political animal (πολιτικὸν ζῷον) as a way to distinguish between membership in civic society and social institutions vs private sphere membership such as a family household, see Mulgan (1974).

such as actual participation in civil society and public decision-making. Further lacking is data on the individual dimension of suicide.

3. BIBLIOMETRIC ANALYSIS OF SOCIAL COHESION

3.1. Evolution and disciplinary distribution of research

The birth of the concept of social cohesion can be traced to the early 1990s. The evolution of research over the past 3 decades shows that while interest in social cohesion has progressively increased in the last 10 years, the concept is still a rather marginal subset of the broader concept of social capital (Fig.1). In our literature review we found that in academic publications social capital and social cohesion are for the most part distinguished. The former concerns only relations between individuals; the latter encapsulates the collective relations between individuals and social institutions additionally. In the policy-oriented literature on social cohesion the distinction is rarely made. The total number of records for social capital from 1900 onwards is about 23,000, more than 95% of which were published during the last 3 decades. Social cohesion records come to around 6000 for the same period.

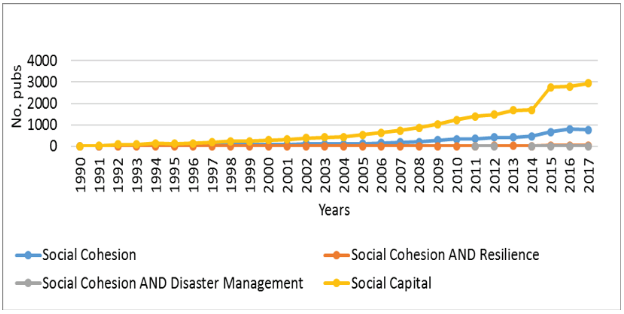

Figure 1- Evolution of research on social cohesion 1990-present

Even more marginal is research on social cohesion, which focuses on combing disaster risk and resilience, with a total number of records just over 100, mostly published in the last several years.

Social cohesion is a budding area of academic inquiry that has spurred interest from a number of different academic domains. In Fig. 2 it can be seen that social cohesion is studied in different application areas and from a number of different disciplinary perspectives. The two dominating knowledge areas are Psychology and Sociology and Social Sciences. Psychology research on social cohesion focuses primarily on the individual, while Sociology, Anthropology and Political Science study social cohesion from the collective perspective of social groups or society as a whole. The Social Sciences produce mostly theoretical research, whereas research in the areas of Psychology, Public & Environmental Health, Business and Government and Law tend to be more problem-oriented and focus on empirical research.

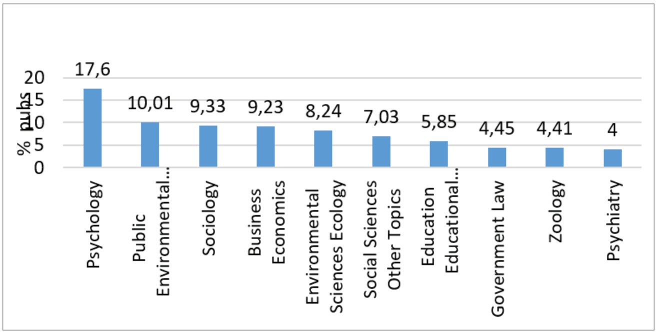

Figure 2- Social Cohesion Top 10 contributing research areas

3.2. Keyword co-occurrence analysis of social cohesion

As a qualitative literature review yielded a large number of contradicting definitions of social cohesion, largely stemming from different disciplinary camps, we used a quantitative data mining technique, namely keyword co-occurrence analysis, to attempt to strip some of the subjectivity and polemicism from the debate what constitutes social cohesion. In Fig. 3 the results based on the 6000+ records extracted from the Web of Science is visualized as network composed of keywords and links. The larger the circle, the more frequent the keyword occurrence. Links are connections or relations between two keywords. The stronger the link, the thicker the line. Keywords are also grouped together into clusters. A cluster represents a set of keywords strongly linked together.

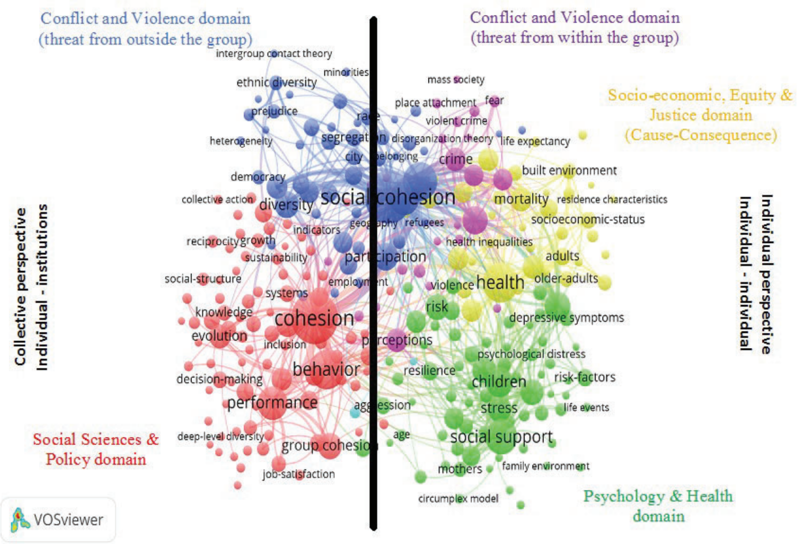

Figure 3 - Network visualization of social cohesion 1990-present

The five clusters in this network correspond to the dominant disciplinary perspectives on social cohesion. The red cluster contains items pertaining to the Social Sciences and Policy domains. Here dominant elements are behavior and performance, decision-making, systems, social structure, diversity, and elements such as reciprocity, collective action, and sustainability. This cluster is clearly about collective rather than individual relations and behavior.

The blue and pink clusters are about social cohesion from the perspective of conflict and violence. We believe that we see a difference between them in that the blue is more oriented toward collective threat by outsiders of a group while the pink represents more an individual level of violent crime from within a group.

The yellow cluster is what we call the “cause-consequence” cluster where we see different socio-economic and demographic indicators, such as life expectancy, inequality, health, age, etc. They may be individual or aggregate but we argue that they are conditions for or results of social cohesion rather than essential elements of social cohesion.

Finally, the green cluster is clearly the domain of psychology, family and health and represents exclusively the individual dimension.

3.3. Keyword co-occurrence analysis of social cohesion in the context of disaster risk management

While the co-occurrence analysis of social cohesion helped to narrow down some elements we could consider in defining and measuring social cohesion, it was too broad for the problem context, namely the link between social cohesion and disaster response. A second co-occurrence analysis based on the 100+ records combining social cohesion and disaster in the titles and abstracts facilitated a further comparison between the broader and narrower terms (Fig. 4)

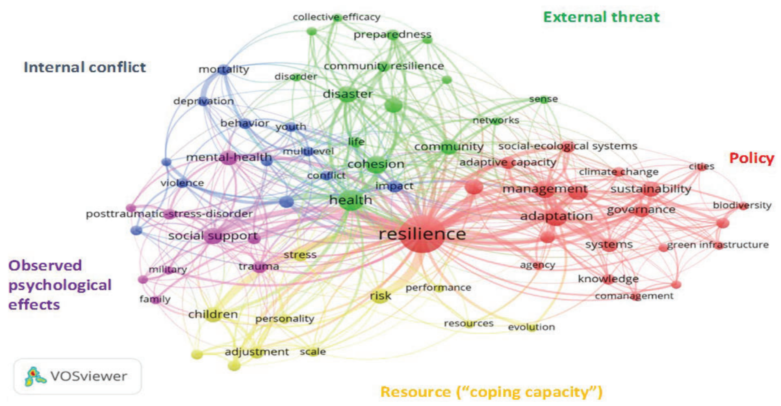

Figure 4 - Network visualization of social cohesion in the context of disaster risk management 2000s – present

In this network visualization there are 5 clusters again. The dominant one is the red one, which represents more or less the Policy domain, only here Social Science has been replaced by Environmental and Ecological Sciences, e.g. adaptation, adaptive capacity, social-ecological systems, biodiversity, green infrastructure, systems, etc.

The green cluster is clearly the external threat cluster, in this case pertaining to the natural hazards domain. The blue is internal conflict and violence probably more linked to socio-economic conditions, e.g. deprivation and mortality. It merges together with the pink cluster of observed psychological effects of social break down on the individual level such as trauma, post-traumatic stress, mental health. We could ascertain here relation to suicide, the available statistical data for which is very poor or non-existent.

The yellow cluster is the „resource" cluster of psychology and health at the individual level, which we label „coping capacity".

4. SELECTED VARIABLES

Based on the qualitative literature review and the bibliometric analyses, we selected a number of variables, for the subsequent regression analysis. The variables are divided into three types: flood exposure variables, social cohesion variables and control variables.

The flood variables relate to a major, so-called 100-year flood event that occurred in May 2014 and severely affected two of the countries in the region – Serbia and Bosnia and Herzegovina – for the purpose of determining variations in the social cohesion outputs before and after this event. Albania and Macedonia were not affected by this flood event. We are further interested in comparing variations in the variables we have chosen to represent the state of social cohesion between the affected and unaffected countries in the region (Table 1). According to an impact and needs assessment report of the Serbian government, prepared under the guidance of European Union, the United Nations and World Bank, the highest impact of the disaster was in terms of production and access to social services (1,312 million EUR or 86% of the total) while infrastructure damages amounted to 192 million EUR or 12% of the total). Economic consequences of the disaster were predicted to include decline in real economic growth, worsening of the current account of the balance of payments and a decline in the fiscal position as a result of lower tax revenues and higher expenditures for recovery and reconstruction. Social consequences were predicted to include temporary loss of employment and a decline in the country's HDI score due to GNI decline and limited access to education and health services. All socio-economic impacts were expected to have higher effect on the poor, ethnic Roma, women, and disabled persons.

In a similar needs assessment report prepared by the government of Bosnia and Herzegovina and the guidance of the international organizations listed above, the event was estimated to have caused the equivalent of nearly 15% of GDP in damages (9.3% of GDP) and losses (5.6%), amounting to 2.04 billion EUR. The report refers to the event as the most serious natural disaster experienced by the country in the past 120 years, affecting approximately one million people of the total 3.8 million population and in particular, families, small, medium and large businesses, agricultural producers, and an undefined number of vulnerable sectors of the population.

Table 1- Exposure variables

Exposure Variables	Note
POSTt	1 if t>=2015 (the occurrence of the major flood event in 2014); otherwise, = 0
Influ by Flood2014	if the country is influenced by the major flood event in 2014, it will be 1 for t>=2014; otherwise, = 0
POSTt x Influ by Flood2014	interaction between the above two variables

To represent the multi-facetted concept of social cohesion, the social cohesion variables (the model's outputs) are grouped into three thematic domains: (i) Trust and Social Relations, (ii) Altruistic Behavior and (iii) Compliance (Table 2). In our classification, we further distinguish between factors positively or negatively influencing social cohesion as well as whether a variable measures perceived or observed behavior.

Table 2 - Social cohesion variables

Dimension	Social Cohesion Variable	Note	Pos (+)/ Neg (-)	Individual (I)/ Collective (C)	Perceived (P)/ Observed (O)
Trust and Social Relations	Trust in Fellow Citizens	"Generally speaking, would you say that most people can be trusted or that you need to be very careful in dealing with people?" (V23/V25 World Values Survey)	+	I	P
	Government Effectiveness	Perceptions of the quality of public services, the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies. (World Bank - Worldwide Governance Indicators)	+	C	P
	Marriage	Crude Marriage rate per 1000 population (Eurostat)	+	I	O
	Divorce	Crude Divorce rate per 1000 population (Eurostat)	-	I	O
Altruistic Behavior	Giving Money	A composite country score for charity based on data from Gallup's WorldView World Poll. The survey question is "Have you donated money to an organization in the past three months?" Incl. political parties/organisations as well as registered charities, community organisations, and places of worship. (World Giving	+	C	P

		Index)			
	Volunteering Time	Same as above. The survey question is: "Have you volunteered time to an organization in the past three months?"	+	C	P
	Helping a Stranger	Same as above. The survey question is: "Have you helped a stranger or someone you didn't know in the past three months?"	+	I	P
Compliance	Rule of Law	Perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence. (World Bank - Worldwide Governance Indicators)	+	C	P
	Corruption	Perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests. (World Bank - Worldwide Governance Indicators)	-	C	P
	Crime	Intentional homicides per 100,000 people (World Bank – World Development Indicators)	-	I	O

The socio-economic and demographic conditions relevant for social cohesion have been included as control variables (Table 3). In here, variables related to health, wealth and inequality as identified in the bibliometric analysis are deemed to be causes and/or consequences of the presence or absence of social cohesion. They are implicit in the HDI and Gini country scores. Variations in the Gini could be taken as a proxy indicator on the grid axis of the cultural grid-group model, which represents a range of societal acceptance for social assymetry of roles and the degree of hierarchy in a given society. The HDI we believe is a proxy indicator for quality of life in that it aggregates economic purchasing power, health and education. The majority of models measuring social cohesion include quality of life or life satisfaction as an indicator of social cohesion. We take a position that it can be both a cause and a consequence but it is not a necessary condition for social cohesion.

Unemployment is a widely accepted cause of social unrest and breakdown. Particularly interesting in terms of the interplay between the individual and collective dimesnions of social cohesion is informal employment or shadow economy, which is alledgedly very high in the Balkans region. While informal employment may be said to undermine community resilience in that it hinders socio-political institutions to accumulate resources that may be distributed as relief and reconstruction efforts after a disaster event, informal employment may also be seen as a proxy indicator for social cohesion on the individual scale of informal relations between individuals, which are important in determining co-operative and altruistic behavior that fosters community resilience. Ineffective governance and corruption decrease trust in institutions and people's willingness to contribute to public goods in the form of taxes. These potential contributions remain or are exchanged in an informal way between individuals, which strengthens the individual dimension of social cohesion while at the same time weakening the collective. If a hypothetical society is culturally prone to be low grid and low group, i.e. place value on individualism and freedom expressed negatively as freedom from control, it will show a political preference for social structure where the individual, not the collective institution is the dominant actor. By contrast, a high grid high group society will seek to convince its members that absolute institutional control is necessary to ensure the availability of equal public goods.

Table 3- Control variables

Control Variables	Note
Gini	Gini index measures the extent to which the distribution of income (or, in some cases, consumption expenditure) among individuals or households within an economy deviates from a perfectly equal distribution. A Gini index of 0 represents perfect equality, while an index of 100 implies perfect inequality. (World Bank)
HDI	The Human Development Index (HDI) is a summary measure of achievements in three key dimensions of human development: a long and healthy life, access to knowledge and a decent standard of living. The HDI is the geometric mean of normalized indices for each of the three dimensions. Data inputs for the HDI index include: Life expectancy at birth, Expected and mean years of schooling, and GNI per capita. (UNDP)
Unemployment	Unemployment (age 15+) per 1000 persons, 1 year period average (SEE Jobs Gateway database, based on data provided by national statistical offices and Eurostat)
Informal Employment	Informal employment as a percentage of total employment. Data on informality are collected by the labor force surveys of Albania, the FYR Macedonia, and Serbia only; no data is available on Bosnia and Herzegovina. All countries use the comprehensive International Labor Organization (ILO) definition for informal employment, covering (1) Self-employed in unregistered businesses, (2) Wage workers without written contract and, (3) Unpaid family workers. (SEE Jobs Gateway database, based on data provided by national statistical offices and Eurostat)

5. REGRESSION ANALYSIS RESULTS AND DISCUSSION

We build on the work of Calo-Blanco et al. (2017) who conducted a similar study of social cohesion and earthquake disaster recovery in Chile. While in principle the same regression model, the exposure, social cohesion and control variables were changed to fit both the different type of natural hazard and the different socio-cultural elements relevant for the Balkans region. Our model is written as:

$$\gamma_{ct} = \alpha + \beta_1 POST_t + \beta_2 \text{Influ by Flood } 2014_c + \beta_3 \, POST_t \text{ x Flood } 2014_c + \gamma X_{ct} + \varepsilon_{ct}$$

where,

y_{ct} is an indicator of social cohesion in a country c at time t

β_1 -shows the average increase or decrease in the indicator between the period before and after the 2014 event for the unaffected countries

β_2 shows the difference between affected and unaffected countries before the 2014 event

β_3 shows the average difference in the evolution of the indicator between affected and unaffected countries from before the event to after the event

γXct is a vector of control variables

α represents regional fixed effects

ε_{ct} represents an error term

Our main interest lies in the parameter β3 which estimates the average difference in the evolution of the indicator between affected and unaffected countries from before the event to after the event.

