UNIVERSITY OF COPENHAGEN
FACULTY OF HEALTH AND MEDICAL SCIENCES

From Risk to Resilience

Challenging Predictability in Contemporary Disaster and Emergency Management Thinking

Uncertainty ahead: A view from the bridge of the HDMS *Knud Rasmussen*, heading slowly towards Ella Island in the uncharted waters of King Oscar Fjord, Northeast Greenland, September 2016. Photo: Rasmus Dahlberg.

PhD Thesis

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This thesis was submitted to the Graduate School of Health and Medical Sciences, University of Copenhagen, on December 6, 2016. Revised and resubmitted April 25, 2017.

Contents

Dedicated to my father. Be strong, be resilient.

Summary

This thesis investigates unpredictability in contemporary disaster and emergency management. The thesis traces the shift from risk thinking towards the resilience approach that has recently characterized the field. It asks how resilience manifests itself in practice and discusses how to incorporate this approach into preparedness planning to improve the ability of socio-technological systems to cope with unexpected disruptions. Those working in the field understand *resilience* as a broad umbrella term linked to risk thinking and concerned with flexible systems that are able to absorb and adapt to disruption. However, at the same time, some in the field protest that the concept lacks a clear and commonly shared definition. We investigate this by employing a conceptual historical approach to unpack the contents of central concepts, such as *risk*, *predictability* and *uncertainty*. We then analyze *resilience* and *complexity* discourses in an attempt to conjoin the two concepts. This broad discussion leads into a case study of resilience thinking in contemporary disaster and emergency management: preparedness planning for long-term disruptions of the Øresund Bridge between Denmark and Sweden. Through observational studies and policy analysis of the proceedings and results of the Work Group for Øresund Preparedness, the thesis argues that "possibilistic" risk assessment is a relevant and necessary addition to probabilistic risk assessment. In addition, it argues that examples of previous disruptions of infrastructures provide valuable lessons for preparedness planners. To further investigate the potential adaptive capacities of the infrastructure system, a small qualitative study was designed and carried out. Its main findings indicate that citizens perceive themselves as, to a large degree, able to absorb and adjust to even major disruptions, and that authorities and infrastructure operators may rely on their ability and willingness to partake in problem-solving as long as they are provided with adequate information. The study also shows that citizens intend to cooperate with each other and coordinate with their employers before counting on assistance from authorities and infrastructure operators. From the broad conceptual analysis and the narrower case study, the thesis concludes that the shift from risk to resilience in contemporary disaster and emergency management is closely related to the acceptance of some degree of uncertainty and the unpredictability of complex societal systems.

Resumé

Denne afhandling diskuterer uforudsigelighed i moderne beredskabstænkning gennem en undersøgelse af den overgang fra risiko- til resiliensfokus, som gennem det seneste årti har kendetegnet feltet. Der spørges til, hvordan resiliens kommer til udtryk i praksis, og hvordan denne tilgang kan integreres i forebyggende planlægning med henblik på at styrke socio-teknologiske systemers evne til at håndtere uforudsete forstyrrelser. *Resiliens* forstås som en bred samlebetegnelse, som er koblet til risikotænkning, og som omhandler fleksible systemer, der er i stand til absorbere og tilpasse sig, men samtidig ses begrebet som omdiskuteret og uden en klar og generelt accepteret betydning. For at undersøge dette nærmere anvendes en begrebshistorisk tilgang, som udfolder begreberne *risiko*, *forudsigelighed* og *usikkerhed*, hvorefter *resiliens* og *kompleksitet* analyseres diskursivt i et forsøg på at forene de to begreber. Denne brede diskussion fører ind i en undersøgelse af en konkret manifestation af resilienstænkning inden for moderne katastrofehåndtering og beredskab: beredskabsplanlægning vedrørende langtidsafbrydelser af Øresundsbron mellem Danmark og Sverige. På baggrund af observationsstudier og en dokumentanalyse af processen bag en rapport om langtidsafbrydelser fra Arbejdsgruppen for Øresundsberdskab viser afhandlingen, at "possibilistic" risikovurdering er en relevant og nødvendig tilføjelse til risikovurdering baseret på sandsynlighed, samt at eksempler på tidligere afbrydelser rummer nyttig viden for beredskabsplanlægning. For at undersøge mulige adaptive kapaciteter i infrastruktursystemet anvendes en begrænset kvalitativ analyse. Resultaterne heraf viser, at borgere i et vist omfang opfatter sig selv som værende i stand til og villige til at deltage i problemløsning, forudsat at de modtager nødvendige informationer. Undersøgelsen viser også, at rejsende agter at samarbejde med hinanden og koordinere med deres arbejdsgivere i højere grad end at forvente hjælp fra myndigheder og infrastrukturejere. Konklusionen på baggrund af den brede begrebshistoriske analyse og den mere fokuserede case-undersøgelse er, at overgangen fra risiko- til resiliensfokus i moderne beredskabstænkning er tæt forbundet med accept af en vis usikkerhed og uforudsigelighed i komplekse samfundssystemer.

