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Published in:
Sustainable and Resilient Infrastructure

DOI (link to publication from Publisher):
10.1080/23789689.2021.1937775

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

Taylor & Francis
Taylor & Francis Group

Sustainable and Resilient Infrastructure

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tsri20

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To cite this article: Linda Nielsen & Michael Havbro Faber (2022) Toward an information theoretic ontology of risk, resilience and sustainability and a blueprint for education– Part I, Sustainable and Resilient Infrastructure, 7:5, 459-479, DOI: 10.1080/23789689.2021.1937775

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SUSTAINABLE AND RESILIENT INFRASTRUCTURE
2022, VOL. 7, NO. 5, 459–479
https://doi.org/10.1080/23789689.2021.1937775

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

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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.

ARTICLE HISTORY
Received 13 September 2020
Accepted 24 May 2021

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 the potential 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 Bernoulli (1738) and Bayes (1763), and further based on axioms of utility theory by von Neumann and Morgenstern (1944). Since the 1970s, the discipline of psychology and its offshoots behavioral economics and cognitive science have contributed to descriptive decision analysis with theoretical insights such as, e.g.,, Prospect theory (Kahneman & Tversky, 1979), applied, and theoretical research in mental models (Craik, 1943; Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991), cognitive biases, and heuristics (Gigerenzer, 2007; Gigerenzer & Gaissmaier, 2011; Heuer, 1999; Kahneman, 2011; Kahneman et al., 1982; Tversky & Kahneman, 1973, 1981, 1974), and applied and theoretical research in emotional and volitional processes (Damasio, 2001; Slovic, 2010; Slovic et al., 1980, 1986). 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 & Wildavsky, 1983). A sociological theory of risk is outlined in Beck et al. (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 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

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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 & Faber, 2019), the acknowledgement of the generic aspects of risk analysis, independent of application area, and the social and political trends 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 shortcomings 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 redesign 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 Figure 1.

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 educational programs that have sprung up over the past decade (Nielsen and Faber, 2018), we provide the system understanding – or baseline 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 presents 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. Section 5 concludes with a summary of the motivation and the methodological basis of the proposed framework, presented in detail in the subsequent parts of the triad.

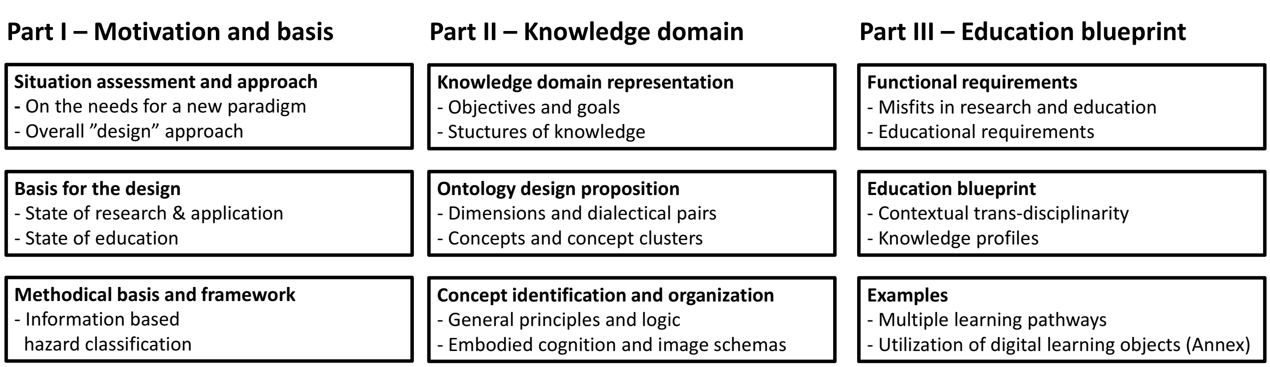

Figure 1. Overview of the structure and contents of the three papers presenting the information theoretic ontology of risk, resilience and sustainability and a blueprint for education.

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.'

- Functions define 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.
- Forms include 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 content 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-form of data. Information can thus be thought of as immaterial material, that is, the structure that structures and the structuring process, the building of structures. As an element of the ontology and blueprint design, the 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, and 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 which sequence, and (iii) with which weights.

An analogy to the educational 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.
- Forms include the natural laws of physics and 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 the geometry and characteristics of materials, which might be chosen to fill into the equations of mechanics to optimize the 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 similarly 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 in the term matter, we refer to the manifold context of risk, resilience, and sustainability governance. Formally, matter may be seen to be comprised 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. 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), the historical aspect of natural selection is set in perspective to physical and mathematical laws such that the 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] However, 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 is then 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 most often framed and solved marginally, with exogenously given boundary conditions for 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 domain of risk, the practice of compiling 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 infinite number 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 the problem at hand as it is through the perception of misfits that the problem's essence is perceived.[4]

In synthesizing the knowledge domain of risk, resilience and sustainability and designing the education blueprint, we take guidance in the design methodology of Alexander, wherein 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 on 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 at 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 (2021b)).

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 'functional requirements'. The design objective is to minimize misfits, in the same sense that decisions might be optimized to minimize the expected value of losses, which implicitly and subjectively weighs the misfits.