Typically, the two important values to consider are the R-square value and the p-values. The R-square value expresses how much variation is explained by the model. The greater R-square value indicates high correlation and a good model fit. The p-value is an expression of the statistical significance. If the p-value is less than the significance level (0.05) then the model fits the data well. In general, the best scenario is a combination of high R-square and low p-value. However, due to the very limited data we were able to obtain (7 or 8 observations per variable, and in the case of some variables the data was statistically interpolated), the 0.05 p-value cut off criteria cannot be justified in our model. We focus therefore on comparing the R-square values, which give us a good preliminary indication of the relevance of our hypothesis, namely that a linear correlation exists between social cohesion and disaster response while keeping in mind the uncertainties associated with the correlation values. In Fig. 5 the solid lines represent the R-squared values or the regression; the punctuated lines show the p-values, or the uncertainties of the model. The higher the correlation of a given variable, the closer the uninterrupted line is to the outer boundary of the spider diagram. The higher the uncertainty associated with a particular variable, the larger the surface of the punctuated lines. The best fit for a variable, i.e. high correlation with small uncertainty is therefore a combination of a solid line value residing on the outer boundary and a punctuated line value residing closest to the center. For Bosnia and Herzegovina no data could be collected for the variables Marriage and Divorce.

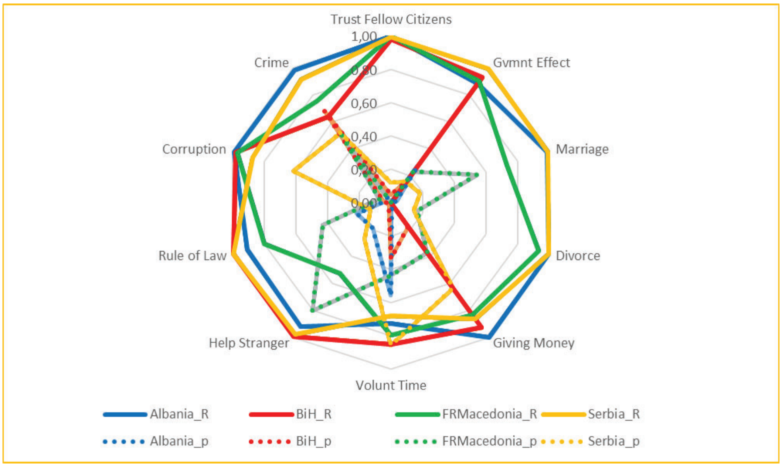

Figure 5 – Comparative correlation results for Albania, BiH, FR Macedonia, and Serbia

While most variables show high correlation irrespective of country, the uncertainty associated with the results is smaller in the case of Albania and Bosnia and Herzegovina and significantly larger for the FR Macedonia and Serbia. To compare, the results between the two countries affected in the 2014 flood event – Bosnia and Herzegovina and the two that were unaffected – Albania and the FR Macedonia we compare the values of the root mean squared error (RMSE) of the regression, which express the average model prediction error. RMSE ranges from 0 to ∞, where a lower value indicates a better model prediction. Fig. 6 shows that the two unaffected countries show an almost perfect fit to the data, while the affected ones show less certain results.

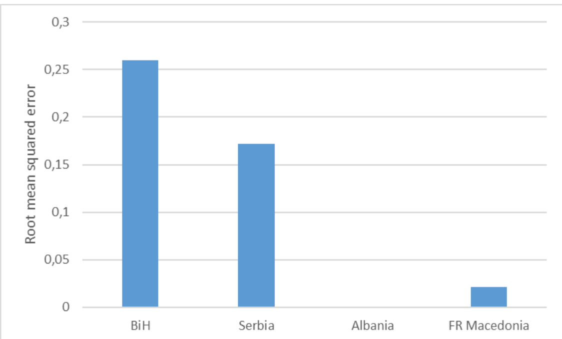

Figure 6 – Comparative root mean squared error results for the affected and unaffected countries

The choice of control variables when dealing with social phenomena is very subjective. A dependency among the control variables could result in multicollinearity, which in turn can invalidate the model prediction of how well each independent variable can be used to describe changes in the dependent variable. In our case, there might be linear relation between HDI and Gini or between the variables representing the flood events. However, our goal is to be sure whether there is a multiple linear relation between the social cohesion variables and the explanatory exposure and control variables. The high R-square values indicate that the relation is strong, so we can conclude that the linear relation is valid.

In the social sciences a principal component analysis (PCA) is typically performed to identify the principal, i.e. most important components of the data. This is especially relevant for multiple regression with a large number of independent variables as the method helps to decide which less significant components can be eliminated and whether some of the omponents can be grouped together. PCA uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components. If there are n observations with p variables, then the number of distinct principal components is no larger than min(n-1,p) (Jolliffe and Cadima (2016). For our problem at hand, we do not have sufficient data points, e.g. in our case n and p are equal to 8 and 7 respectively, and in some instances we even rely on statistical data interpolation. For this reason we conclude that a principal component analysis is not of relevance for our case.

We turn instead to engineering reliability analysis, where a sensitivity analysis helps to identify the influence of change the value of an independent variable x (for our problem all exposure and control variables) has on the change of reliability y (for our problem - social cohesion) by calculating the value of the derivatives dy/dx (or $\partial y/\partial x$ for multi variable cases precisely). For our multiple linear model here, the value of $\partial y/\partial x$ for different independent variables x is the corresponding coefficient that was calculated. In Fig.7 the sensitivity results for the four countries are shown based on the standardized regression coefficients for each independent variable.

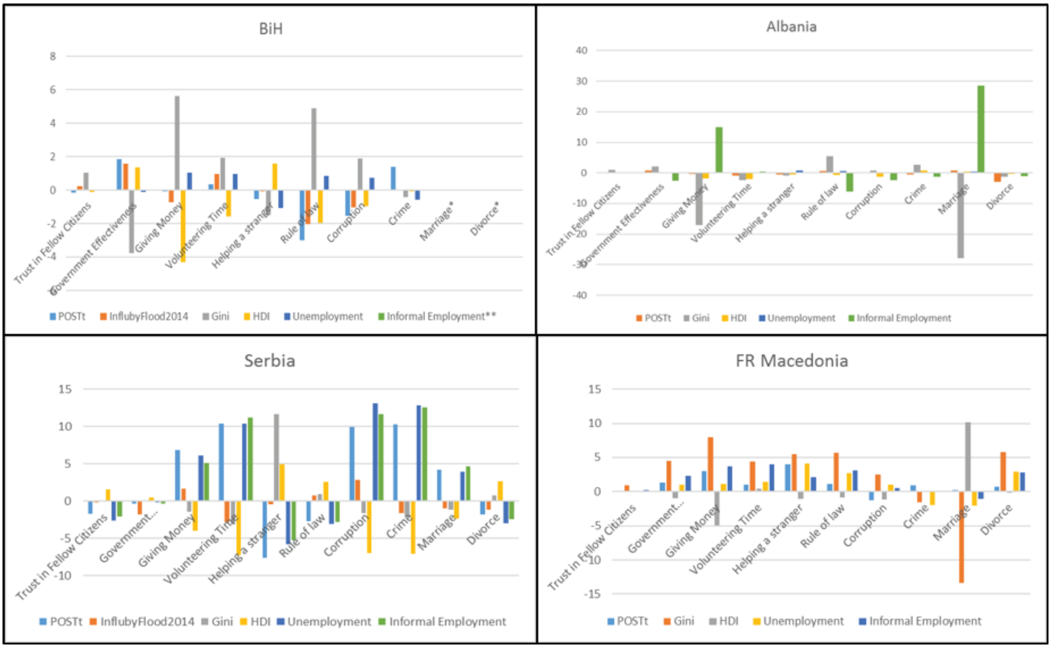

Figure 7 – Sensitivity results for Albania, BiH, FR Macedonia and Serbia

** No data could be obtained for Marriage and Divorce for Bosnia and Herzegovina*

*** No data could be obtained on Informal Employment for Bosnia and Herzegovina, however various grey literature sources estimate that its labor market is also characterized by a substantial informal economy. Estimates of its size vary between one third and one half of total employment. A report by the ILO (2009) based on a 2006 labor force survey, informal employment makes up around one third of all employment.*

The results of the sensitivity analysis appear similar for all the countries except Serbia. For Bosnia and Herzegovina the most significant variables are the Gini and the HDI; for Albania – Gini and Informal Employment; for the FR Macedonia – Gini and the HDI; for Serbia, the weight of all control variables as well as the exposure variable POSTt are similar and significant. In most cases, the absolute value of the coefficients of GINI is bigger than that of the others while Informal Employment has significantly higher values for Albania and Serbia. Potentially, this could be indicative of Bosnia and Herzegovina if we are able to support the qualitative information we obtained on informal employment in BiH from grey literature with a dataset. From the mathematical point of view, we propose that the multiple linear model describes the relation between the social cohesion and all independent variables (control and exposure), meaning that the model, itself, is formulated here independent of the occurrence of the flood events.

6. CONCLUSIONS AND FUTURE OUTLOOK

The goal of this study has been to investigate whether there is multiple linear relation between social cohesion and a major flood event affecting parts of the Western Balkans region. We find that despite the limited and often highly uncertain data, a linear relationship does indeed exist. While our model cannot be statistically verified with the present amount of observations, it nevertheless points to the fact that a hypothetical correlation between disaster response and social cohesion could be an empirical phenomenon of the world and not simply of the model. The need for a better data set on all the identified variables will be indispensable in the further calibration of the model.

The generally accepted 0.05 p-value as a criteria for the model's goodness of fit is in our problem context too strict to justify due to the high uncertainty in the data and also the insufficient number of the data points. We have therefore proposed other statistical measures to investigate the hypothesis: R-squared to test the preliminary indication of the relevance of our hypothesis; root mean squared error to compare the results for the affected vs the unaffected countries; and standardized regression coefficients for each independent variable as a sensitivity measure.

The differences in the value of the correlation coefficients across the countries as shown in the sensitivity analysis might further come from cultural or historical factors that are not captured in the variables we have selected. To examine such effects the functional grid-group model developed by anthropologist Mary Douglas in the 1970s could shed additional light on how homogeneous or heterogeneous the Western Balkans region is with regard to the dynamics of social cohesion in the aftermath of a natural hazard event. In the social sciences, functionalism is a theoretical perspective arising from the influence of the biological conceptualization of organisms as holistic systems, where the whole is greater than the sum of its parts. The first theory of social cohesion stemming from this perspective is Durkheim's theory of *organic solidarity* which is what makes a society maintain its internal stability over time, or in present days words, what makes a 'resilient society'. Functionalist methods rely on emprical data („social facts") to describe objective social conditions that influence human behavior at the macro scale of a collective or whole society. Douglas' grid-group models social organization on a two dimensional axis, where the vertical grid dimension is a measure of the degree of social hierarchy within a given society and the horizontal dimension is a measure of the group's cohesiveness, expressed as a degree of individual or group centeredness (Douglas 2007). While conducting a grid-group analysis is outside the scope of the present study, we believe that the model could be a relevant complement in the context of providing a culturally-nuanced policy advice because the relative position of a country on the grid-group axis will give an indication of the societal preference system for governance and whether this preference supports the collective institutional dimension exemplified by a system of strong state political and economic institutions or the individual dimesion exemplified by a system of private contracts and informal arrangements.

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CHAPTER 7. OBJECTIVES AND METRICS IN DECISION SUPPORT FOR URBAN RESILIENCE

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Objectives and Metrics in Decision Support for Urban Resilience

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ABSTRACT: A holistic framework for the representation of systems resilience in the context of decision support on societal developments at urban, national and global scales is presented with emphasis on the identification of objectives and corresponding metrics of systems resilience performances in the context of technical, social and environmental systems. The proposed framework facilitates for inclusion of specific policies and stakeholder interests that might be relevant as boundary conditions for the ranking of decision alternatives. The application of the proposed framework and metrics is illustrated through a principal example considering an interconnected system comprised by the subsystems infrastructure, governance and environment. It is shown how decision alternatives for the management of urban systems can be related to societal welfare and capacity to cope with disturbances in the long run and thereby facilitating a systems resilience optimization.

1. INTRODUCTION

The modeling and assessment of systems resilience has gained increased interest over the past 1-2 decades. Based on the foundational works by Pimm (1984) and Holling (1996) significant new ideas and developments have been identified and brought further in the quest of defining, understanding, modeling, and analyzing resilience of systems. Initially the concept of systems resilience, and the related research works, mostly addresses ecological or socio-ecological systems. In the recent decades, however, the research is targeting more directly the interconnected systems enveloping human welfare at local, community, regional and global scales, including in addition to socio-ecological systems, critical infrastructure and built environment systems.

Significant achievements have been made with respect to the understanding of how societal systems interact, how they may be exposed to and perform with respect to disturbances of different types and how they may be adequately designed and managed. There is however still, considerable way ahead before a fully holistic, consistent and applicable appreciation of systems resilience can be established. Challenges yet to overcome include the identification of robust frameworks and metrics for the representation of human welfare, which allows for an adequate consideration of important interrelations and dependencies between society, individuals, technology and the qualities of the environment.

In the present paper, we take up this challenge. Building upon a recent framework for resilience modeling and quantification (Faber et al. (2016) and Faber (2018)), the societal performance with respect to preparedness, response and recovery in case of disturbances is addressed in a novel long-term perspective of societal developments.

Section 2 starts out with a discussion on the role and adequacy of decision analysis in support of societal developments. Thereafter, in Section 3 objectives of resilience management and relevant metrics of systems performance characteristics are identified and outlined. In Section 4, a framework is presented and discussed which accounts for the identified objectives and metrics and supports decision making with respect to resilience management of systems at urban, national and global scales. Finally, the application of the framework is illustrated with a principal example in Section 5.

2. ON DECISION ANALYSIS FOR SOCIETY

Planning, implementing, measuring, directing, and adapting resilient societal developments at urban, national and global scales is generally appreciated to comprise decision problems subject to significant uncertainty. In the following, considering resilience at urban scales, resilience and sustainability is addressed jointly.

2.1. Decision analysis for resilient developments

As suggested in Faber et al. (2017) and Faber (2019), Bayesian decision analysis lends itself as a theoretical framework to support decisions in pursuit of resilient and sustainable developments. The formalism, as outlined in Fischhoff (2015), is relatively straight forward. Given that adequate models are available to i) represent the preferences of the decision maker through a utility function and ii) to select and map decision alternatives into expected value of utility, decision analysis is reduced to what could be termed an exercise of systematic and consistent information management. However, the tasks associated with i) and ii) are generally not trivial, for a range of reasons. One important reason is that the selection and mapping of decision alternatives onto expected value of utility necessitates a rather deep and specialized understanding of the context of the decision analysis, e.g. how technical systems perform individually, interact mutually as well as how they perform jointly with socio-ecological systems.

In practical applications of decision analysis indeed much emphasis is directed on these aspects. However, Fischhoff (2015) concludes by underlining that the tasks associated with i) are absolutely key for the usefulness of decision analysis as a means for decision support. The representation of the preferences of the decision maker and their mapping into utility determine in a fundamental manner the objectives, which are represented in a subsequent ranking of decision alternatives. This may as clearly shown by e.g. Tversky and Kahnemenn (1981), be realized to comprise a highly ethical problem for the utilization decision analysis as an instrument to guide societal developments. The framing of decision problems strongly affects the preferences of decision makers, stakeholders, the identification and selection of relevant decision alternatives and the associated valuation of the possible outcomes of these.

Sen (1985) contributes to the discourse on ethical and economic decision making by introducing the concepts of “functionings” and “capability” for individuals, and underlines that not solely revealed preferences but rather the process of informing preferences is of central importance: In Murhy and Gardoni (2006) and Gardoni and Murphy (2010) the concept of capabilities is introduced in the context of risk management and as a means to direct and measure resilient developments.

In the quest of pursuing decision support for implementation of what in the political scene is declared to be frameworks for resilient societal developments, we take the perspective that the right questions are not known a-priori but must be identified successively in an informed and transparent process. Directions on resilient societal developments must be set based on preferences and available knowledge, but preferences and knowledge should be continuously assessed and directions adapted accordingly. Here it is advocated that this process is best supported by knowledge consistent assessments on how possible decision alternatives, including policies, affect resilience, sustainability and welfare.

3. OBJECTIVES AND METRICS IN RESILIENCE MANAGEMENT

Appreciating that resilience of societal systems at urban scale depends on sustainability at Earth scale – and that the two concepts, resilience and sustainability indeed merge at Earth scale (see Faber (2018)), the following identification and discussion of objectives and metrics will address both of these system characteristics jointly.