Foreword

This thesis is the product of a highly multidisciplinary process. In 2012, I was fortunate enough to be one of the founders of the Copenhagen Center for Disaster Research (COPE). Since then I have benefitted tremendously from working closely with scholars from many different disciplines. The distinctive feature of the “Copenhagen version” of multidisciplinary disaster research is the notion that disasters are multidisciplinary phenomena requiring a 360-degree perspective to comprehend (see Dahlberg et al. 2015d). With my background in history, I suddenly found myself immersed in discussions of disaster research with anthropologists, health experts, economists, sociologists, political scientists, and even an occasional theologian. This context allowed for and inspired challenging and innovative approaches. These approaches often resulted in surprising insights and constant broadening of horizons.

Disasters are also trans-boundary phenomena. Grasping them requires a global outlook. Even though my efforts have focused on the Danish context, my work with scholars and practitioners from Sweden, Norway, Finland, Iceland, Greece, Italy, and many other countries has benefitted me greatly. I wish to thank my supervisors, especially Professor Kathleen Tierney. She invited me to stay for a month at the Natural Hazards Center in Boulder, Colorado. I also wish to thank Professor Anna Nagurney, who asked me to guest lecture at the Isenberg School of Management at UMass Amherst. I also thank Associate Professor Kristian Cedervall Lauta, Associate Professor Olivier Rubin, and all my colleagues at COPE and the Danish Emergency Management Agency (DEMA) for enlightening discussions. Trine Juul Reder read several drafts of this thesis and provided very useful feedback. I will return that favor in due time.

From the outset of the thesis process, I have emphasized interacting with the practitioners who have to deal with disasters on a daily basis. I am very grateful to the Danish Emergency Management Agency (DEMA) for partially funding my scholarship and for allowing me to work closely with some of the best minds in emergency management in our country. They generously shared their experience, ideas, and worst fears with me.

Over the last three years, I have spent many hours in the company of highly skilled and dedicated men and women. They face uncertainty, complexity, and unpredictability all the time and must constantly navigate uncharted territory. I hope that whatever small contribution I provide will be useful to some of them in the future.

Rasmus Dahlberg

Odense, April 2017

Introduction

Until recently, Denmark did not have a strong tradition of research-based practice in disaster and emergency management. That changed, however, with the establishment of the Copenhagen Center for Disaster Research (COPE) in 2012 at the University of Copenhagen. The founding launched a highly multidisciplinary initiative aimed at bringing together the expertise of scholars and experts in the field. The research presented in this thesis represents the outcome of a joint venture between the Danish Emergency Management Agency (DEMA) and COPE to investigate the challenges that complexity poses to contemporary emergency management.[1]

The original project description for this thesis stated that "perceptions of risk and attempts at prediction are closely interlinked, especially in emergency and disaster planning and response." The research project aimed from the outset at the following: mapping current perceptions of risk and attempted prediction within emergency planning and management; challenging these perceptions and predictions through a discussion based on complexity theory, and, finally, developing a set of tools for disseminating a novel mindset among emergency planners and managers. The project was divided into three phases: Phase One delineated the current paradigm and formulated a new "complex paradigm" through a desk study. Phase Two aimed at investigating complexity in disaster and emergency management case studies, while Phase Three sought to develop tools for organizing this new complex paradigm. The overall goal was to strengthen emergency and disaster managers' abilities to analyze, manage, and act in complex, unpredictable settings.