2.2. Elements of the design process

As mentioned earlier, the ontology and education blueprint design problems 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 Figure 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 (forms) with a representation of functional properties or constraints (functions) is referred to as 'constructive diagram'.

The constructive diagram shown in Figure 2 illustrates the four phases of the design together with their interactions. The diagram indicates that 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:

(I) Defining the design problem, design objectives, and desired outcomes
(II) Defining the context
(III) Defining the functional requirements
(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 subdivided 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

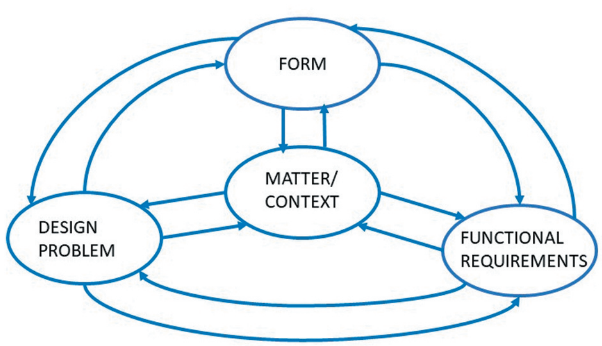

Figure 2. Constructive diagram illustrating the (interacting) phases in establishing the domain ontology and the design of the education blueprint.

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 redesign risk education in accordance with a redefined 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 all have high relevance but is not of our concern in re-designing risk education. The focus of our knowledge domain synthesis and education blueprint design concern 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. Figure 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.

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.' The gap between knowing what should be done but failing to do it is largely a result of inadequate best practices in governance and education.

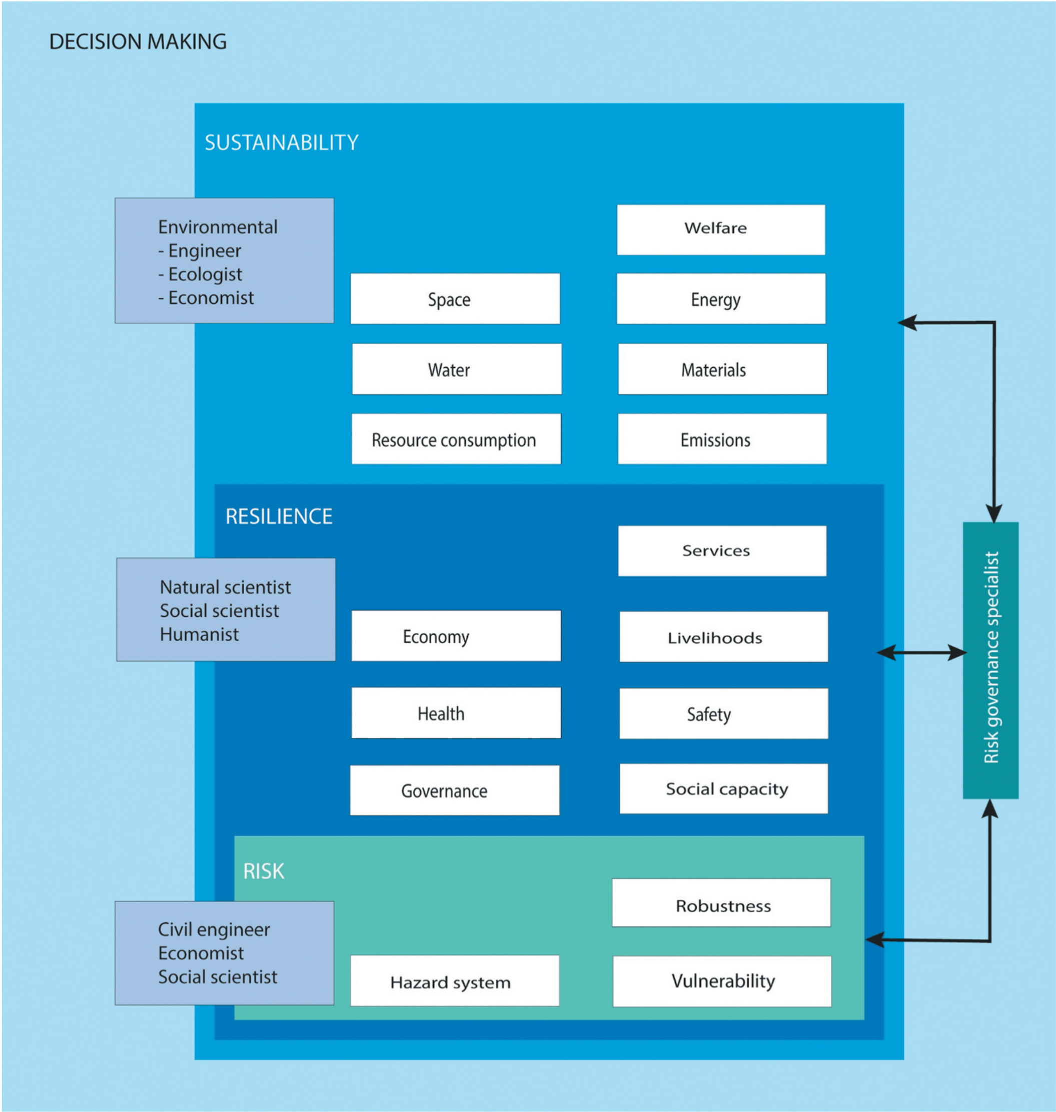

Figure 3. Roles of disciplinary experts and risk governance specialists in governance of risk, resilience and sustainability (adapted from Faber (2018)).