3.1. On societal preferences for welfare

A large variety of propositions have been put forward on how to measure, assess and plan for sustainable societal development. Mainstream measures of sustainability and sustainable development stemming from academia include ecological footprint accounting, based on the concept of carrying capacity from population biology (Rees 1992, Wackernagel 1994); (environmental) life cycle assessment developed continuously from the 1960s to present as an aggregate measure of the environmental performance of products and services throughout their lifecycle; and most recently, just over the past decade - social life cycle assessment as an aggregate measure of the positive and negative socio-economic impacts along the life cycle of a product. For industry such measures include environmental social governance reporting, triple bottom line reporting, and corporate social responsibility reporting. By far and large, the most widespread approach to measuring sustainability is through developing and monitoring composite metrics and indices. Since the adoption of The Human Development Index by the United Nations in 1990 as a benchmark indicator of societal development at the nation state level, the number of indices put together by policy-supporting research institutions has grown to include the Environmental Sustainability Index, (see Esty et al. 2005), the Environmental Performance Index (Wendling et al. 2018), and a number of proxy indicators for sustainability, based on the shared assumption that the GDP is not an adequate indicator of growth and development, e.g. the Genuine Progress Indicator (Cobb et al. 1995), and the Happy Planet Index (Marks et al. 2006). Most recently, based on the ideas of Sen (1985, 1999), the concepts of inclusive wealth and inclusive growth have emerged (Kakwani and Pernia 2000, Dasgupta and Mäler 2000, Ali and Son 2007, Ianchovichina and Lundstrom 2009, Klassen 2010, McKinley 2010) resulting in the adoption by the UN in 2012 of the Inclusive Wealth Index (Arrow et al. 2012) as an index for monitoring sustainable societal developments. The IWI is composed of three terms: human capital, natural capital and manufactured capital, together with their respective shadow prices. The shadow pricing concept is introduced to reflect the degree to which societal developments at present depend on resources which are exhaustible.

Inclusive growth in a similar manner as inclusive wealth aims to reflect the prospects associated with societal development and does this by means of accounting for the social equity characteristics of policies for societal development. In this manner, not only expected value improvements of societal developments, in terms of e.g., life expectancy, safety, education and income but also their distribution over the population are accounted for.

In common for the aforementioned measures and indicators is that these are merely representations or models of societal developments, which aim to reflect high-level political objectives. They reflect stated societal preferences at policy level with respect to both the end objective and the path to get there. At the present time, there is however no scientific basis for assuming that these preferences are or will ever be observable at behavioral level in society, i.e. as revealed preferences.

Nathwani et al. (1997) formulated the Life Quality Index (LQI) as a representation of societal preferences for tradeoffs between life expectancy, time spent at work vs leisure and economy (GDP per capita) invested into improvement of health. The philosophical background of the LQI builds on the fact that the only asset and resource available for individuals to spend is time. As quoted in Rackwitz (2002) from the book "Walden" written by David Thoreau in 1852: "The cost of a thing is the amount of what I will call life which is required to be exchanged for it, immediately or in the long run." Both Nathwani et al. (2009) and Ditlevsen and Friis-Hansen (2009), on the basis of this philosophical insight reformulated the LQI based tradeoff between investments into life safety and resulting life safety improvements, into pure time formulations, expressing that the time spent at labor to improve life safety should not exceed the gain in leisure time at good health.

The approach taken here is to measure, assess and direct long-term societal performance through the Life Quality Index (LQI). The LQI is a relative utility function which facilitates a representation of societal welfare developments in dependency of the services and life safety provided by technology, the services provided by the qualities of the environment and the back-couplings which exist between these interconnected systems.

Rackwitz (2002) verified the LQI empirically and in Faber and Virguez-Rodriguez (2011) it is shown that 71 nation states in the World (corresponding to 70% of the global population) develop in accordance with the LQI. Thereby the LQI as opposed to the IWI can be understood to comprise a revealed preference for societal developments at aggregate level.

In the modeling of societal developments we take the perspective that the LQI could comprise an adequate utility function for representing the objective. With this utility, decision analysis provides a means for ranking decision alternatives at policy level in the context of resilience management. Following the approach outlined in Faber et al. (2017), the development of the LQI as a function of economic developments can be modeled with given demographical characteristics such as the GDP per capita, life expectancy at birth and the ratio of time spent for work. Based on the LQI concept it is possible to assess the marginal life saving costs, (see e.g. Faber and Maes (2010), i.e. the costs which should and can be afforded by society to invest into life saving activities.

3.2. *On the representation of the environment*

All the foregoing considerations take basis in the assumption that human activities predominantly have local, and only minor or even negligible global implications for the living conditions of humans. The capacity of the Earth system to provide adequate living conditions for humans is not accounted for. However, during especially the last decade significant progress in research on the capacities of the Earth system with respect to anthropogenic influences has been achieved. In Rockström et al. (2009) and Steffen et al. (2015) the concept of Planetary Boundaries has been proposed and quantified for characteristics such as atmospheric CO_2 concentrations, bio-diversity, fresh water and phosphor. Substantial uncertainties still prevail in these quantifications but the scientific basis has been established for assessing limits for human activities with impacts on the environment. The concept of Planetary Boundaries may be realized to provide a strong instrument in the context of optimizing strategies for societal developments and for assessing tradeoffs between welfare, resilience and sustainability.

Thus to account for physical limits to anthropologic effects on the Earth system we propose to use the concept of Planetary Boundaries and to assess policies for societal developments in terms of their associated likelihood or probability that the Planetary Boundaries, i.e. the capacities of the Earth Life Support System, are exceeded; the principle is illustrated in Figure 1.

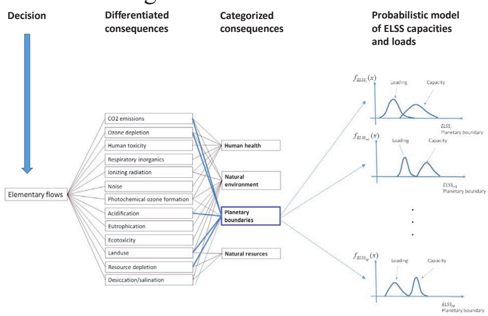


Figure 1 Proposed approach for representing the effect of decisions with respect to resilience management on sustainability.

To take benefit of the concept of Planetary Boundaries two aspects must be considered, namely the quantification of the capacities of the individual Planetary Boundaries and the loading on the individual Planetary Boundaries. The modeling of the capacities is surely a task of natural scientists, however the modeling of the loading side appears to be a task of engineers. Following Faber (2018) and Faber et al. (2017)

any decision in the context of resilience management related to use of materials can be assessed with respect to its associated elementary flow, assessed through Life Cycle Assessment (LCA). In addition, health and safety risks caused by accidents and failures following the decision may be assessed based on probabilistic risk analysis, see e.g. JCSS (2008). The elementary flows and risks may finally be categorized into impacts affecting health, environment, Planetary Boundaries and natural resources.

3.3. *Urban scale objectives for resilience and sustainability*

To account for political preferences for sustainable societal developments as well as possible specific preferences of stakeholders, e.g. at urban scale, we propose to assess the paths of feasible or optimal policies in accordance with the IWI and the IG. Moreover, we propose to utilize the concept of resilience as a measure of appropriateness and stability of local societal developments and to assess and measure resilience performance at policy level through the associated likelihood or probability that local societal developments exhaust local capacities with respect to environment, human capacity and economy. Finally, it is highlighted that any requirement, such as fulfillment of local regulations and stakeholder preferences, can be accounted for as boundary conditions for the optimization of the LQI.

4. RESILIENCE MODELING FRAMEWORK

As highlighted in the foregoing, the concepts of resilient and sustainable societal developments may be understood as being constructs of contemporary stated preferences with respect to different possible future evolutions of society at local and global scales. Whereas the overlying objectives of resilient and sustainable societal developments are relatively clear, it is less clear how i) such objectives can be operationalized and ii) how different possible policies aiming to reach the objective, and their associated societal development paths, may be compared and benchmarked.

4.1. *Organizational systems*

To cast light on these issues it is informative to relate the concepts of risk, resilience and sustainability to the context of societal decision making. Figure 2 provides an illustration of how societies at different scales and distributed geographically are hierarchically interconnected at different organizational levels. For the purpose of simplicity the lowest level of representation in the illustration is chosen at municipality level. Further detailing may be introduced depending on the need for resolution in a given context to ensure e.g. appropriate representation of the systems comprised of local communities, livelihoods, ecosystems, qualities of the environment together with specific types and objects of infrastructures and their mutual interdependencies.

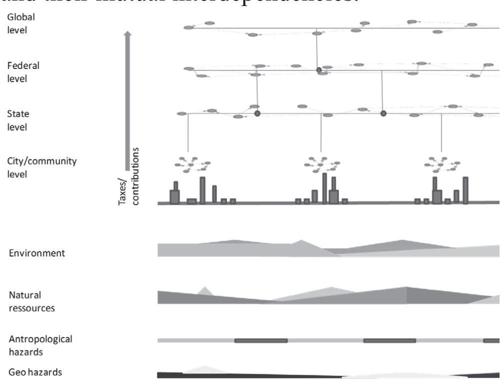


Figure 2 Societal organization and geographical constraints. Adapted from Faber et al. (2017).

The main purpose of Figure 2 is to highlight that societal systems at different organizational levels interact with each other and with the boundary conditions provided by nature. Nation states, regions, municipalities and communities are connected by governance structures. Different levels in the organizational hierarchy have different roles and responsibilities in the overall governance system and depending on the particulars of the governance system they share natural resources, income and risks.

Traditionally, at a given level in the societal organizational hierarchy the main emphasis is directed on the management of risks, in the sense of reducing the expected value of losses and damages associated with geo-hazards and anthropological hazards. Such losses may typically relate to safety and health of people, but also to the qualities of the environments, loss of production, reduction or loss of infrastructure services as well as associated monetary expenditures and lost income.

Figure 3 shows that societies, due to differences in geographical location, are subject to different geographical boundary conditions for what concerns at least three main aspects, namely available natural resources, environmental conditions and geo-hazards. Anthropological hazards may, as suggested in Figure 2, also differ over geography, but such differences may to a large degree be explained by the other mentioned geographical boundary conditions. Risk management at different geographical locations for this reason often has significantly different foci. Moreover, due to differences in availability of natural resources and environmental conditions also the livelihoods vary substantially over geography. Indeed the mentioned differences to a large extent may be considered covariates in the context of understanding why the economy in some nation states appears to be under developed; such nation states may in most cases be realized to be geographically challenged rather than anything else.

Risk management at the different individual levels of societal organization is a strong instrument for decision support on societal developments but as risk management is implemented in practice, by means of regulations, standards and codes, it generally fails to capture important system effects. Interdependencies, and cascading failures within and between different systems such as infrastructure systems, ecological systems and social systems are often neglected or overly simplified.

4.2. Interlinked systems and resilience failure

The concept of resilience addresses these interdependencies and directs focus on the ability of the combined system in the face of disturbance events caused by geo-hazards or anthropological hazards to maintain services and functionalities over time – without any support from the outside of the considered combined system, see also Figure 3 and Figure 4.

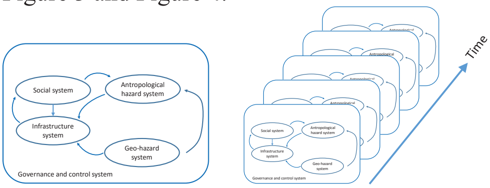


Figure 3 Illustration of interconnected systems which must be accounted for in resilience modeling. Adapted from Faber (Routledge, 2019).

Figure 3 illustrates an interlinked system comprised of a social system, an infrastructure system, together with geo-hazard and anthropological hazards systems, imbedded and managed in regulatory and monitoring systems.

In Figure 4 the principle of resilience failure from Faber et al. (2017) is illustrated. Resilience failure for an interlinked system takes place when one or more of the vital capacities of the system are exhausted. Such capacities may relate to the economic capacity, human capacity availability of vital resources like fresh water, food etc.

As illustrated in Figure 4 the capacities of a system may be represented and modelled in dependency of the services provided by the system. The modeling of this relationship is crucial for the modeling of resilience failure. Following the discussion of sustainability and Planetary Boundaries from Section 3.2 it is readily realized that events of sustainability failure may be modeled in the exact same manner as events of resilience failure.

Appreciating that there are significant uncertainties associated with the modeling of capacities as well as loadings both in the case of resilience modeling and sustainability modeling it follows that events of both types of failure are most adequately modeled and assessed probabilistically, see also Faber et al. (2017) and Faber et al. (2018).

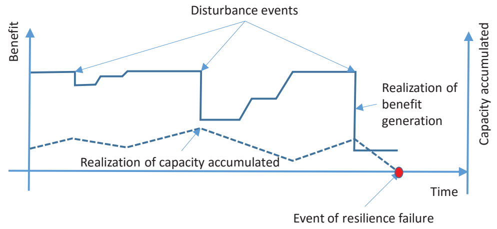


Figure 4 One realization of the benefit and capacity generation – as well as a resilience failure event for a system subject to disturbances.

4.3. Tradeoffs in resilience management

Based on the foregoing propositions on the representation of resilience of urban systems in the context of societal decision support for resilient and sustainable societal developments, it is instructive to assess the possible insights which may be derived on a purely qualitative basis. In the following we will focus on the tradeoffs between welfare, resilience and sustainability.

An urban system is considered represented by an infrastructure system providing basis for economic growth (GDP) and contributions to welfare (LQI). The infrastructure system is subject to disturbance events which may lead to loss of services and events of resilience failure over time. The management options for the infrastructure system are represented through different decision alternatives p. In Figure 5 the decision alternatives are ordered along the x-axis in accordance with reducing probability of resilience failure $P_{RF}(p)$.

Assuming that improvements of resilience performance of the infrastructure system are associated with use of more material and more costs – and accounting for uncertainties and random characteristics of the resilience and sustainability performances of the infrastructure system, it may be assumed that the expected value of the contributions to GDP, i.e. $E[\Delta GDP(p)]$ will follow the general trend of the curve shown in Figure 5.

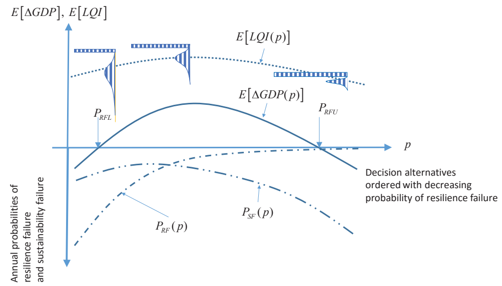


Figure 5 Illustration of tradeoffs between resilience, welfare and sustainability.

For systems with very poor resilience performance, $\Delta GDP(p)$ will be low and maybe even negative even if the cost of such systems is small due to repeated losses caused by disturbances. As the resilience performance is increased it can be expected that also $\Delta GDP(p)$ increases – until a point where the costs associated with increasing resilience performance over weighs the benefits associated with the high resilience performance. Since the LQI depends on the GDP it may be assumed that the expected value of the LQI, i.e. $E[LQI(p)]$ and the GDP follow the same trend as a function of p.

In Figure 5 the general characteristics of probability density function of $LQI(p)$ are shown on top of the $E[LQI(p)]$ curve. It may be expected that for low resilience performance the variance of the resilience is high and vice versa. The same applies of course for the variance of $\Delta GDP(p)$.

Finally, the probability of sustainability failure may be expected to follow the curve $P_{SF}(p)$. For systems with poor resilience performance it may be expected that repeated failures of the infrastructure system will lead to increased material consumption. Increasing resilience performances will reduce the probability of sustainability failure – to a certain point where the use of material required to achieve further resilience performance improvements exceeds the use of material needed to restore the infrastructure system after disturbances. From the qualitative assessment of the tradeoffs between resilience, welfare and sustainability it is apparent that resilience management must be undertaken with care to achieve the optimal balance.

Finally, based on the general characteristics observed from Figure 5 the trends of time evolutions of welfare (LQI) illustrated in Figure 6 may be anticipated. If the system is managed such that the probability of resilience failure P_{RF} satisfies $P_{RFU} \geq P_{RF} \geq P_{RFL}$ (see Figure 5) the welfare (LQI) will develop positively. If P_{RF} is outside this interval welfare will develop negatively.

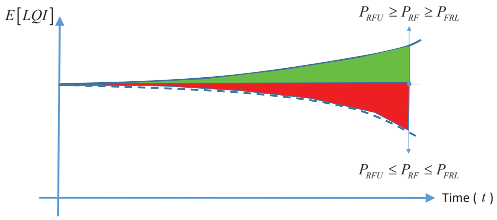


Figure 6 Trends of welfare development as function of infrastructure resilience performance.

5. PRINCIPAL EXAMPLE

The present example takes basis in the infrastructure system also considered in Faber et al. (2018) where details on the applied modeling may be found. The infrastructure system is represented through a Daniels system with 100-year service life and n_C constituents, see Figure 7. Here we investigate the economic growth (ΔGDP), contributions to welfare (LQI) and the resilience of the system, subject to four selected decision alternatives namely the;

a. number of constituents n_C,
b. design requirements in terms of constituent reliability represented by the variable z_1,
c. preparedness level and
d. percentage of annual benefit $\chi\%$ which is saved for financing of future potential economic expenditures, e.g. repair and replacement activities after future disturbance events.