The beginning of the project process (2013) coincided with the arrival of a novel concept in the Danish disaster research environment: resilience. The fact that the word "resilience" is only mentioned once in the original project description testifies to this. Similarly, resilience as a managerial approach for practitioners only reached Danish disaster and emergency management around the starting point of the thesis project in late 2013. This meant that the au-

[1] The formulation of the project drew upon the author's experience from lecturing on and writing about disaster history and emergency management from the point of view of complexity theory (Dahlberg 2004, Dahlberg 2008a, Dahlberg 2008b, Dahlberg 2012a, and Dahlberg 2012b). The project drew as well on the author's expertise from working as a lecturer and consultant for large corporations, such as Maersk Oil and Gas and Statoil, in the areas of safety culture, process safety, and human factors. A common trait in the author's work on the topic from the beginning has been the concept of risk. How do larger organizational and societal frameworks define, interpret, manage, and integrate risk? Several presentations and publications during the project period have also explored this from various angles. See, for example, Dahlberg 2013, Dahlberg 2014, Dahlberg 2015c, Dahlberg et al. 2016, and Eydal et al. 2016).

thor had the opportunity to help introduce this novel term to a national audience of practitioners[2]. Scholars as well as practitioners quickly picked up the concept as a convenient umbrella term to inform and inspire a renewed dialogue on preparedness, prevention, response and recovery in a Danish as well as an international context. We may thus speak of a "turn towards resilience" in Denmark, just as a number of other countries, including the United Kingdom, the United States and Sweden, have switched to a "resilience approach" to disaster risk reduction and emergency preparedness in recent years (see, for example, Cabinet Office 2011, National Research Council 2012, Lindberg & Sundelius 2012).

In other words, what the project description termed a "new complex paradigm" actually surfaced and matured into a turn from risk towards resilience in Danish disaster and emergency management thinking. To a certain degree, the project thus became more an exploration of this turn than a developmental process as the new paradigm unfolded in written and oral discourse. Other nations could see the turn as movement away from previous concepts, such as "vulnerability" or "sustainability". However, in the Danish context, it seems more appropriate to focus on the concept of "risk" as the departure point. Risk here is broadly a concept concerned with the likelihood of loss (Bernstein 1996). The title of the thesis reflects this interpretation: *From Risk to Resilience*, while the subtitle: *Challenging Predictability in Contemporary Disaster and Emergency Management* derives directly from the title of the original project description.

Structure of the thesis

The thesis is divided into two main parts: an introduction and a collection of papers. The introduction describes the background and motivation for the project, delineates the research question and objectives, and presents the overall methodological considerations behind the work, while the state of the field contextualizes the turn towards resilience. A presentation of the papers then follows, including summaries of the main findings and discussions of contributions and limitations. These lead into a conclusion and epilogue. The second part of the thesis consists of four papers in the form of working papers, journal articles and contributions to anthologies. Paper I provides background information, definitions, and discussions of core historical concepts, while Paper II addresses the old and new paradigms mentioned in Phase One. Papers III and IV investigate manifestations of complexity and resilience (Phase Two).

[2] The author was asked to give a presentation with the title "From Risk to Resilience" at a preparedness planning workshop organized by DEMA in Copenhagen in February 2014. This was probably the first formal definition of resilience in a disaster and emergency management context in Denmark.