Box 1 presents a non-exhaustive list of examples of poor governance best practices. There are furthermore numerous examples of inadequate educational practices, the large majority of which are due to the tendency of educational programs to focus on preparing students to fill out functional needs according to established governance best practices rather than on equipping students with fundamental conceptual knowledge that enables students to critically assess, and if necessary, challenge the adequacy of so-called 'best practices'. Concrete examples of inadequate practices stemming from research and education are presented as the two sets of 'misfits' that the education blueprint developed in part III of the triad aims to optimize.

Box 1 Selected examples of poor best practices in risk, resilience, and sustainability governance

- Inconsistent representation of knowledge, i.e., uncertainties, dependencies, and dynamic back-coupling, multiple terms, and definitions for the same concepts
- Mix-up of descriptive and normative decision analysis
- Neglect of Bayesian decision analysis as the normative basis for ranking of decision alternatives and optimization
- Incoherent risk acceptance criteria across application domains and sectors
- Cognitive biases dominate governance focus on most recent events of large consequences and small probabilities – neglecting high probability low consequence events
- Governance focus on loss reduction (tactical governance) rather than risk mitigation (strategic/operational governance)
- Resilience governance of societal systems most often focus on the recovery phase immediately after particular disruptive events – and fails to holistically account for multiple hazards and system performances over (longer) time horizons
- Resilience is presently a top priority in governance of socio-ecological systems – but there is little/no focus on affordability – how resilient is resilient enough?
- Societal decision makers are responsible for long-term societal developments – but focus on short-term accomplishments

- Sustainable societal developments are generally understood to ensure equity over time – considerations on equity over space are, however, generally limited to a rather narrow 'nation state' perspectives

We view 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 takes 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 based on 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–Tables 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 of the state of knowledge and the state of decision-making. On the basis of those considerations, in Figure 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.

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

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 total sum of all hazards and their manifested consequences. The conceptual dimension is the immaterial world of knowledge and information flow 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 Figure 5, into four mutually interacting elements,

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' M.Sc. – '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 instructions to justify the nomination of 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 predefined but emerge as a map of potential consequences in space and time. Thus, context rather than a-priori disciplinarity and/or best practice defines a system and categorizes it as technical, environmental/ecological, social, or hybrid. • A generic, information-based approach to the assessment and management of hazards provides a 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-the- Art Research	• 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 terms. Divergent methods, procedures, and metrics follow as a result of the lack of a shared conceptual system. • Rigor in the 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 the study of social-technical systems, 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 the 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 public via decision-makers is ineffective and inefficient due to misinterpretation and distortion of information in the communication channel. Loss of trust and legitimacy for 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 ability at the level of conceptualization results in an inability to critically assess the nature of data and 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 is necessary for holistic understanding and modeling of systems dynamics. • Contextual understanding of concepts facilitates 'shared language' across academic, professional, and cultural traditions. • All hazard approaches to the assessment and management of hazards and risks • Whole-of-governance approaches 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-the- Art Research	Partial (incomplete and/or biased) knowledge of systems dynamics. Conceptually irreconcilable tradeoffs between resilience and sustainability at local scale.
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 a 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.