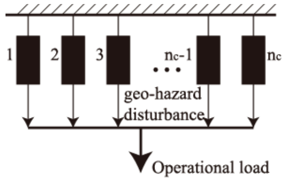
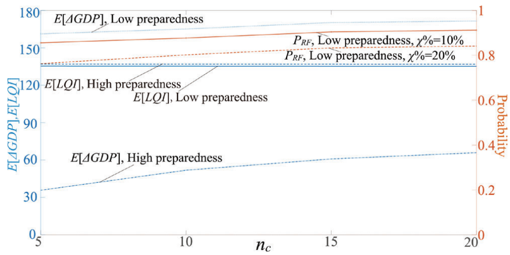
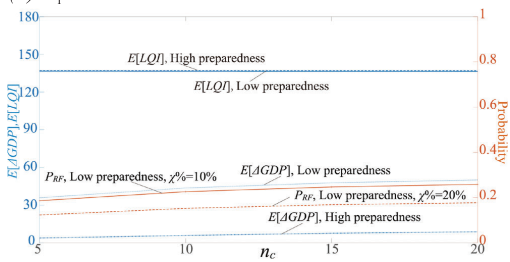


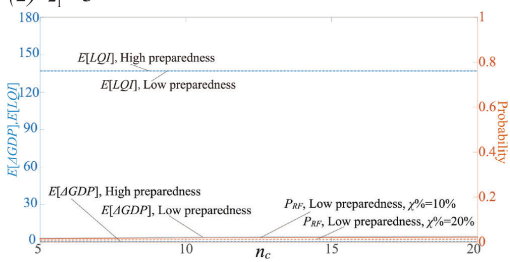
Figure 7 Illustration of the infrastructure system represented through a Daniels system.



(1) z_1 =2



(2) z_1 =3



(3) z_1 =4

Figure 8 Illustration of $E[\Delta GDP]$, $E[LQI]$ *and* P_{RF} *for the system subject to different scenarios.*

These decision alternatives represent governance decisions with respect to infrastructure, government, regulatory and social systems respectively. Three different values of z_1 are considered, corresponding to different target

annual probabilities of constituent failure, from approximately 10^{-1} to 10^{-4}. The results from 10^6 numerical simulations are provided in Figure 8.
It is seen that the contribution to the development of GDP i.e. $E[\Delta GDP]$ reduces for the case of high preparedness level and for small design target levels of failure probability. Also the increase of the number of constituents increases $E[\Delta GDP]$ moderately.
The $E[LQI]$ is not sensitive with respect to variation of n_C, but increases with the preparedness level. As the design target level of failure probability becomes low (z_1 is large), the effect of preparedness level on $E[LQI]$ is also small. The probability of resilience failure, P_{RF} gradually decreases with decreasing levels of the design target annual failure probability. The same applies to the increase of the percentage $\chi\%$ and the preparedness level. The probability of resilience failure for systems with high preparedness level and high percentage $\chi\%$ is always close to zero, and not shown in the figures.

6. DISCUSSION AND CONCLUSIONS

A framework together with objectives and metrics have been formulated which facilitates governance of resilience of societal systems of a certain size such as urban habitats. The framework builds on the idea that systems will fail to be resilient if their vital capacities are exhausted and they need help from the outside to recover from disturbances. Sustainability at Earth scale is identified to comprise a necessary condition for resilience of systems at any scale – and the two notions indeed merge at Earth scale. Based on the proposed framework it is possible to quantify resilience and sustainability in probabilistic terms, and decisions may be assessed relative to their effects on the probability of resilience and sustainability failure, respectively. In the governance of resilience of systems at urban scales, it is proposed to optimize decisions on societal developments based on the Life Quality Index; the only societal preference for the tradeoffs between expenditures and health improvements which has been empirically verified so far. Optimization of societal developments based on the LQI should however be undertaken subject to fulfillment of in principle any policies and/or stakeholder preferences for the distribution of welfare as well as possible inconveniences over the population. Moreover, any decision made must conform with regulations and standards at local scales – which is also facilitated by the proposed framework by imposing such requirements through constraints on the optimization of welfare. It is found that there are rather significant tradeoffs between welfare, resilience and sustainability. Welfare and sustainability may be at stake both if too little or too much is invested into resilience improvements. It is imperative that more knowledge is established to quantify and assess these tradeoffs for the enhancement of resilient and sustainable developments.

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CHAPTER 8. RESULTS AND DISCUSSION

The present chapter summarizes the results of the PhD study and aims to provide concise answers to each research question stated in Chapter 1.

The initial point of departure for conducting research in the present PhD study is to investigate how and why there appears to be a gap between what is known in theory and what is done in practice in the context of governance of systemic risks and propose a solution for how the gap may be minimized. Three knowledge traditions are identified as the chief contributors to the general body of knowledge on the causes, consequences and governance mechanisms of systemic risks. The first is a cluster of specializations within the traditional disciplines of civil and environmental engineering, economics and psychology that deal with problems related to reliability, safety and optimization. In the present thesis this cluster is referred to as the knowledge tradition of risk. The second is a cluster of specializations stemming from the discipline of ecology that deal with problems related to organism-environment interactions and population dynamics. In the present thesis this is referred to as the knowledge tradition of resilience. The third is a cluster of specializations within the traditional disciplines of economics, political science, ethics, and business administration that deal with problems related to the efficient use of resources and optimization of processes. In the present thesis this is referred to as the knowledge tradition of sustainability.

The objective then is to develop a baseline understanding of the structure and evolution of these knowledge traditions and the extent of their individual or combined contribution to addressing problems related to the governance of systemic risks. The challenge of developing such a baseline is analogical to developing a system representation of interacting functional parts. Risk, resilience and sustainability knowledge traditions are taken as the functional parts of a conceptual knowledge system whose purpose is to provide informative input into the phenomenal system of decisions and actions we call behavior. A balanced interaction between the conceptual and perceptual systems, increases an organism’s likelihood for survival.

Matter-Form-Function is chosen as a generic structuring principle of design, where matter is analogous to the content (subject matter) of a knowledge domain; structure – to the topological form of relations among the various subject matters; and context – to the ensemble of objectives the structure is intended to provide. Seen from the matter-form-function perspective, the rather abstract problem of defining the causes and consequences of the gap between knowing and doing, becomes a more tangible design problem. Using matter-form-function reasoning, the design problem can be restated as the task to identify:

(i) a set of decision problems to be addressed,

(ii) a set of concepts that describe and explain phenomena relevant to the scope of (i);

(iii) a topology of the relations within (ii); and

(iv) a topology of the possible interactions between (i) and (iii) that would maximize the goal of diminishing the gap between knowing and doing.

The first three steps of the design task therefore correspond to the formulation of an integrated risk, resilience and sustainability science while the fourth steps corresponds to the formulation of rules for how a synergy between research and education in this discipline can help to achieve the high level objectives of governance.

8.1. SUMMARY OF RESULTS

Following a pragmatic research design philosophy whereby the problem-context determines the relevance and validity of further methodological choices, the results of the thesis can be grouped according to three stages in the design process. These are:

(i) System Identification, which encompasses data collection, mapping and evaluation;

(ii) Logical Inquiry, which encompasses inferential and abductive procedures for defining the rules of classification in the physical realm of phenomena, e.g. what counts as a hazard, and in the cognitive realm of concepts - what counts as a concept; and

(iii) Synthesis, which encompasses the formulation of a logical solution to the design problem. The results from each design phase are presented here in a summary form:

System identification (understanding the problem-context)

- Observations (quantitative and qualitative) regarding present practice in research and education
- Identification of a set of concepts that define the subject matter of a risk, resilience and sustainability science independent of context, i.e. not specific to any academic discipline or application area
- Pattern identification and analysis based on statistical cluster analysis and hermeneutic interpretation
- Identification and study of the available theory and methods on risk, resilience and sustainability across sciences, disciplines and application areas
- Identification and study of the available theoretical/philosophical frameworks for design of knowledge domains

Logical inquiry (problem analysis)

- Identification and assessment of pitfalls in relation to governance of risk, resilience and sustainability
- Identification and assessment of causes of pitfalls with emphasis to present practice in research and education
- Establishment of a unifying theoretical basis for risk, resilience and sustainability based on the concept of 'information', which decouples the theoretical basis from prevailing practices of decision-making based on stated (political) preferences
- Identification of relevant concepts to form a basis for a flat domain ontology for the integrated science of risk, resilience and sustainability in accordance with Bayesian reasoning and empirical embodied cognition research

Synthesis (solution)

- Formulation of educational requirements targeted to fix the pitfalls in knowledge acquisition (education and research)
- Establishment of a model for the knowledge domain of an integrated risk, resilience and sustainability science in terms of a topology of concepts such as to facilitate a representation/organization of concepts that offers a context driven weighing of relevant concepts (contextual trans-disciplinarity)
- Design of a blueprint for education as a dynamic template of context-driven planning for educational activities along multiple learning pathways (from degree program to project level)

- Exemple 1: the application of one such learning pathway at project level
- Exemple 2: the application of the logic and conclusions from the conducted PhD study for the applied context of governance of urban systems.

8.2. ANSWERS TO RESEARCH QUESTIONS

In the following brief answers are provided to the research questions related to the objectives of the thesis, together with references to the relevant thesis chapters, where the questions are addressed in greater detail.

Q1. What are the trends and challenges driving research in the knowledge domain of risk?

The bibliometric literature review revealed that since the 1990s the individual knowledge traditions of risk, resilience, and sustainability show an upward trend in the production of research. Of the three, the risk tradition has the longest history and the largest volume of research. The risk and sustainability traditions cover wider application domains than that of resilience. However, over the past 30 years the risk tradition has transformed from a predominantly engineering specialization in reliability, safety and process optimization to a broader knowledge domain that considers additionally problems related to environmental and social conditions in interaction with engineered systems and processes (Fig. 3). The traditional engineering specialization in health and safety has been strongly marginalized, while new specializations have emerged such as adaptation of the built environment to climate change, natural hazards, and food safety.

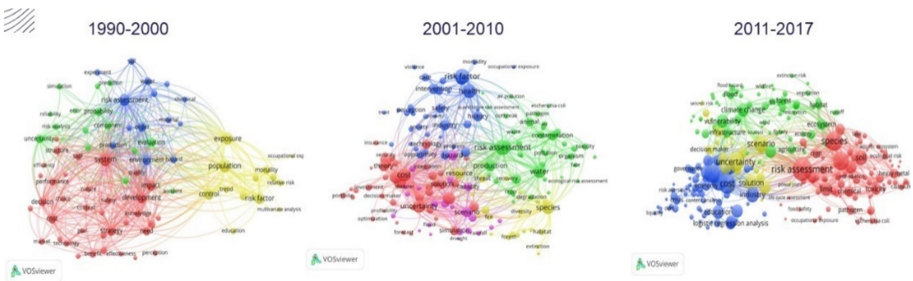

Fig. 3 Transformation of subject matter focus in the knowledge tradition of risk from reliability and safety to systemic and environmental considerations 1990-2017 (Nielsen and Faber 2019).

Three major contributing disciplinary areas to the risk, sustainability and resilience knowledge traditions are environmental science and ecology, engineering, and economics (Fig. 4). The contribution of the social sciences is marginal. The contribution of the human sciences is practically non-existent.

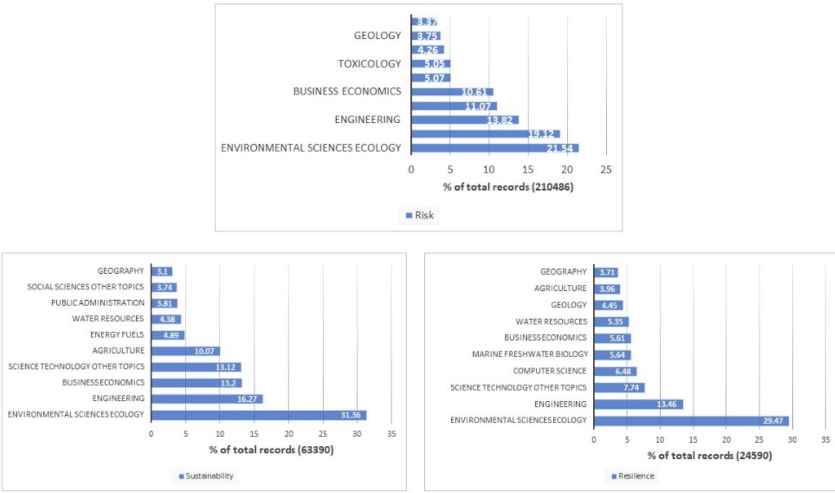

Fig. 4 Disciplinary distribution in research on risk, resilience and sustainability 1990-2017 (Nielsen and Faber 2019).

Research in risk, sustainability and resilience is dominated by the highly developed Western countries, especially the Commonwealth countries, the U.S. and the Scandinavian countries (Fig. 5). China is a major contributor to research in the domain of sustainability and circular economy.

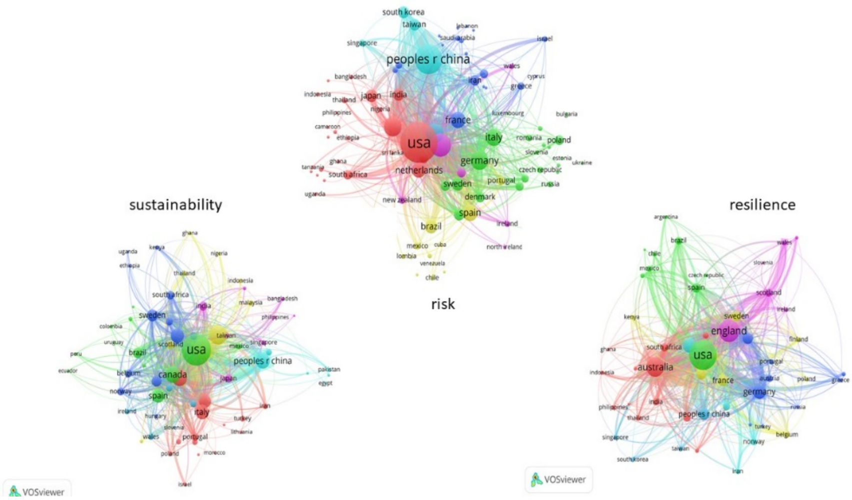

Fig. 5 Geographic distribution of research in risk, resilience and sustainability 1990-2017 (Nielsen and Faber 2019).

This research question is answered in detail in the entire Chapter 3; Chapter 5, Part I, Sections 1, 3; Chapter 5, Part II, Section 4.1; and Chapter 5, Part III, Section 3.1. In Nielsen L. and Nielsen, MHF. (2018) a report is provided that includes all bibliometric maps and a description of the methodology.

Q2. To what extent are resilience and sustainability considerations integrated in the knowledge domain of risk?

The bibliometric literature review revealed that there is some integration between risk and sustainability and between risk and resilience but that research combining all three is in its infancy (Fig. 6).

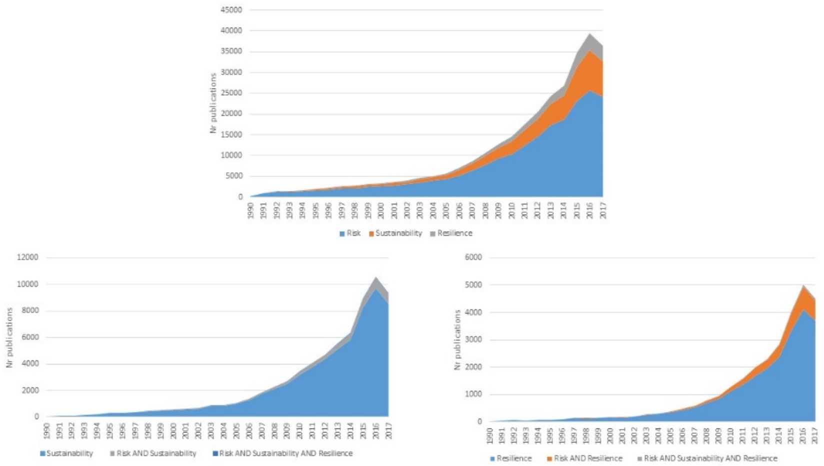

Fig. 6 Level of integration among risk, resilience and sustainability research 1990-2017 (Nielsen and Faber 2019).

This research question is answered in detail in the entire Chapter 3. The scientific and operational framework of Faber (2018) has served as a specific example for a model logic in designing the ontology and blueprint, instantiating the generic matter-form-function design method.

Q3. What are the benefits to decision-makers and stakeholders at different scales of integrating risk, resilience and sustainability considerations into a common scientific and operational framework?

Stakeholders, in the context of the present thesis, are understood and represented as a nested hierarchy system of categories of social actors (Fig. 7) with mutually dependent functionalities.