They use the case of the Øresund Bridge, which connects the Copenhagen area with Sweden. Participation in various projects at DEMA, the Copenhagen Fire Brigade and the Danish National Police during the process completed Phase Three.[3]

Research questions and objectives

This thesis discusses the shift from risk to resilience thinking in contemporary disaster and emergency management thinking. The main research question is *How does the concept of resilience manifest itself in contemporary disaster and emergency management thinking?* It does so in a three-tiered process. The first specific objective is to discuss the concepts of risk and resilience through a literature review. It investigates how notions of risk, uncertainty, and predictability have been interpreted historically. The second specific objective is to analyze understandings and applications of a resilience approach in contemporary disaster and emergency management through a case study. The third specific objective is to discuss the implications of this shift towards resilience and suggests novel approaches to disaster and emergency management based on insights emerging from the case studies.

Delineation of central concepts

Two very common definitions of risk state are that it is the product of probability and consequence or the product of hazard and vulnerability. That is, you can calculate the likelihood of something happening and multiply it with some measure of the potential impact in order to describe risk in quantitative terms, or you can view risk as the outcome of a hazard intersecting with a vulnerable system. The latter is central to the understanding of risk in disaster research and is often expressed in qualitative terms (Blaikie et al 2004). On the other hand, risk thinkers have challenged the former for decades. However, many people working with assessing and managing risk in practice still subscribe to some variant of this simple interpretation, which presupposes that the likelihood and consequence of an event can actually be measured quantitatively (see, for example, Aven 2010, 2014).

There is a certain relationship between the concepts of risk, crisis, catastrophe, disaster, and prediction. Risk can be understood broadly as concerned with predictions of loss, while, to some extent, disaster and catastrophe and disaster represent the consequence of failures in forecasting and prediction. While "crisis" denotes a time of great uncertainty, difficulty and impending danger, it implies that future development may be for either better or worse. Im-

[3] The materials produced for these purposes are not included in the thesis as they are all in Danish (see, for example, Dahlberg & Sørensen 2015).

perfect and/or unknown information characterize such a situation, i.e., uncertainty. This term has many different meanings depending on the context and discipline, but to a disaster manager, it describes the ambiguity and lack of information that often accompany emergencies. Uncertainty is philosophically related to the concept of risk and forms a core part of the ISO 31000 standard for risk management, which states that risk is the "effect of uncertainty on objects" (ISO 2009).

"Katastrofe" is the word for both "disaster" and "catastrophe" in Danish, which does not have an equivalent to disaster, as is the case in English, French, Spanish and Italian. With its etymological roots in the Ancient Greek "katastrophe" for "overturning" or "sudden end", the term catastrophe acquired its broad modern meaning in the middle of the 18th century when it merged with "disaster". This word originates from the Italian "dis astro" ("ill-starred"), meaning a calamity due a planet's unfavourable position (Harper 2016). Catastrophe is also used in medicine (for an unexplained death) and insurance (as "catastrophic loss", e.g., bankruptcy or loss of life). People in disaster and emergency management often use the terms catastrophe and disaster synonymously. However, some scholars have argued that these terms are different—the latter being a qualitative leap over the former (Quarantelli 2011).

Like catastrophe, in everyday use, most people understand "disaster" as a generic term covering all kinds of dramatic events resulting in mass fatalities and/or great structural and economic losses. For example, UNISDR defines disaster as a "serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources" (UNISDR n.d.). An emergency is here understood as a serious, unexpected situation requiring immediate action. While no formal definition exists, an emergency is typically distinguished from a disaster by its urgency and from crisis by the situation's having already taken a path towards negative outcome. On the other hand, in a crisis situation there is still hope for a positive or at least a neutral outcome. In practical terms emergencies are also often distinguished from disasters on the basis of capacity: emergencies can be handled with the resources available in a given area, while a disaster or catastrophe requires assistance from outside the area and/or prioritization of resources.[4]

One interpretation of these concepts stands out as a fundamental inspiration for the approach in this thesis: a 16th century understanding of catastrophe as the "reversal of what is

[4] These sections are based on the entries for "Catastrophe", "Crisis", "Disaster", "Emergency" and "Uncertainty" in the *Oxford Dictionary of Disaster Management* (Dahlberg & Rubin 2016).

expected" (Harper 2016). This notion coincides with the beginning of the natural scientific revolution. It indicates an expectation about the future, based on scientific prediction. The predictive power of a model was the gold standard for scientific value in the Newtonian world because it enabled man to understand, predict, and control the world. Then, if something happened other than what was expected, it was a catastrophe.