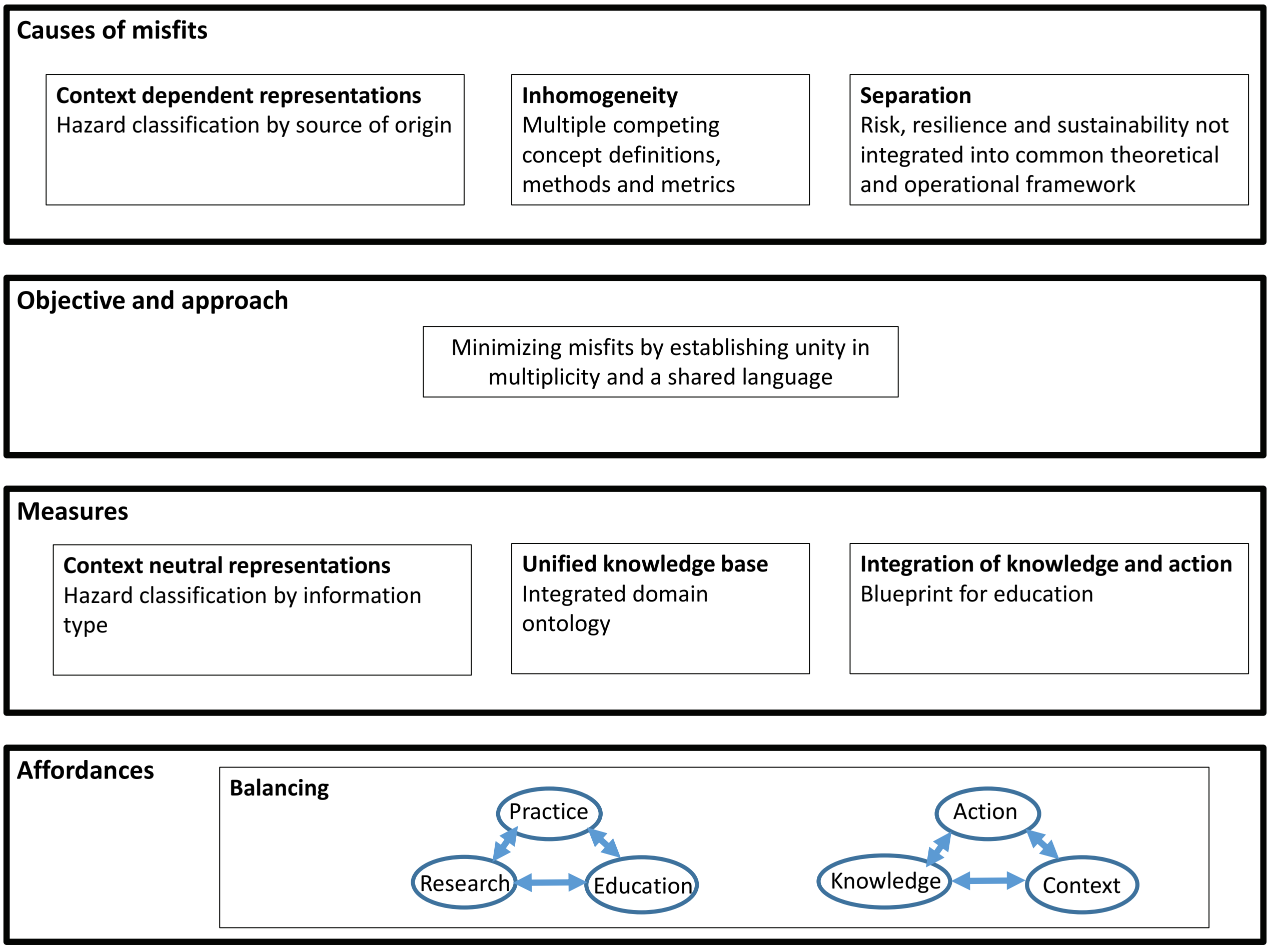

Figure 4. Design problem context, objectives and purposes.

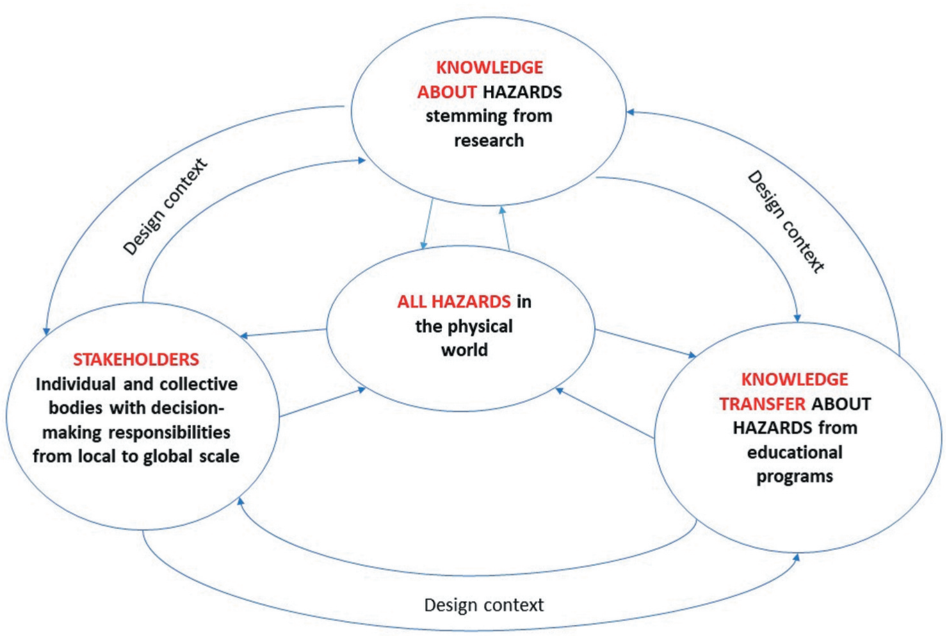

Figure 5. Elements of the design context for the domain ontology and education blueprint.

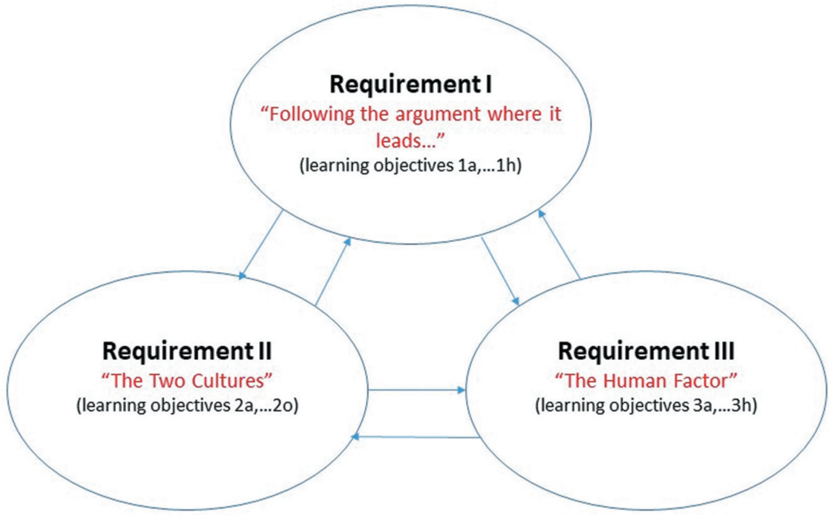

Figure 6. Functional – educational requirements.

named 'All Hazards,' 'Knowledge About,' 'Knowledge Transfer,' and 'Stakeholders'.