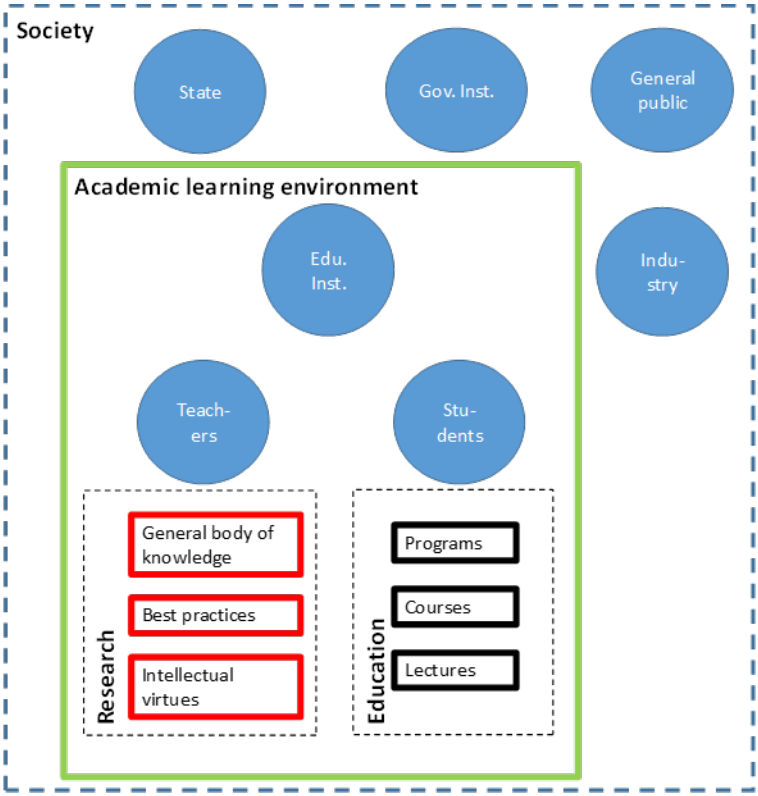

Fig. 7 System representation of stakeholders as categories of social actors (Faber and Nielsen 2017, Nielsen and Faber 2020 Part III).

The category 'Research' designates universities, research centers and institutes. The category 'Education' designates education programs, teachers, students, and education managers at the level of tertiary education. The category 'Practice' designates individuals and collectives who make decisions based on uncertain outcomes of alternative options and act upon them (Fig. 8).

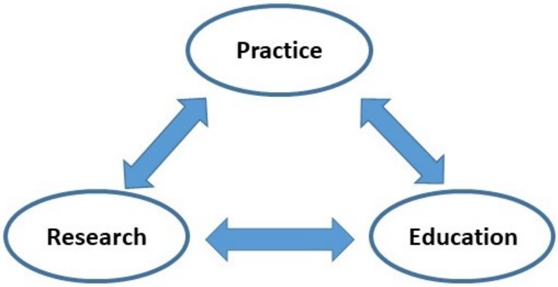

Fig. 8 Interaction among categories of stakeholders

The functionality of this social system depends on the functional interactions among the three categories of actors, namely the interaction among context, knowledge and action (Fig. 9).

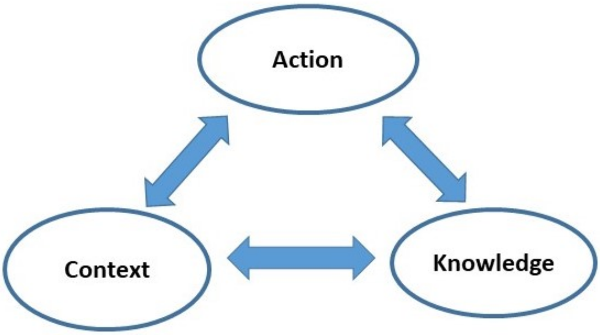

Fig. 9 Interaction among functions of stakeholders

In the present thesis it is assessed that the lack of integration of risk, resilience and sustainability considerations into a common scientific and operational framework is one of three major causes for the rift between knowledge and action. The integration of these considerations into a unified theoretical and methodological framework based on a shared conceptual and inter-cultural language is proposed as part of a portfolio of three measures that can improve the balance among the functional relations of research, education and practice (Fig. 10).

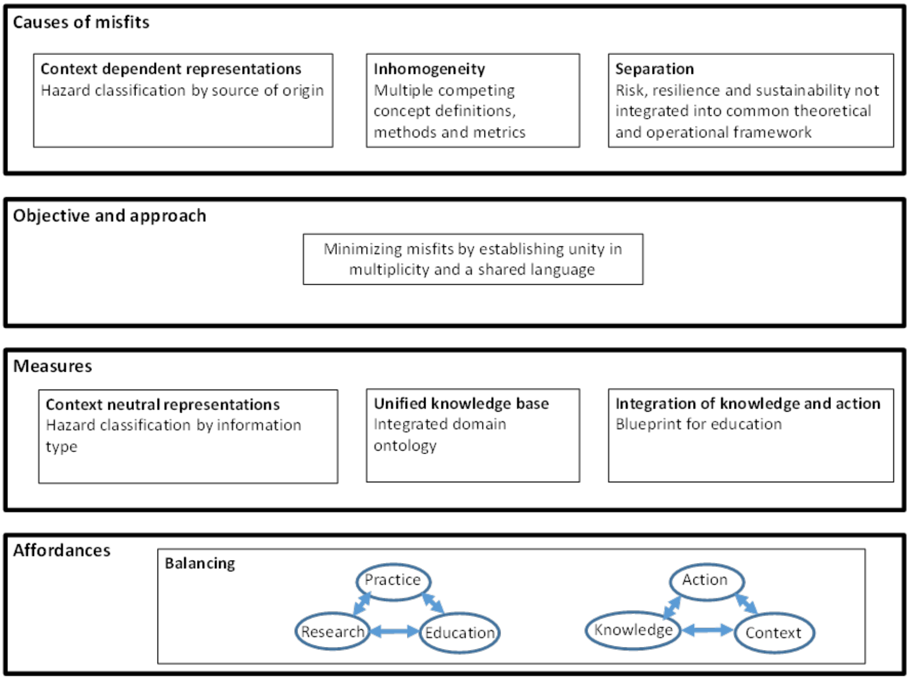

Fig. 10 Benefits (affordances) to decision-makers and stakeholders from an integrated scientific and operational framework for risk, resilience and sustainability as function of misfits and requirements (objectives).

This research question is addressed in some detail in Chapter 3, especially sections 2-3; Chapter 5, Part I in its entirety; Chapter 5, Part III, especially section 2; and Chapters 6 and 7 in their entirety.

Q4. Are trends and challenges driving research in the knowledge domain reflected in educational practice?

The increased volume of research produced since the 1990s in the knowledge traditions of risk, resilience and sustainability is parallel to a dramatic increase in the number of higher education degree programs that have emerged since around 2008 addressing the subject matters of risk, resilience and sustainability. A desk top survey conducted as part of the present PhD study identified 107 such programs at the master level in the European space alone.

Yet the survey also revealed that the majority of curricula are not research, but industry-driven, training students in the best practices of particular application areas rather than cultivating their knowledge of the processes underlying phenomena where risk, resilience and sustainability considerations are significant. The transformation toward a systems understanding of risk, resilience and sustainability has not yet occurred in educational practice.

The overwhelming conclusion of the survey is that despite the large number of programs offered across risk domains, there are very few programs, which appear of high academic standard as well as add value to society by means of decision support. As decision support is the fundamental purpose of an applied risk (or resilience or sustainability) science, the evident lack of decision theory and its applications in the majority of risk programs, diminishes their utility to both direct consumers (decision-makers in the public and private realm) and society as whole – risk, resilience and sustainability-informed decision-making being a public good for all members of society.

The bias encountered in both researchers and practitioners in the field of risk whereby quantitative risk assessment is considered the scientific and rigorous part of the risk analysis process while the qualitative risk management is demoted as subjective, politicized and not scientifically rigorous is reflected in the design, organization and marketing of educational programs on risk. Despite paying lip service to concepts such as integrative, holistic, multi-stakeholder, and multi-disciplinary, program curricula tend to exemplify this bias rather than attempt to counter it. The impression remains that specialized programs are more rigorous than those, which attempt to incorporate a multi-disciplinary approach. Trans-disciplinarity is not observed in any of the 107 programs that make the sample.

Just as decision analysis is absent from most curricula, consequence analysis is similarly absent. An exception are programs within engineering specializations (e.g. Reliability Availability Maintenance Safety (RAMS).

Although both researchers and practitioners in the area of risk acknowledge that risk communication is one of the most difficult challenges in practice, the subject is only partially addressed as a problem during the emergency stage of a disaster. Absent any theoretical understanding of information and information modeling, risk communication in education practice does not extend beyond the checklist. The subject of risk perception is likewise almost entirely absent at the level of education activities.

This research question is discussed further in Chapter 5, Part I, Section 3.2; Chapter 5, Part III, Sections 3.1 and 3.2; and in the desktop survey by Nielsen, L., 2020.

Q5. What are the generic theoretical underpinnings (concepts and methods) of risk analysis that are applicable to different kinds of hazards, academic disciplines and application areas?

The situation assessment of present best practices in research, education and decision-making revealed that the current lack of homogeneity among concepts, methods and metrics in the context of risk analysis stems from the disciplinary approach to research and education and the sectoral approach to governance and regulation. Aven (2018) makes an attempt to outline a theoretical basis for a risk analysis science on its own right, independent of application area; however, the concepts that are selected as generic to the multiplicity of applied areas, are simply terms for stages of procedural frameworks for risk analysis. The procedural frameworks are indeed generic, but terms for procedural stages do not provide understanding of concepts. They do not even require a conscious capacity to carry them out as recent advances in artificial intelligence decision support systems demonstrate.

To answer this research question therefore it is necessary to first specify the rules under which something counts as a concept in the context of establishing a scientific domain of inquiry. This thesis argues that when a science is defined by subject matter, the result is a multiplicity of specializations, a multiplicity of technical definitions for the same terms, and a multiplicity of methods only applicable to the circumstances of a given technical term definition. This multiplicity is not inherently problematic, but it becomes problematic when narrow technical boundary definitions - precise as they might be - turn out to be inaccurate. Whether the inaccuracy stems from partiality experienced as biased information or partiality experienced as incomplete information makes little difference. For this reason, the solution of finding unity of form in multiplicity of meanings is presented as a flat hierarchy of concepts based on the Bayesian notion of uninformative priors. Identifying concepts by means of weighing their statistical significance in a corpus is therefore precisely wrong. However, the statistical technique is tremendously helpful in identifying the possible range of concepts. The question of which rules specify that a concept is identified as generic to the integrated science of risk, resilience and sustainability is further answered in Q7 below.

Instead of laying the foundations for an integrated risk, resilience and sustainability science on the basis of aggregating multiple definitions, methods and metrics, this thesis seeks to identify a unifying method of investigation, in which the multiple forms are the model's parameters under given conditions. This method rests on Bayesian logic for updating information and for weighing the relevance of multiple informations. The same logic is found to underlie human cognitive processes according to empirical research in embodied cognition, where meaning is a product of differentiated experience – a selection from all possible inputs from perception into a bounded unit of conception, i.e. a concept.

This question is addressed at various places in the thesis. In Chapter 1 it is discussed why the discipline and sector specific definitions of concepts, use of methods and establishment of regulations is a problematic practice in the context of governance of systemic risks. In Chapter 3 the concept of 'information' as a unifying generic principle for decision support is identified and generic examples are given of how this principle and the related method of Bayesian decision analysis can be used to in-form the preferences of decision makers. In Chapter 4 the set of possible generic concepts for an integrated risk, resilience and sustainability science is derived on the basis of statistical cluster analysis of the scientific corpus. In Chapter 5 a domain ontology and a blueprint for education are developed that illustrate the generic theoretical underpinnings for an integrated risk, resilience and sustainability science. In Chapter 6 these theoretical underpinnings are used in an educational setting as a test for the education model presented in the thesis in an in-situ inquiry based problem learning activity. In Chapter 7 again the concept of 'information' as a unifying generic principle for decision support is presented together with its Bayesian methodological basis in a hypothetical example in the context of urban resilience.

Q6. What classification methods can be used to develop a domain ontology?

A domain ontology is a map of concepts and their relations typically for a single domain of knowledge. The domain ontology presented in this thesis is an integration of three knowledge domains. In the practice of ontology design, formal specification of concepts and their relations must capture the shared, consensual knowledge of the domain by its academic experts or practitioners. This requirement cannot be fulfilled in the context of the present PhD thesis since no consensual knowledge conceptualization exists for either the individual domains of risk, resilience and sustainability or an integrated domain of the three domains. Indeed, it is the very purpose of the present ontology to establish a structure that enables the creation of shared, consensual knowledge among researchers, practitioners, teachers, and learners. Thus the developed domain ontology is a non-formalized description of the conceptual system that underlies an integrated risk, resilience and sustainability science. It includes the rules, in a natural and visual language, by which entities are defined and assigned to categories as well as the relations among the entities at various hierarchical levels.

The function of a domain ontology is the same as the function of a system representation. An ontology and a system are structurally identical – they are hierarchies. An ontology can thus be structured as a particular kind of hierarchy. A linear hierarchy is typically chosen to represent parent-child and general-specific or vice versa relations. In such hierarchies membership in a category depends on shared attributes of form with other members in the category such that instances in a category a different kinds (forms). Linear hierarchies are used in building taxonomies to classify entities for which there is a general consensus that they are what they appear to be unambiguously (e.g. a dog is not an elephant). Taxonomies are not the optimal structures for classifying entities that may belong to more than one category (e.g. a platypus). For such entities, a branching hierarchy as exemplified in various radial tree structures can also be used to classify entities taxonomically but in addition it offers the possibility to classify items not only in terms of directly inherited relations but in terms of shared functions. The latter method of classification is based on the grouping of items in a category not because they are instances of the same kind of form but because they are instances of the same type of function. This classification method relates parts to their functional wholes and is technically called mereological classification.

The hierarchical organization of the domain ontology presented in this thesis can be described as a radial mereo-topological structure, which reflects:

(i) the flat radial structure of concepts;

(ii) the part-whole relations among categories (concept, concept cluster, dimension, dimensional pair); and

(iii) and the positioning of the categorical elements in relation to each other.

This research question is addressed in detail in Chapter 5, Part II, Section 2.

Q7. What logical criteria should be used for including/excluding a concept and relating concepts topologically?

To derive a set of possible concepts for a domain ontology of integrated risk, resilience and sustainability science, a cluster analysis on a corpus of 0.5 million peer-reviewed journal articles indexed in the Web of science was conducted. Twenty six cluster maps of concepts were established based on expert-selected keyword search of the database, in which concepts were given a significance score on the basis of the number of times a concept (term) occurs in a title or abstract and the strength of a link between two concepts measured as the number of times the concepts occur together. While the datamining technique may be said to provide an objective measuring standard for the statistical significance of a concept in the corpus, it provides no contextual understanding of the relevance of a concept. For this reason, the statistical approach was complemented by a qualitative hermeneutic interpretation. It was found indeed that many of the concepts with high statistical significance scores were ideologically driven from particular disciplinary perspectives. Since the design challenge is to formulate a domain ontology of concepts generic to all possible application areas for an integrated risk, resilience and sustainability science, the data mining technique fell short of providing the logical criteria for including or excluding concepts.

To achieve coherence between the formal requirement that the ontology should be a flat hierarchy of uninformative priors and the prescriptive functional requirement that the ontology should be instrumental in minimizing the misfits stemming from present research and education practices, three criteria for the inclusion of concepts was established. The first relates to modularity, the second - to the treatment of synonyms and the third – to the inclusion of concepts not encountered or estimated statistically insignificant in the cluster analysis.

With respect to modularity, compound concepts (e.g. inclusive growth) were avoided whenever possible as well as concepts referring to e.g., particular hazards so that concepts may be applicable across application domains at the level of categorization associated with that of a genus rather than a particular life form or a species.

With respect to synonyms, the concept, which most resembled a lay term was chosen in following empirical evidence from Rosch's (1975) prototype theory according to which basic level categories tend to coincide with best or salient examples (prototypes) that instantiate a category. Lay terms tend to be categories at the basic level of the genus.

Finally, to shift the balance from what the bibliometric analysis revealed to be a strongly value-driven conceptualization of the domain to an information theoretical logic, a number of concepts were added to support the understanding of information as a concept and the understanding of how information can be modeled.

The logical criteria for inclusion and exclusion of concepts is discussed in Chapter 5, Part II, Section 3. Chapter 5, Part II, Sections 4-5 explain this choice of logic by summarizing theoretical and empirical findings of embodied cognition research. In doing so this thesis has aimed to dig to the bottom of a-priori knowledge that structures human perception and conception of abstract notions such as risk, resilience and sustainability. Supplementary material is presented in Appendix A where individual concepts and categorical pairs from the four dimensions of the ontology are discussed in terms of the embodied image schemas that in-form them.

The topological arrangement of concepts, concept clusters, dimensions, and dimensional pairs combines the logic of Bayesian uninformative priors, concentric and sectioned circle models, and a family of radial trees (e.g., sunburst, hyperbolic network). These are discussed in the answer to research question Q9 below in relation to the visualization techniques used throughout the thesis.

Q8. What design methods can be used to develop a blueprint for the design and planning of educational offers, for which the domain ontology provides the structuring principle such that research and education may evolve concurrently and relative to the challenges posed in a given decision context?

The generic principle of matter-form-function is a principle of causal logic applied in philosophy (e.g. Aristotle's doctrine of the four causes, see Book 1933), evolutionary biology (e.g. Thompson's (1961) seminal work On Growth and Form, where a form is described as a diagram of forces), architectural design (e.g. Alexander's (1967) semi-algorithmic method for developing criteria for an artifact's goodness of fit as a process of minimizing misfits), and structural engineering design (the ingenious combination of materials and geometry which at the same time serves functions and fulfills requirements to e.g. safety and efficiency). In all its contextual applications, the purpose of this generic principle is to enable a contextual or systemic understanding of part-whole functions.