It follows from this line of thought that risk thinking presupposes some ability to predict, and vice-versa that prediction is closely related to the concepts of uncertainty and probability. However, the increased interconnectedness of everything in our modern societies apparently makes it increasingly difficult to precisely predict the effects of causes, and the growing interdependencies between systems that previously had little or no effect on each other create synergies that may result in unforeseen cascading effects (KPMG 2011). For example, in 2003 the malfunctioning of a single transformer station resulted in a power grid failure on the US East Coast. It affected an estimated 50 million people and lasted as long as four days in some areas (U.S.-Canada Power System Outage Task Force 2004). Complexity therefore plays an important role in contemporary disaster and emergency management.

Scope and limitations

As DEMA partially funded this project, it naturally follows that the project has a Danish/North European focus. While the theoretical discussions are more general, the case study relates directly to the reality of Danish actors and authorities, and the examples provided and the insights discussed in this project are not relevant for or valid in all geographical settings. Denmark has, however, strong ties to its neighboring Scandinavian countries, as well as other member states of the European Union and the United States. Denmark formally shares with these countries valuable knowledge about disaster and emergency management and informally, through networks, joint exercises, and real-life operations. Much of what follows should therefore be of at least some interest and relevance to researchers and academics in these countries.

Positioning the study in the philosophy of science

The overall research design of this thesis stems from the author's background in the humanities. In order to understand the current interpretations of concepts like risk and resilience, we must approach them from a historical point of view, trace their roots, and visit some of the pivotal moments and important actors who contributed over time to the current contents of the concepts. Such an approach is inspired by *Begriffsgeschichte* (Conceptual History), as developed by Reinhardt Koselleck. It aims at understanding fundamental concepts not by defining them objectively, but rather by acknowledging them as dynamic and ever-changing through discursive negotiations on how to define their contents (Richter 2001, Dahlberg 2015a: 31). This literature-based conceptual historical approach is fundamentally discursive and hermeneutic since it focuses mainly on interpreting and explaining how people and organizations have talked or written about concepts. A more social-scientific handling of the case study supplements this approach. In moving from the humanities into the social sciences, the thesis increasingly applies observational methods, employing description, measurement, and analysis.

The four included papers approach risk and resilience from different angles. They nevertheless include diverse theoretical points of departure. This is a strength rather than a weakness: the complementarity of the theoretical points mirrors both the complex realities of emergency management and the multidisciplinary approach of disaster studies in general and the "Copenhagen School" in particular (Dahlberg et al. 2015c). However, as argued in Dahlberg et al. (2015d), a common pitfall of multidisciplinary research is that the disciplines remain separate due to differences in language and incompatible foundations in the theory of science. The specific configuration of approaches in this thesis seeks to avoid this pitfall by constructing a convergent-divergent double funnel pattern. First, this thesis historically traces broad concepts, such as risk, uncertainty, probability, resilience and complexity, and narrows them down. They are then applied to a specific case and used as prisms through which the empirical data is analyzed, yet again broadening the understanding of the central concepts.

The rationale for mixing historical and sociological theory is simple: disaster and emergency management cannot limit itself to a single discipline or narrow approaches due to the complexity of its object. Based on the author's experience from DEMA's Center for Preparedness Planning and Crisis Management, including many different disciplines and approaches when preparing for and managing disasters and emergencies is of key importance. In this case, history provides experience and insights from previous incidents. They might not be similar to future adverse events. They nevertheless represent valuable knowledge as sociological enquiry allows us to understand how individuals and groups make sense of the systems they interact with. The study also draws upon economic theory as well as general risk theory.