2.2.3. Phase III – Defining the functional requirements

As shown in Figure 6, the functional requirements consist 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.

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 reunite the 'The Two Cultures' (Snow, 1959) – of the natural and human sciences in the pursuit of holistic systems understanding and modeling. System 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 explanations for a-priori knowledge not based on pure reasoning, but on a synthesis of physical perception and mental conception.

The educational blueprint is prescriptive in function, but informed 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 blueprints 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.

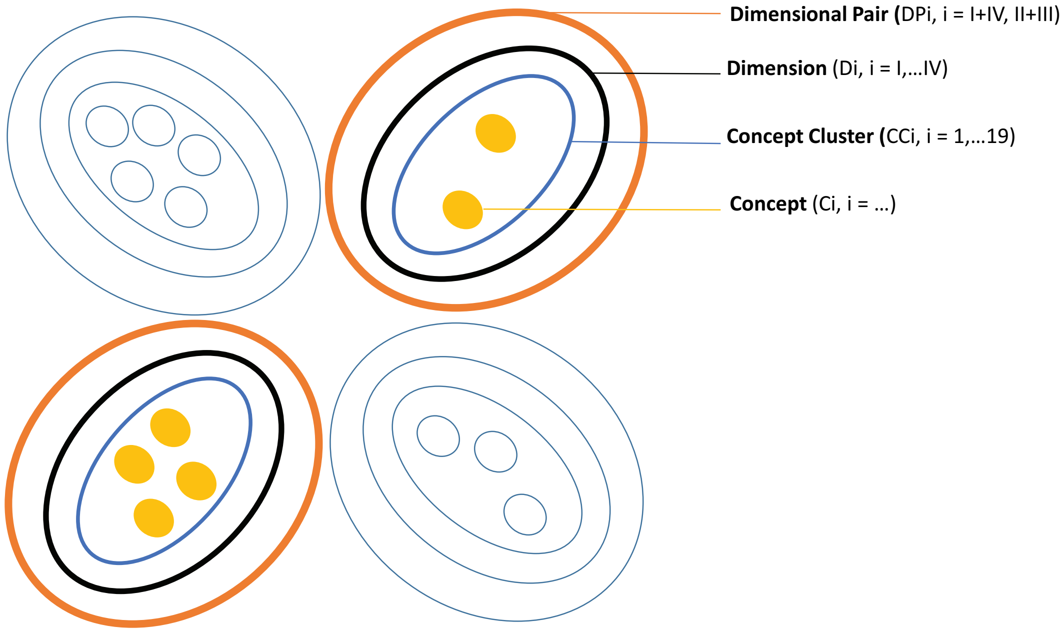

Figure 7. Structural elements of the domain ontology.

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.

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

The smallest object is an individual concept. The 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. The concept cluster is located in one dimension.

The four dimensions comprise a higher category of association based on a concept function in the ontology. Concepts in Dimension I (DI) 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 & 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 & Schlaifer, 1961).

The fundamental mechanism of Bayesian reasoning is that knowledge is acquired through a 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 wherein principle no prior knowledge is available, the representation of prior knowledge is generally chosen such as to weigh any possibly 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 has also already been 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 – contains 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 can 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 that due to the subjective elements associated with cognition, the selection of relevant concepts cannot be predetermined, 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 intercultural understanding of the different logical rules for structuring conceptual systems. To this end, in Part II of the triad we go to 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 also 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 & 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 this 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 the 1990s to the present, a distinct categorical demarcation is visible in the divisive labeling of ‚engineered, and ‚ ecological, ‚ and social, or from about 2009 onward 'social-ecological-systems' (SES), see Figure 8. The foundational conceptual work behind the SES was laid down by (Berkes & Folke, 1998) (Berkes et al., 2003); Ostrom (2007, 2009); and Anderies et al. (2004). The idea behind all the early work on SES was to develop an analytical structure for studying local resource management systems. During the first decade of the 2000s the concept of SES was thus a very 'local' concept in Ecology (in taxonomic terms: subordinate level of individual life forms). What can be seen in Figure 8 is the transformation of a subordinate level concept to a higher level of abstraction as the concept was 'picked up' by disciplines ranging from Engineering to Management to Social Sciences domains. With the politicization of the SES concept, the world of artifacts was labeled 'The Built Environment' – in direct opposition to that of nature and humans. Introducing concepts such as SES and their family relations 'resilience', 'adaptive governance', 'sustainability', etc. into the semantic range of the concept 'risk' is clearly seen on the cluster maps as making a dramatic jump in the number of these publications at just around 2009–10.

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

More than an ideological construct, it is also covertly deceptive as the following network visualization of the term 'community resilience' illustrates (Figure 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 an 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.