In the present thesis, using inferential analogical reasoning, the problem of designing a domain ontology and a blueprint for education is transformed to a challenge for system design, as considered in structural engineering, on the generic principle of matter-form-function (Fig. 11). Alexander's (1967) method of identifying functional requirements on the basis of observed misfits between form and context underlies the design of the blueprint for education.

	ONTOLOGY & BLUEPRINT DESIGN CHALLENGE	STRUCTURAL ENGINEERING DESIGN CHALLENGE
FUNCTION	High-level objectives of the ontology (fulfillment of educational requirements)	High-level objectives of the structural system (intended use, adequate safety, economic optimization, maintenance and continuity)
FORM	Basic elements of the ontology and their relations (concepts and their categorical relations)	The interaction of forces with matter (fundamental equations of mechanics that allow functionality)
MATTER	Contents of form (information – understood as the subject matter or problem context of management and governance of risk, resilience and sustainability or the set of challenges their integration will help to solve)	All possible choices of parameters (information – understood as characteristics of materials and geometry that may be chosen to optimize the structure with respect to its intended functionality)

Fig. 11 Analogical scheme for the design of the ontology and blueprint as a structural engineering design challenge using the generic principle of matter-form-function

The matter-form-function design methodology is discussed in Chapter 5, Part I, Section 2.

Q9. What design principles, methods and tools can be used for the visualization of the ontology and the blueprint in order to most effectively communicate the logic of the design to stakeholders and users?

Because visualization is central to both helping to understand the logic of the domain ontology and education blueprint as well as help communicate the design to stakeholders and users, it merits a more detailed discussion within the overall methodological framework. First three scales of visualization are identified and described. Subsequently, the formal aspects of network visualization are discussed in relation to their contribution to:

- the bibliometric mappings (illustrated and discussed in Chapter 2; Chapter 5, Part I, Section 3; and Chapter 5, Part II, Section 4);
- the construction of the ontology (illustrated and discussed in Chapter 5, Part II, Section 3);
- the construction of the education blueprint (illustrated and discussed in Chapter 5, Part III, Sections 3-5); and
- the sketch for a repository of digital learning objects (illustrated and discussed in Chapter 5, Annex A).

Three scales of network visualization are used in the PhD project: macro, meso and micro.

On the macro scale the method of network visualization provides a bird's-eye view of the problem and its context. The aim here is not to show any particular nodes and connections but larger patterns in the corpus of research on risk, resilience and sustainability such as historical evolution of the individual knowledge domains in terms of growth in the number of publications and evolution of disciplinary contributions. Similarly, the desired scale of the visualizations showing geographic distribution and distribution by author and institution producing the research are intended to show macro level patterns and trends. The macro level horizon scanning serves as partial input in compiling a list of "misfits" (problems) stemming from the research knowledge domain, which in turn serves as partial input in compiling a list of "requirements" (educational requirements) for the blueprint.

At the more fine grained meso scale, the method of network visualization is used as an aid to understanding how the nodes are related, what can be inferred by the strength values of the connections as well as the relative position of clusters to their neighbors and their centrality in the network as a whole. Examples at this scale of visualization are the term co-occurrence cluster maps, the ontology, the blueprint, the interaction between misfits and requirements, and the three exemplary learning pathways. The macro scale's purpose is to define the boundary conditions for the problem context based on synthesis. The meso scale is a relational view of the scope of the problem based on analysis.

Finally, an example of a micro scale visualization is the sketch for an interface for a digital learning object that corresponds to an individual node in the networks of the ontology, blueprint and digital object repository, namely 'social cohesion'. The micro level view provides detailed information on the composition of a digital object, which corresponds to the cognitive schema of the concept 'social cohesion' and its family resemblance to concepts in cluster family 14, titled 'Practice'. This rich visualization is thus able to simultaneously facilitate understanding of (i) the structure (metadata), (ii) the content and (iii) the relative position of the digital learning object with respect to hierarchically higher levels of the ontology (the cluster family and the dimension clan) as well as non-inherited friendships with concepts from other families and clans. Adaptive zooming in and out of a digital learning object is part of the object's functional description in accordance with the notion of "re-use", or the ability of the object to dynamically hop from context to context.

Network visualization is used throughout the PhD study to contrast the linearity of genealogical hierarchies and the non-linearity of networks. Present hazard classification schemes, procedural frameworks for assessment and management of risk, resilience and sustainability, and educational programs in this knowledge domain have predominantly linear structures. If risk, resilience and sustainability are to be united under a common scientific framework, the conceptual, methodological and procedural models must be able to account for non-linear effects. The proposed designs for the domain ontology and education blueprint as well as the sketch for the repository of digital learning objects curve with the context.

Network visualization in the bibliometric mappings

In the bibliometric mappings of the state-of-the-art research in risk, resilience and sustainability network visualization serves the following purposes:

(i) Map a scientific domain that has never been mapped before. Although there are numerous literature reviews of the individual knowledge traditions of risk, resilience and sustainability, there is no global map that provides a visualization of the extent the individual traditions are integrated.

(ii) Provide clarification on the conceptual links among risk, resilience and sustainability and aid a compact, glance understanding of the conceptual system comprised of the concepts and their inter-relations. Visualization is the method through which such a vast, complex and non-linear data set can be compressed from a description in a natural language to a graphic image. In this clarifying function, the visual image represents a synthesis of the integrated domain that is graspable in one whole macro scale glance.

(iii) Reveal patterns in the raw data set about the conceptual structure of the domain that may not be explicit in a traditional literature review. Non-bibliometric qualitative literature reviews are based on the subjective judgment of what counts as significant in a given knowledge domain based on citation indices. A data-driven statistical clustering method based on co-occurrence of terms and link strength among terms while still subject to subjective filtering is a more transparent and inclusive method than the partial and inherently biased method of selection based on citation indices.

(iv) Use the output of (iii) as a basis for synthesizing and re-structuring the maps of term co-occurrences into a new map which functions as a formally organized domain ontology that integrates the conceptual systems of risk, resilience and sustainability

The principles and rules of visualization for the purpose of communicating design choices is first discussed in terms of a visualization grammar (Fig. 12) that explains the choices for graphical elements (marks and symbols) and categorical and relational attributes (color hue, color saturation, and part-whole containment).

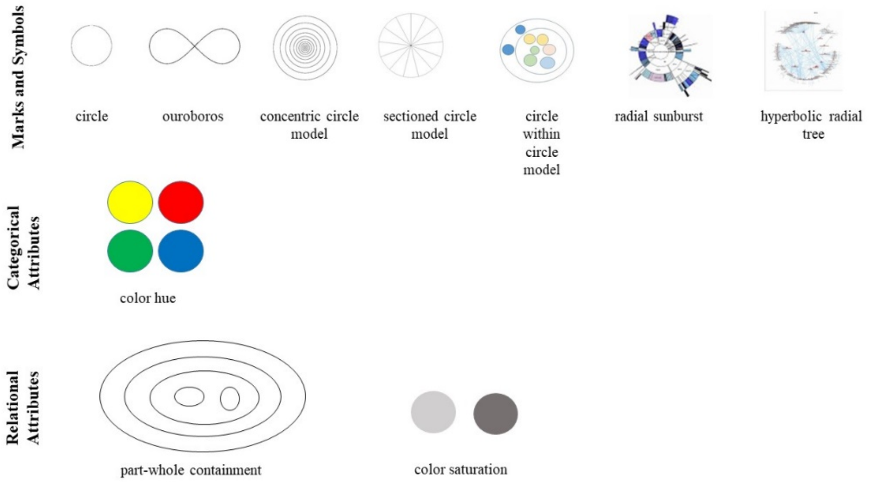

Fig. 12 A visualization grammar for the ontology, blueprint and repository of digital learning objects.

Visualizing the ontology

The logic underlying the ontology is based on the concept of non-informative priors used in Bayesian parameter estimation. Since the ontology should in principle contain all concepts possibly relevant to a risk, resilience and sustainability science regardless of disciplinary or application area, the formal plane of the ontology must represent absolute equality among the concepts. In other words, the formal plane has no particular context because it contains all possible contexts. When the function of the ontology is considered in relation to an applied context, the formal plane acquires meaning in that particular context in the sense that the flat world of equal possibility becomes categorically structured on the basis of weighing the significance of any given concept in relation to the context. The world of perception is transformed into the world of conception. Equality thus must be graphically represented as a flat (non-hierarchical) structure. However, when we consider the semantic plane, the graphical representation must show the inequality among the objects in relation to a context. The resulting structure must be hierarchical. Since the objects in the ontology are concepts, which are abstract immaterial entities, the attributes that distinguish them are qualitative attributes of categorization and relational attributes that refer to their mereological (part-whole) properties.

To visualize equality and inequality in a single form is challenging. The proposed solution is structured in the form of overlapping layers of circular models. The concentric circle model is at the core of the ontology. To visualize the notion of an object as a single unit, the circular form is used as a symbol of solitary unity (Fig. 13).

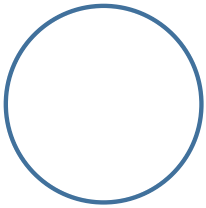

Fig. 13 Image of circle as solitary unity.

The circle is furthermore a symbol for "pure" form, i.e. an invariant form into which variant matter (content) can be poured. Seen this way, the circle is a container: a whole with a hole (Fig. 14).

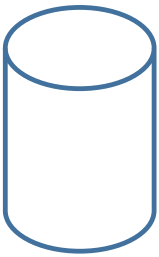

Fig. 14 Image of circle as container.

Thirdly, a circle marks a boundary. As such it is a classifier. It gathers things in and keeps things out (Fig. 15).

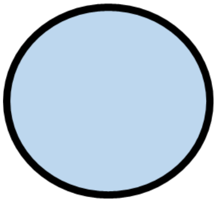

Fig. 15 Image of circle as a boundary marker.

These formal attributes of the circle combine at the focal concentric circle of the ontology, i.e. the slice containing all individual concepts in the knowledge domain of risk, resilience and sustainability. A flat domain ontology can thus be thought of and represented as an ontological container of uncategorized concepts, prior to their consideration in a problem context or particular application area.

The formal visualization of the ontology is a depiction of the logical structure, to which the concentric circle model adds perceptual significance as the eye focuses the attention of the perceiver (Fig. 16).

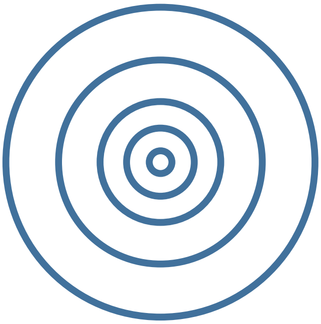

Fig. 16 Concentric circle model focusing the glance of the observer.

The focusing can only occur if a form can be differentiated from a background context. When objects enter a perceiver's context they lose their formal flat equality. We exit the formal plane and enter the semantic plane of classification, categorization, relations, and meaning. To visualize this, we overlay the concentric circle model with a sectioned circle model to differentiate the categories concept cluster and dimension while at the same time retaining the idea that the individual concepts should be depicted as uninformative priors by using a shape and boundary model of circles within a circle (Fig. 17). The latter is typically used in packing models used to maximize the space of a container. When the objects to be packed are not uniform, the packed circles are given multi scales, i.e. they can be illustrated as having different size or color. Since we wish to emphasize the equality of the concepts in the ontology prior to their consideration in a context, there is no scaling within a concept cluster of the ontology.

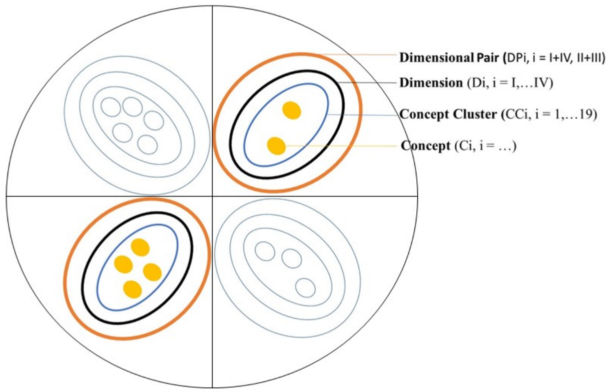

Fig. 17 Combined concentric, sectioned and circle packing models in the ontology.

Color hue is used as a demarcation of the four dimensions of the ontology while the choice of containment as a relational attribute of the structure is used to indicate that the grouping rule for concepts in a cluster is not one of inherited genealogical hierarchy, but rather that of family allure and resemblance.

The ouroboros symbol is overlayed on top of the concentric and sectioned circle models as a means of illustrating a different type of categorization than the one typical of the Western conceptual system of philosophy, where a category is by logical necessity a mono category. Eastern conceptual systems tend to categorize in pairs of opposites rather than in single units. The pairing of asymmetrical complementarities is ubiquitous in Eastern conceptual systems of philosophy, language and visual art and provide a different kind of perception, conception, understanding and learning about the phenomenological world. The ouroboros is then chosen to visualize a possible parallel containment structure as a grouping of two asymmetrical but complementary dimension pairs rather than four individual dimensions.

Through the visualization of the dimensional pairs, the design aims to enhance the user experience of a Western audience to whom asymmetries and contradictions appear as logically inconsistent. Simultaneously, it attempts to aid understanding of an Eastern audience unfamiliar with the Western notion of an ontology and practices of categorization by means of re-structuring the familiar pairing perspective.

Since the design is more interested in highlighting similarities rather than differences as a basis for a shared language, it should be pointed out that the circle and the ouroboros are not altogether different. From the rules of perspectival drawing we know that if only the distance between an observer and an object changes, only the size of the object appears different. This is the effect produced by zooming in and out of the concentric circle model. However, when the angle changes, the object alters its proportions. It becomes extended. Thus the dimensional pairs D I - D IV and D II – D III (see Chapter 5, Part II, Section 3) can be viewed as extended, sequential states of the same thing.

The ouroboros adds movement and causality to the static a-temporal circle. The ouroboros is a perspectival distortion. It is an extended circle. If the circle represents invariance at the formal level of logical organization, the ouroboros is the distorted projection, the variant form of the invariant circle as it appears and is perceived in perspective. Using natural language we can describe the visual language of distortion as the logical basis for grouping D I – D IV and D II – D III. In D I "things in the world" are defined through the perspectival "values" of D IV. These same values depend for their formulation on how things in D I are classified. Similarly, how the "processes" of D III are perceived, conceptualized and computed depends on the assumptions made along the ways of D II regarding knowledge and truth. The belief whether knowledge is conceptual or perceptual creates the pair mind – body. The belief whether true knowledge is conceptual or perceptual creates the pair objective – subjective. This is what lies at the bottom of a-priori assumptions regarding what is and is not knowable and whether what is there is really correspondingly out there or possibly coherently in here.

Visualizing the blueprint

The blueprint, like the semantic plane of the ontology, combines the concentric and sectioned circle models to form a radial sunburst. The slices denote the categories misfits, educational requirements and concept clusters. The sections denote how a particular instance of each category relates to instances of the other categories. Typically, a radial sunburst follows a hierarchical tree logic, with the root at the center and the sections expanding outwards. In the design of the present blueprint, the root of the radial tree is the middle slice (educational requirements). From there the sunburst contracts toward the inner slice (misfits) and expands toward the outer slice (concept clusters). The visualization is thus able to illustrate in a compact form the complexity of relations in designing for contextual and adaptive learning.

Color hue facilitates an immediate grasp of the design's choice to increase the learning content with D II concept clusters united in their family relations to the concept of information and to information modeling. Shading or color saturation is used in conjunction with hue at the inner slice level (misfits) to show the extent to which a particular requirement is problematic for research and education. Saturation thus helps to highlight a pattern of gaps between research and education.

Saturation instead of hue is used at the middle slice level (educational goals) to emphasize that they are different aspects of one category and that they must be pursued in concert, not individually. The same aspectual attribute of saturation is applied at the inner slice level (misfits) to emphasize the design's normative proposition that research and education should be pursued in balance.

Visualization in the sketch for a repository of digital learning objects

The purpose of the repository of digital learning objects is to support classroom activities with a form of e-learning (blended or flipped), which combines physical and digital educational environments in terms of instructors, learners, activities, resources, and spaces. A digital learning object corresponds in modularity to a concept in the ontology. The repository is thus a digital version of the ontology structure. A hyperbolic radial structure is chosen because hyperbolic trees are essentially enhanced radial trees for the digital medium. Hyperbolic structures follow non-Euclidean geometric rules and are based instead on Poincare's model for the hyperbolic plane. Munzner and Hanrahan (2000) show how in a hyperbolic space there is literally more space than in Euclidean space for the visualization of large networks since in Euclidean space a circle's circumference and area are said to increase polynomially, whereas in hyperbolic space they increase exponentially. Hyperbolic space enables a visualization technique called "focus and content" in digital interaction design, which allows the allocation of focus to a given node by increasing its size while retaining an overview of the slightly smaller nodes on the periphery of the network, i.e. the context.