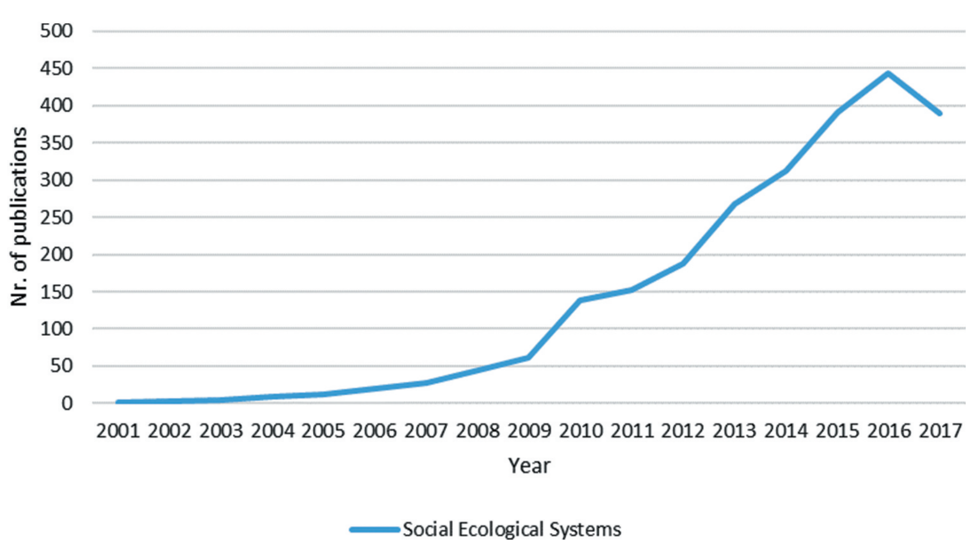

Figure 8. Evolution timeline of SES based on data from WoS (Nielsen & Faber, 2019).

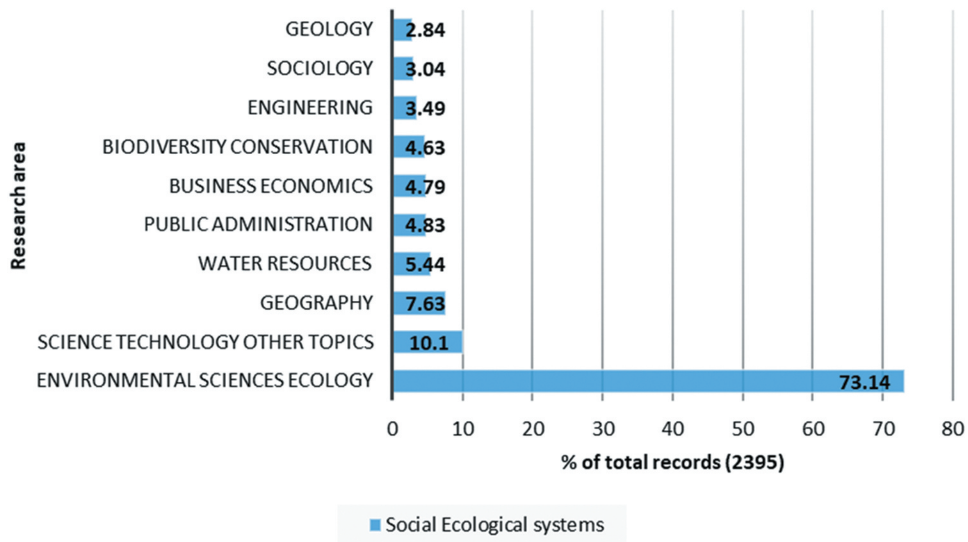

Figure 9. Distribution of research on social-ecological systems by discipline (Nielsen & Faber, 2019).

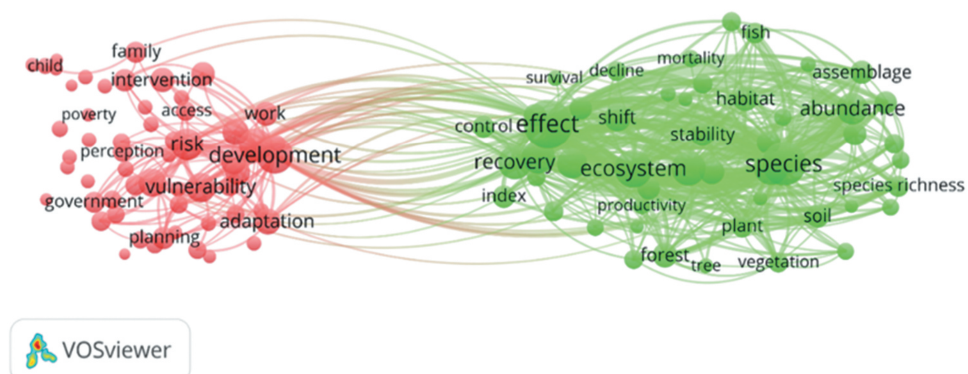

Figure 10. Cluster term map of research on community resilience.

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 (Figures 9 and 11).

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 practices of 1990s. Methods such as risk matrices and FN curves, which have been discredited as ineffective and outright hazardously misleading (Anthony (Tony) Cox Jr, 2008), are a staple in courses on risk methods. To the best of our knowledge, there exists no academic program that integrates risk, resilience, and sustainability in its curriculum in a logically coherent and operational manner. In a desktop survey of educational programs at risk in Europe (see, Nielsen & Nielsen, 2017), 107 post-graduate programs are identified, all of which date back less than a decade, i.e., to about 2010 or later. Although 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 (Figure 12):

The integration of resilience and sustainability considerations into the knowledge domain of risk renders the above

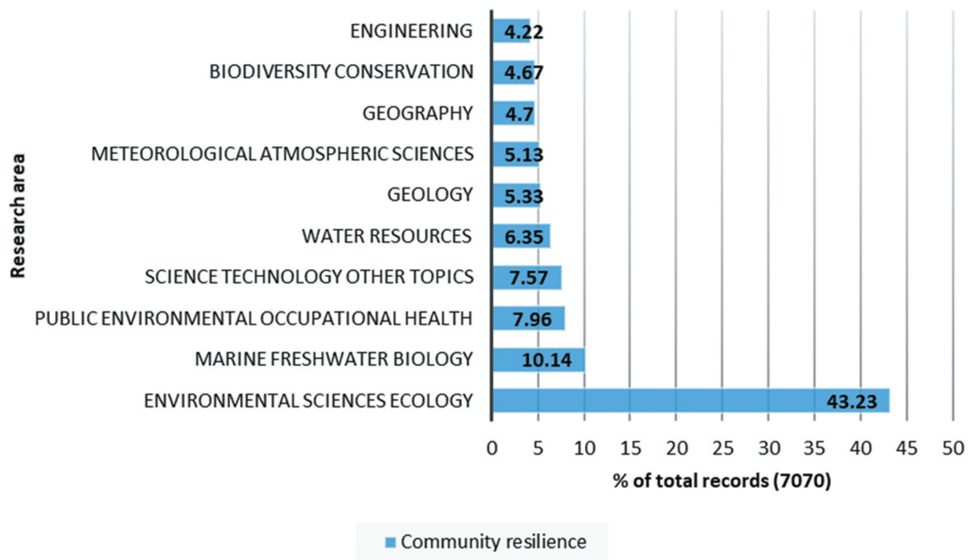

Figure 11. Distribution of research on community resilience by discipline.

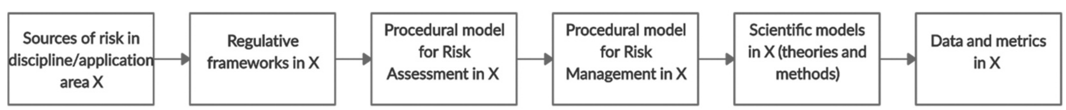

Figure 12. Elements and sequence of risk programs curricula.

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. Non-linearity in the context of comparing engineering and design problems should be understood to be a product of the potentially much higher uncertainty associated with understanding the context of a design problem and the dynamic interactions a design problem poses, i.e., in terms of back-couplings between form and context, whereby the process of designing becomes non-linear.

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 percent of 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

Current best practice hazard classifications are based on their source of origin: man-made hazards, environmental hazards, biological hazards, etc. (Figure 13). This classification may be realized as a strong contributing factor for the