The hyperbolic radial structure of the repository of digital objects functions as a navigation tool for situational awareness, offering a view of both how far and how deep a learner is in relation to a starting inquiry.

CHAPTER 9. CONCLUSION AND FUTURE OUTLOOK

In recognition of the challenges humanity faces in establishing a safe operating space for its present and future activities, this PhD project has sought to contribute to the theoretical and practical knowledge needed to support decisions on the governance of systemic risks.

In Faber (2011) the traditional approach of risk management with its focus on the risk assessment of individual hazards has been criticized for coming short of addressing the decision-making process in the context of risk governance on issues related to the sustainable development and management of societal resources from a holistic and long-term perspective. Particular challenges associated with the management and governance of risks identified in Faber (2011) include:

(i) sub-optimal public-private collaboration in the use of methodologies and tools for the treatment of risks;
(ii) lack of consensus among experts on basic principles of risk assessment and best practices;
(iii) insufficient or inappropriate education about risk assessment at the level of decision-making;
(iv) inconsistent criteria and decision processes regarding the prioritization of resources for global life safety risk reduction; and
(v) insufficient consideration of long-term issues related to sustainability in normative decision-making.

The postulate that these challenges are to some extent a result of epistemic uncertainty but primarily due to behavioral factors, or in Faber's words: "We know what should be done, but fail to do it.", has been taken up as the initial problem-context for investigation in the present thesis. Behind the public and private sectors demand for 'actionable knowledge', lies an implicit understanding that this knowledge must be evidence-based. In practice, 'evidence-based' is used interchangeably with 'risk-based' and 'science-based'. The concept of 'evidence', however, extends beyond deductive hypotheses verification. In the phenomenal world, a diversity of stakeholder evidences (information, interpretations, constraints, and priorities) form not one but many sources of evidence. These interacting information flows become multiple sets of evidence that inform decision-making through the strength of their influence. This influence is not necessarily risk-informed in the scientific sense, yet it is a powerful framer of the political agenda for prioritizing and allocating resources for the treatment of risks. Not even the scientific community of experts is immune to the influence of stakeholder evidence since research is commissioned and funded subject to the same framing, prioritizing, and allocating processes.

Since the concept of risk is fundamental to governance in that risk analysis is used as a tool for providing evidence in support of both decisions for actions and the legitimization of actions, an initial step in the research project has been to trace the historical development of the knowledge domain of risk and to identify patterns and trends driving its development. Using statistical datamining techniques, a corpus of 0.5 million peer reviewed journal articles indexed in the Web of Science were analyzed, and over a hundred cluster network maps produced, showing the history, disciplinary composition, authors, institutions, and countries involved in the production of research between 1990 and 2017.

In addition to the archival, historical value of mapping the evolution of the domain, the datamining has produced evidence of the significant and continuous growth in research on resilience and sustainability over the past 30 years. The cluster maps of conceptual terms have revealed that the content of the individual research traditions of risk, resilience and sustainability is to a very large extent overlapping. However, the actual integration of risk, resilience and sustainability considerations into common operational frameworks for science, governance and education is at its infancy. It is to the pragmatic integration of the above that the present PhD project is believed to have made a foundational contribution.

It has further been found that each knowledge tradition is itself internally dis-coherent and lacking a unifying theoretical and methodological framework and agreement on conceptual definitions, methods and metrics. For the knowledge tradition of risk, definitions, methodologies, metrics, and decision objectives have been found to be fractured on multiple levels. First, the PhD thesis has revealed that present hazard classification practices divide the academic disciplines that study any given hazard. Second, private and public sector institutions have been found to be fractured in terms of ownership and accountability of the processes involved in the management of hazards. Third, the methods and metrics applied in the study of individual hazards have been found to be split along two chasms: (i) the chasm between quantitative and qualitative and (ii) between deterministic and probabilistic methodologies. The thesis has constructively addressed both by proposing an ontology and a blueprint for education that are designed to build a bridge across such partial positions.

In illustrating the chain along which the internal fracturing of the knowledge domain propagates from ill-suited hazard classification practices to a cacophony of definitions, methods, metrics, and objectives, one of the most significant contributions of this thesis to theory and practice has been the introduction of a hazard classification system by information type. This novel classification system facilitates the contextual modeling of hazards by grouping them into information types based on their associated consequences rather than their sources of origin. This classification logic has in turn, provided a foundational basis for an integrated domain ontology of risk, resilience and sustainability.

Similar to the risk tradition, the tradition of resilience research is fractured into no less than ten partially overlapping perspectives: ecological resilience, spatial resilience, engineering resilience, infrastructure resilience, robustness, disaster resilience, community resilience, urban resilience, economic (development) resilience, and psychological resilience.

In the context of sustainability, the major rift between weak and strong interpretations of sustainability results in a tradeoff between weak interpretations of sustainability based on a narrow risk-based perspective that values efficiency and strong interpretations of sustainability based on an ecological resilience-informed perspective that values efficacy.

In designing a domain ontology that integrates the conceptual knowledge of the individual traditions, this PhD thesis attempts to contribute with a theoretic foundation to an emergent science. The education blueprint offers a dynamic template not simply for learning but for adaptive learning in interaction with knowledge producers (research) and knowledge consumers (practitioners in the public and private spheres of decision-making). For a framework such as the adaptive governance framework developed by Folke et al. (2005), a significant challenge remains how to, in practical terms, ensure that different types and sources of knowledge are incorporated in the decision-making process. The adaptive governance framework postulates that it is precisely the diversity of knowledge that engenders a system's adaptive capacity because diversity is key to ensuring that goals, strategies and knowledge are never fixed but continuously evolving with the context. Diversity is indeed a natural early warning system. Both the proposed ontology and education blueprint attempt to provide an operational model for Folke et al. (2005) conceptual framework for adaptive governance.

Unification and diversification are in the present thesis not opposing but complementary strategies. Unification has been the strategy with respect to theory building while diversification has been the strategy with respect to practical implementation. In using the concept of information as a fundamental psycho-physical principle in-forming the model world of scientific knowledge and the phenomenal world of engineered, social and ecological systems, the present thesis' chief contribution can be viewed as a stone in the foundation for a unified theoretical basis for an integrated risk-resilience-sustainability science based on a shared language not of technical terms but of concepts and their semantic ranges. It is believed that this science may, in turn, facilitate a better fit between the epistemic realm of what we know and the axiological realm of what we do.

Diversification underlines the scheme for operational trans-disciplinarity, multiple and non-linear learning pathways, creativity, and self-reliance in learning. Diversity is also followed as a principle for multimodal scientific communication where equal representation is given to words, numbers and images as sense-making tools.

In combining unification and diversification strategies, this thesis has sought to address the perennial question of how to stay on track of goals and objectives while keeping all options opened. In nature, specialization is a strategy that ensures the short-term efficiency of an objective, while diversification optimizes the successful outcome of anticipating surprise. The success of adaptive planning and governance is contingent on the effectiveness and timeliness of warning systems that monitor relevant environmental/contextual changes. Situational learning, which is problem-based, is in this sense a forward-looking indicator-based information processing activity. In the words of Ingold (2011), it is a "knowing along", an "ambulatory knowing". It is not a retrospective monitoring of pre-determined performance indicators. On this logical basis, the deeply held a-priori distinction expressed by the categorical pair teacher – student, is invalidated. The vision for education proposed in this thesis is neither that of knowledge transmitted by the authority of teacher-experts nor a student-centered process of maximizing stated student preferences. It is a journey into the unknown together. What and how to monitor along the way is the subject matter of the integrated science of risk, resilience and sustainability, which together with inquiry-based problem learning is the instrument for governance based on informed preferences.

Much work lies ahead in the continuous adaptation of the proposed domain ontology in concert with stakeholders from contributing disciplines, and in a way that is inclusive of more than Western conceptual traditions. In this thesis, only an initial attempt has been made to bring forth the relevance of the cultural context to descriptive scientific practice and to the local implementation of prescriptive guidelines that are culturally out-of-context. Deeper, anthropologically, linguistically, and philosophically-driven research in this direction could add value to the strategic, operational and tactical management of hazards that spill across borders.

It must be underlined that no ultimate version of the ontology can ever exist if it is to serve the purpose of adaptively co-evolving research-education. Operationally, such maintenance will require a network of collaborative stakeholders, which can greatly be facilitated by digital technologies that enable knowledge sharing in distributed networks.

Using the blueprint to plan and design educational activities will further require the concerted efforts of education managers, teaching practitioners, students, and technical learning designers. The next stage in the development of e.g., a repository of digital learning objects, a sketch for which is provided in the annex of Chapter 5, Paper III, is the design of a prototype that may provide a proof of concept for subsequent implementation.

For Hannah Arendt, the 20th century political philosopher of action, judgment and the human condition, thinking was a form of action. Her concept of the *vita activa* as the highest realization of human capacity attempted to re-invigorate the classical Greek idea that care and public service are the highest good for man's social nature (Arendt 1958/2013). She saw the value of thinking not in the production of knowledge based on theoretical justification, but in the pragmatic search to understand the meaning of experiences, actions, and circumstances in the phenomenal world. She called it "the human duty to think". The research in this PhD is but a single iteration in the dynamic interaction between Arendt's vita *contemplativa* and *vita activa*. Where the conceptual matter-form-function design pauses before a new iteration begins, with input from additional participants, action research continues the process.

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Appendix A

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APPENDIX A

Image schemas and conceptual metaphors in the domain ontology

Appendix A includes a presentation of the image schemas and conceptual metaphors that underlie the four dimensions of the ontology. All image schemas and conceptual metaphors have been selected from the works of Johnson (1990/2013), Lakoff (2008), Lakoff and Johnson (1999), and Lakoff and Núňez (2000). This thesis does not contribute to enhancing knowledge on image schemas, but to a novel application of the already identified image schemas and conceptual metaphors in the corpus of cognitive linguistics, namely the design of a domain ontology for a scientific discipline and an education blueprint. Fig. 1A provides an overview of the correspondence between the categorical pairs and image schemas for each dimension in the domain ontology.

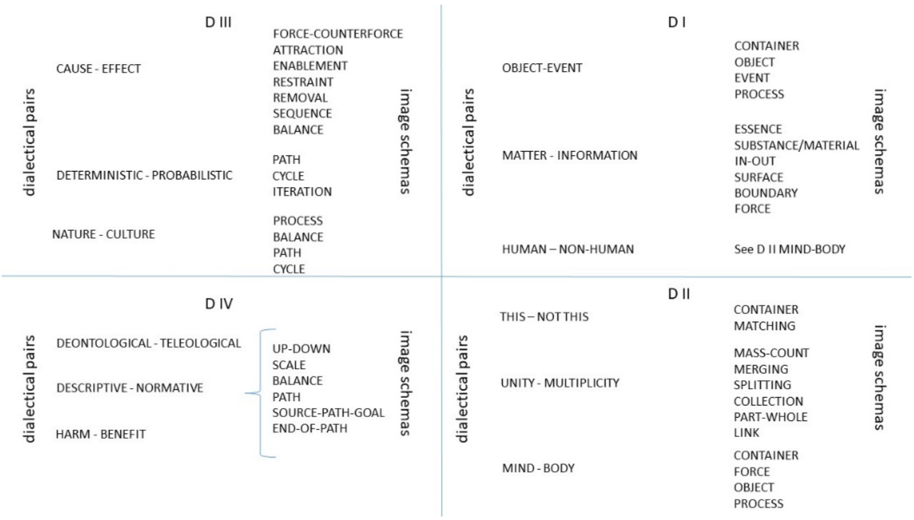

Fig. 1A Image schemas corresponding to the categorical pairs in the ontology.

In the following the image schemas and conceptual metaphors underlying each categorical pair are illustrated and discussed in accordance with the dimension in which they appear. The image schematic structure of Dimension I has already been presented in Chapter 5, Part II of this thesis and is included here once again as the Appendix seeks to provide a full overview of the image-schematic logic of the ontology.

Dimension I

The distinction between objects and events has a very long history in the Western conceptual system, resulting in a cascade of categorical pairs such as atomistic-relational, material-immaterial, etc. In embodied cognition research, the battle between object and event continues among proponents of OBJECT as the primary building block of conception and proponents of spatio-temporal EVENT schemas as primary in cognitive development. Since our design is pragmatically oriented, we disregard the question of origin and grant objects and events equal ontological status in D I. However, objects and events do not exist equally, in that whether an object or an event schema is chosen to conceptualize an experience, the consequences of this choice are not trivial for the modeling of risk, resilience and sustainability.

In Fig. 2A, it can be seen that the underlying cognitive structure for OBJECT and EVENT mirror each other, with the exception that the OBJECT schema is static, while the EVENT schema is dynamic. A possible metaphoric extension of the OBJECT schema is shown for the concept RESOURCE. It can be seen how a resource comes to be defined as an object relative to another object in terms of function. In the Western conceptual cognition system this metaphoric transfer creates a family resemblance among the concepts {resource – expenditure – scarcity – efficiency – waste – time – savings – worthiness – sustainability – efficacy – resilience} located in different dimensions of the ontology. This illustrates how although the image schemas constrain the choice of arbitrary interpretations for what a resource is, they are not universal. They are, instead embedded in a socio-cultural context. But while there might be a widely divergent understanding across cultures and social groups about what defines a single concept such as waste, resource or time, the cluster of concepts sharing a common image schema, affords a pragmatic understanding of the context in which a given concept is used.

The CONTAINER schema is the source domain of inferences about categories. Inferential logic, which is typically considered the epitome of conceptual reasoning in mathematics is actually spatial logic, i.e. it is embodied by virtue of our perception of objects in space as the metaphor Categories Are Containers demonstrates. CONTAINER schema inferences structure the logical concepts of 'Excluded Middle', 'Modus Ponens', 'Hypothetical Syllogism', and 'Modus Tollens', which is also the basic structure of Boolean logic set theory, and probability theory. (see Lakoff and Nuňez 2000).

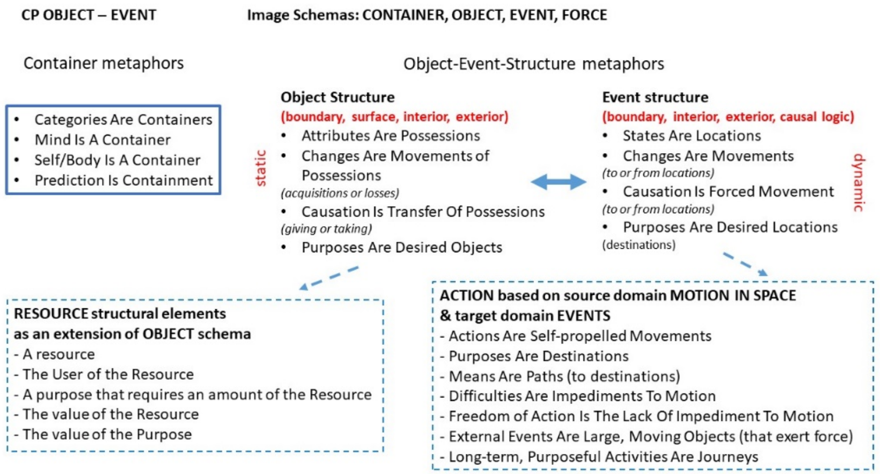

Fig. 2A Image schemas and conceptual metaphors for categorical pair OBJECT-EVENT based on selection from Johnson (1990/2013), Lakoff and Johnson (1999) and Lakoff 2008).

The second categorical pair of Dimension I deals with the material vs informational essence of reality. Fig. 3A shows the image schemas and metaphors on which the distinction between the material and immaterial rests.

Fig. 3A Image schemas and conceptual metaphors for categorical pair MATTER – INFORMATION based on selection from Johnson (1990/2013), Lakoff and Johnson (1999) and Lakoff (2008).

Dimension IV

The image schemas in Dimension IV relate all three categorical pairs, informing the structure for Western moral, legal and decision-making conceptual systems. In Fig. 4A it can be seen that the conception of HARM-BENEFIT is more deeply embodied, i.e. is based on metaphoric transfer directly from the physical domain of the body, than the more abstract notions of morality, justice and legitimacy. The same can be seen from top to bottom, where metaphors at the top appear to be more concrete and primary to physical experience and those toward the bottom appear to be more abstract derivations of experience translated into conceptual moral accounting and decision-making.