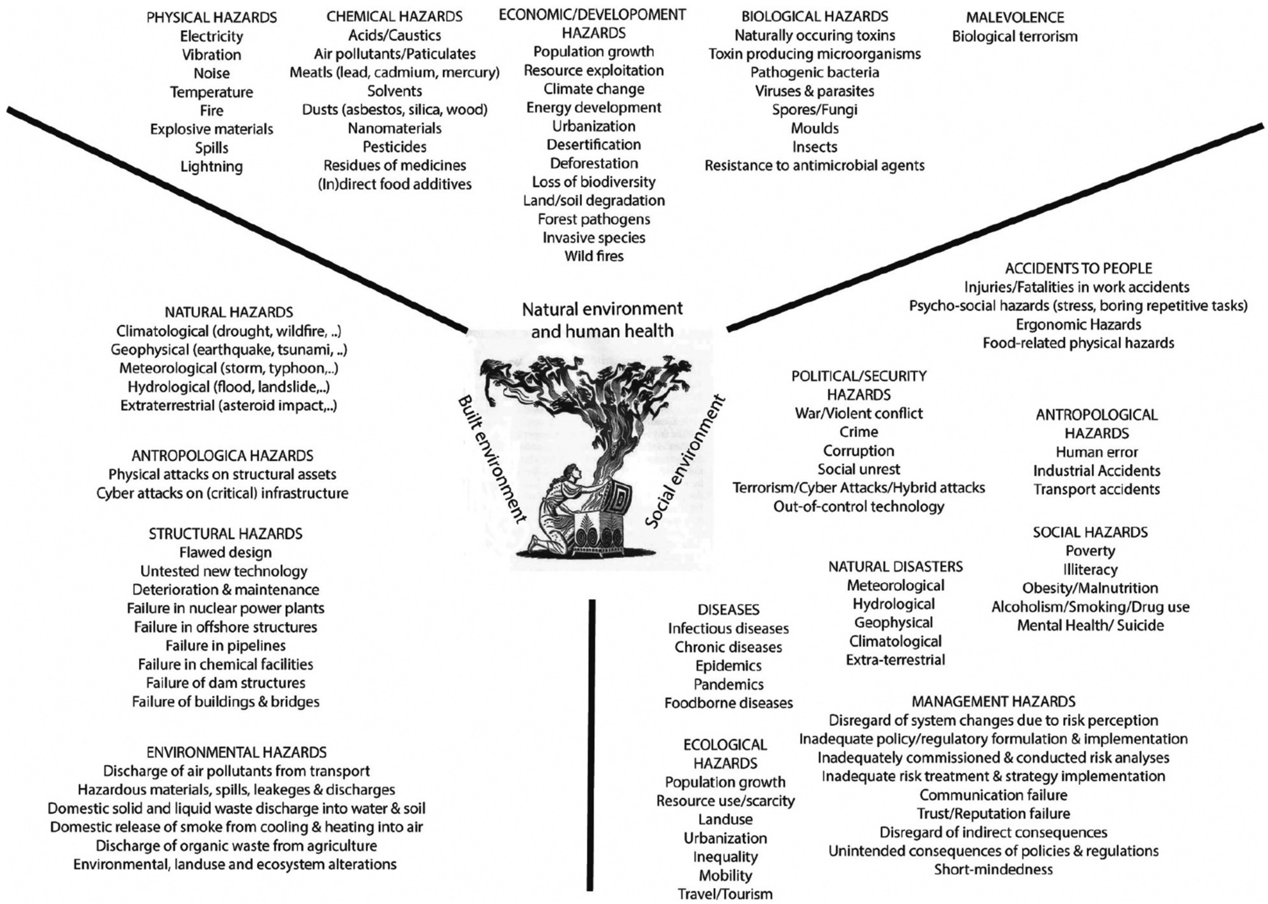

Figure 13. Pandora's Box classification of hazards by source of origin.

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.

These 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 et al. (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)), as illustrated in Figure 14.

Based on the systems representation in Figure 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).

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 dimensional 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 from 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. Summary

The present contribution is Part I of a triad of papers reporting on the development of an ontology and

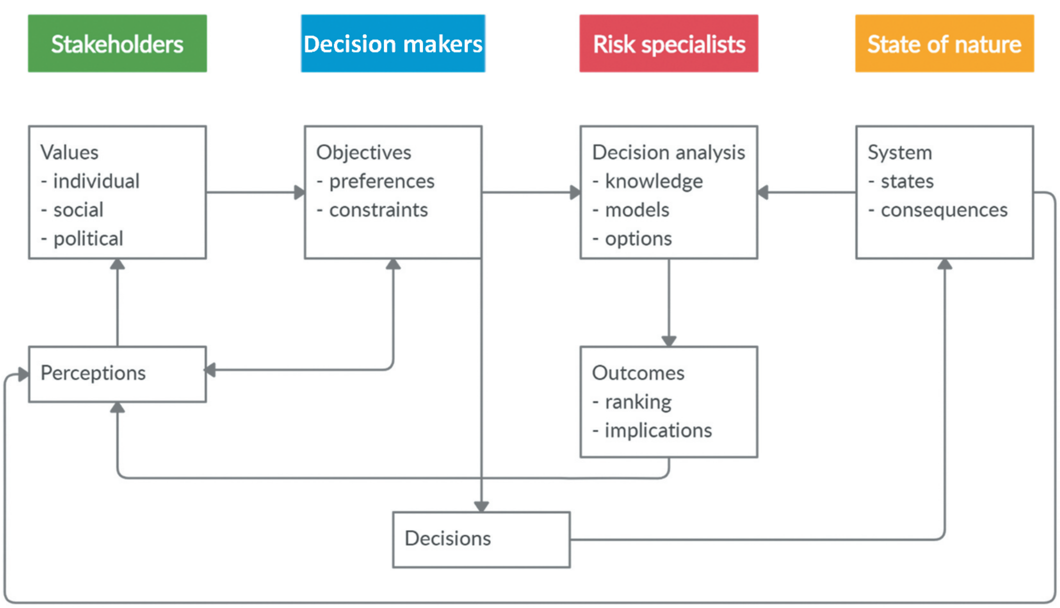

Figure 14. Systems representation of interactions among stakeholders in the decision-making context with focus on the non-linear flow (arrows between boxes) of information affecting decision ranking and outcomes of decision making. Adapted from .Nielsen et al. (2019)

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 & 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 are involved	May play a role for Type I, Type II and Type III

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 scientific 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.

As has been observed from the bibliometric study, there has been and still prevails a societal bias towards solutions to the larger societal challenges through research in natural and engineering sciences. This trend may be interpreted as an implicit societal preference for maintaining our general mode of societal operation – with better tools/technology. It is, however, not evident, nor has it been documented that this preference is in any manner an informed preference, nor superior to a basis for governance and education which unemotionally builds on and weighs the relevance of knowledge in the context of its application.

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 the present practice, organization, and conduct of research and education. This 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. This information-oriented perspective to risk sheds light on the significance not only of available or achievable knowledge related to the state 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.

Notes

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, 2021a, 2021b).
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.'
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.'
5. This is the label we have given to the first overarching education requirement for the blueprint discussed in Part 3 of the triad.

Acknowledgments

The present work was conducted in part under the European Erasmus+ project Knowledge for Resilient Society (K-FORCE), for whose financial support the authors would like to express their sincere gratitude.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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