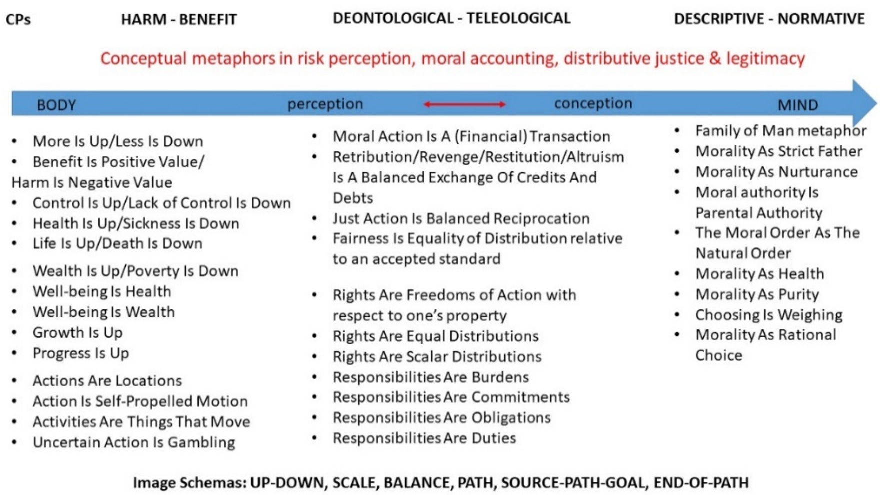

Fig. 4A Image schemas and conceptual metaphors for categorical pairs HARM-BENEFIT, DEONTOLOGICAL-TELEOLOGICAL, DESCRIPTIVE-NORMATIVE based on selection from Johnson (1990/2013), Lakoff and Johnson (1999) and Lakoff (2008).

What we see in this schematic representation is a logic of action and a logic for distributing things of value. Whether responsibilities are conceptualized as burdens, commitments, obligations, or duties determines if the exchange of values (positive and negative) as a balancing act of credits and debts is based on (i) equal distribution (all share equal parts), or (ii) scalar distribution (when greater strength/capacity/capability is allotted higher responsibility), or (iii) a contractual distribution (one gets what one has agreed to) (see, Johnson 1990/2013).

We see furthermore the underlying embodied structure of decision analysis, which we typically take for granted as the crowning achievement of rational, i.e. disembodied reason. In Lakoff and Johnson (1999) the game-theoretical model of rational action becomes a model for embodied decision analysis as the following sequence of conceptual metaphors demonstrates:

Purposes Are Destinations (via Event-Structure metaphor)

- Actors Are Travelers
- Courses of Action Are Paths From Location To Location
- Action Is Motion Along A Path
- The resulting State Is The Final Location
- The Initial State Is The Starting Location
- A Sequence Of Movements Is A History Of Actions
- Payoffs Are Positive Numbers
- Losses Are Negative Numbers
- Tradeoffs Are Gains For One Actor and Losses For Another.

In Dimension III, structural characteristics and further examples of the PATH schema are shown.

Dimension II

The image schemas and conceptual metaphors in the mathematical-linguistic Dimension II clearly show that categories are not objectively in the world (Fig. 5A). There are no natural kinds. Mathematics is not the symbolic language of nature and meaning is not determined based on sense-reference. Concepts and categories are structures in the mind arising from human-environment interactions. Order is neither inherent nor invariant but interactional. Order is co-determined by physical forces and psychological, social, and cultural factors.

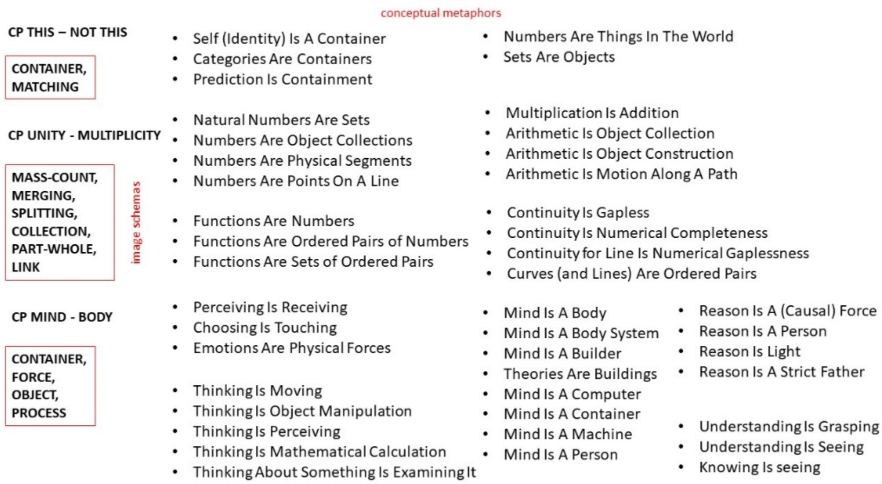

Fig. 5A Image schemas and conceptual metaphors for categorical pairs THIS-NOT THIS, UNITY-MULTIPLICITY, MIND-BODY based on selection from Johnson (1990/2013), Lakoff and Johnson (1999), Lakoff 2008, and Lakoff and Nuňez 2000.)

Dimension III

The image schemas and conceptual metaphors that underlie the dynamic Dimension III provide the framework for understanding cause-effect processes, deterministic-probabilistic order and natural laws vs human conventions. Space and time are the two basic concepts that structure all categorical pairs in this dimension. They are also related to the ontological Dimension I since whether they are given the ontological status of objects or events largely determines how the rest of the concepts in D III are framed. Space and time considerations are explicit and implicit in the modeling of risk, resilience and sustainability regardless the methods and metrics applied in their measurement or for their management. In Figure 6A the most basic source-target domain structures for space and time are given. Whatever the ontological status of space and time may be, cognitively time is typically thought of and described in terms of space, i.e. space is the source domain for time. The space-time relation is the origin of orientational metaphors such as before, after, ahead, behind, front, back, in, out, earlier, later, etc. Conceptualized as an object, space is a bounded region, a CONTAINER, where things exist. When it is conceptualized as an object, it can be measured on a more-less scale. When time is conceptualized as an object, it can be turned into a unit for measuring or into a resource. Time can also be conceptualized in terms of objects in motion observed from different vantage points. In the first case, the observer is stationary and times (future events) are objects moving backwards toward the observer. This conceptualization further yields the concept of consequence as a realized future event. In the second case, times (states) are fixed locations through which the observer is moving. When human actions are conceptualized via the Event-Structure metaphor, with Puposes as Destinations and Means as Paths (see Fig. 2A), the metaphoric origins and embodied cognitive basis of the concept of free will becomes evident. Free will - a central concept for all three categorical pairs of D III – is the experience of moving through time and space without impediment (see Lakoff and Johnson, 1999).

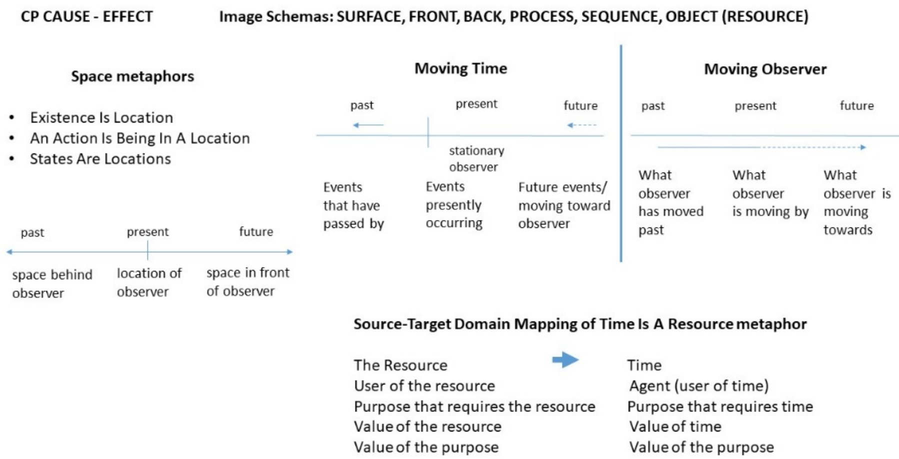

Fig. 6A Image schemas and conceptual metaphors for categorical pair CAUSE-EFFECT based on selection from Johnson (1990/2013), Lakoff and Johnson (1999) and Lakoff (2008).

In Fig. 7A the semantic range of the categorical pair CAUSE-EFFECT is extended through FORCE image schemas that metaphorically structure the conceptualization of change, causality and justified belief (evidence).

CP CAUSE - EFFECT Image Schemas: **FORCE (ATTRACTION, ENABLEMENT, COMPULSION, RESTRAINT, REMOVAL, COUNTERFORCE)**

Metaphoric transfer of modality

Modal verb	Force Image schema	Physical force	Rational force (evidence)
Must	Compulsion	- Parental authority - Peer pressure - Universal authority acting on the human will (biological or theological)	Given the evidence, there is one correct conclusion
May	Absence/ Removal of Restraint	Absence of authority	There is no known evidence to contradict a conclusion
Can	Enablement	Positive potential ability	Can = May Can't - some evidence to the contrary enables me not to reach a certain conclusion
Ought to	Compulsion	Authority	Available evidence influences my conclusion
Have to	Compulsion	Authority	Available evidence forces my conclusion
Need to	Compulsion	Internal state/conditions	Need not – available evidence does not compel me to a conclusion

Change metaphors

- Change Is Motion
- Changing Is Turning
- Essence of Being Is Change

Causation metaphors

- Causal Priority Is Temporal Priority
- Causes Are Forces
- Causation Is Forced Motion
- Causation Is Correlation
- Probability Is Distribution
- Causes Are Reasons
- Causation Is Action To Achieve A Purpose
- Causation Is Making

Fig. 7A Image schemas and conceptual metaphors for categorical pair CAUSE-EFFECT based on selection from Johnson (1990/2013), Lakoff and Johnson (1999) and Lakoff (2008).

In Johnson (1990/2013) six perceptual features of the image schema FORCE are identified as follows:

Force is experienced only through interaction with the environment

Force has a from-to trajectory, which defines a vector path in some direction

Typically, the vector path is mono-directional except in explosions that produce multiple paths

Because forces have origins and directionality, agents can manipulate them or control their movements toward a specific target or purpose

Forces are quantifiable by virtue of having intensity

The experience of force through interaction results in the conceptualization of causal sequence from cause to effect.

Fig. 8A illustrates basic FORCE image schemas as given in Johnson (1990).

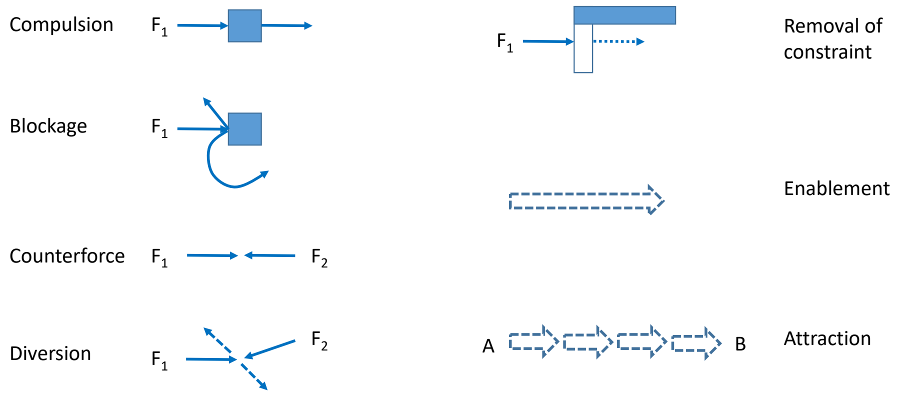

Fig. 8A Basic FORCE image schemas: COMPULSION, BLOCKAGE, COUNTERFORCE, DIVERSION, REMOVAL OF RESTRAINT, ENABLEMENT, and ATTRACTION (from Johnson 1990/2013).

FORCE image schemas are at the root of conceptualizing modality, i.e. states expressed by the modal verbs can, may, might, must, should, and could. In contrast with logic, where modality is analyzed in terms of aspects of actuality, possibility and necessity, Sweetser's (1982) empirical study in the tradition of cognitive linguistics, shows that modality is embodied in physical and social interactions, not only in the epistemic realm of reasoning. Her modal typology compares "root" and epistemic uses of modals such as 'can' (ability), 'may' (permission) and 'must' (obligation), showing that their embodied meaning in the physical domain of human interactions extends to the epistemic domains of logic to conceptualize notions such as possibility, necessity and probability. The implications of this research are significant beyond the applied context of linguistics. The study is an empirical demonstration of how normativity is a-priori embodied in descriptive and explanatory logic of reasoning. At the structural level of image schemas, there is thus no sharp distinction between normative and descriptive. In the context of risk, resilience and sustainability science, this implies that there is no necessary logical reason for (i) separating descriptive risk assessment from normative risk management or (ii) for distinguishing between descriptive thresholds and normative limits in the Planetary Boundaries framework (Rockström et al. 2009, Steffen et al. 2015). 'Action' and 'Thought' are not separate at the embodied cognition level. What is more, it is 'Action' (the embodied human-environment interaction) that gives structure to 'Thought' (human descriptions, explanations and deliberations about the environment) – not the other way around. Practice begets theory. Theory can maintain, change, or bury a practice. Johnson (1990/2013) points out that "reasoning is something people do with propositions, not some abstract relation among propositions". A-priori knowledge is thus not the logical knowledge of a reasoning mind; a-priori knowledge is embodied experience.

Other pervasive image schemas in Dimension III are those of PATH and BALANCE, PROCESS, ITERATION, and CYCLE are variations of conceptualizing sequences in space and time. What all variations of the PATH schema share structurally is a starting point, an ending point, and a sequence of contiguous locations connecting the former to the latter. The PATH schema is used to formulate the alternative learning pathways in the education design presented in Chapter 5, Part III. Here attention is drawn to how a PATH schema is transformed from a measure of space to a measure of time through conceptualizing a path as a CYCLE, and how the further combination of CYCLE and BALANCE forms the concept of equilibrium, which is central to the conceptualization of resilience.

In Johnson (1990/2013) equilibrium is visualized as a sine wave with periodic rise and fall (see Fig. 9A).

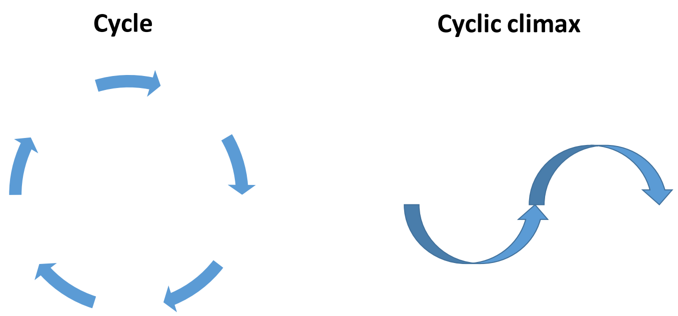

Fig. 9A Illustration of the relationship between cycles and cyclic climax (from Johnson (1990/2013)).

Johnson (1990/2013) points out that the high and low points of the cyclic process are not "objectively" in the world, but are perceived as such by virtue of imposing a SCALE image schema onto the CYCLE schema. The SCALE schema, namely allows for intensity or amount (more or less) to be mapped onto the cycle. The product of this overlay are categorical pairs, e.g. health-sickness, harm-benefit, etc. The structural properties of the BALANCE schema are the backbone of the mathematical-logical concepts of: (i) symmetry (A balances B and B balances A); (ii) transitivity (If A balances B and B balances C, then A balances C), and (iii) Reflexivity (A balances A). The BALANCE image schema is a quasi-universal, which is used at the top level of the ontology (represented as a ouroboros of two dimensional pairs) as basis for finding a shared language not only among the different academic domains that make use of the concept of balance, but across the cultural and epistemic traditions of West and East.

In Fig. 10A combinations (blends) of the image schemas PATH, BALANCE, PROCESS, ITERATION, and CYCLE show deterministic order is differentiated from probabilistic order, and how this further leads to justifications for various moral orders and the separation of humans from their environment.

CP DETERMINISTIC - PROBABILISTIC

Image Schemas: PATH, ITERATION, PROCESS

- Spaces Are Sets of Points
- States Are Locations
- Mathematical Function Is Curve In A Cartesian Plane
- Continuity For Function Is Preservation Of Closeness
- Infinite Sums Are Limits Of Infinite Sequences

- Change Is Motion
- Recurrence Is Circularity
- Indefinite Continuous Processes Are Iterative Processes
- Instantaneous Change Is Average Change
- Instantaneous Speed Is Average Speed

- Purposes Are Physical Goals
- Purposes Are Destinations
- Motion Along A Path Is Achievement Of Purpose

CP NATURE - CULTURE

Image Schemas: CYCLE, BALANCE, PROCESS

Axis balance conceptual metaphors
- Rational Action,
- Rational Actor
- Rational Choice
- Consequentialism

Twin-pan and point balance conceptual metaphors
- Balance of power (political science)
- Balance of argument (scientific/epistemic realm of rationality)
- Cost-benefit balance of losses and gains (economics)
- Moral and legal balance (realm of civil institutions)
- Correspondence theory of Truth (philosophy)
- Natural Kinds (philosophy)
- Equality (mathematics)
- Isomorphism (mathematics)
- Model (mathematics)

Equilibrium conceptual metaphors
All instances of systems (bounded space with in-out orientation), where parts interact in functional unity

Fig. 10A Image schemas and conceptual metaphors for categorical pairs DETERMINISTIC-PROBABILISTIC and NATURE-CULTURE based on selection from Johnson (1990/2013), Lakoff and Johnson (1999) and Lakoff (2008).

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