The provocative contribution to the philosophy of statistics and economics made by Nassim Nicholas Taleb with *The Black Swan* (Taleb 2008) functions as an overarching theoretical framework. It has been very inspirational to the author from the beginning of the project[5]. Taleb, building on the problem of induction in philosophy, uses the Black Swan as a metaphor for the impact of the highly unlikely: rare events of large magnitude. They defy traditional statistical models and are therefore extremely hard to predict as they hide in the "fat tails" of statistical distributions (Taleb 2008). Some events simply happen too rarely or without any precedence at all to provide any basis for prediction, making them in practice "unknown unknowns" or even "unknowable unknowns", especially with regard to intentional man-made disasters such as acts of terrorism.

Much criticism has been leveled at Taleb and his Black Swan concept in the last decade. His harshest opponent is Bayesian statistician Dennis Lindley. In his review of *The Black Swan* Lindley asked how "a reputable publishing house" could accept such material (Lindley 2008).[6] But is the Black Swan just a "Red Herring"? Taleb's ideas originate with investment banking and financial systems and should be taken first and foremost as a source of inspiration (and provocation). However, in the author's opinion he does make a relevant contribution that merits reflection in other fields, such as disaster and emergency management. Societal systems based on classical interpretations of risk are—to use Taleb's term—fragile, because their perceived predictability may be seductive. He suggests the concept of "anti-fragility" as an antidote (Taleb 2012). As argued in Paper II, anti-fragility is somewhat similar to the modern interpretation of resilience, linking the Black Swan to the concept of resilience.

Methodology

It is useful to view the first two papers as outcomes of the conceptual historical approach. Paper I provides an overview of the literature on some important aspects of the history of risk. It traces the origins of uncertainty, probability, and predictability and discusses how the interpretations of these concepts have developed. This discussion focuses on seminal works and pivotal moments in the historiography. The review builds on secondary sources, because the aim of the paper is to provide a broad overview of the historical developments in the field rather than a detailed discussion of specific contributions. English-language sources are somewhat overrepresented in the review although, to some extent, the inclusion of Russian literature (in English) redresses this imbalance. The reviewed works of Ian Hacking, however, also include the French literature in great detail.

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[5] The first person to recommend the book to the author was actually the then Head of Division at DEMA's Center for Preparedness Planning and Crisis Management (in 2010), lately a co-supervisor of this thesis.

[6] For more balanced discussions of the Black Swan concept in risk theory, see Hubbard (2009) and Aven (2014).

Paper II builds on the recent genealogies of resilience published by Martin-Breen & Anderies (2011), Walker & Cooper (2011), Alexander (2013) and others. The paper also adds to their contributions by linking the concept analytically to complexity and relating it to the Cynefin Framework for Sense-making. The latter is a management tool that has proven highly applicable and very useful when discussing the implications of complexity with practitioners in disaster and emergency management. Another important aspect of Paper II is the discussion of resilience and Taleb's "anti-fragility". In other words, Paper II presents itself as a literature review in part and in part as a literary critique of Taleb's writings. Note that the paper was published in a special issue on catastrophes in a journal specialized in cultural studies, not a classic disaster research journal. This explains the paper's very broad conceptual approach rather than a more focused discussion aimed at an expert audience.

For the case study, the thesis employed a mixed-method approach. It included policy analysis and observational studies (Paper III) as well as semi-structured interviews (Paper VI). The author was an observer in the Work Group of Øresund Preparedness and had access to the process leading to the publication of a report on preparedness planning for long-term disruptions of the bridge between Denmark and Sweden. In addition to observations during meetings and discussions with the work group members and analyses of reports, interviews and other sources used for the report, a limited number of short semi-structured qualitative interviews with commuters and travelers was carried out on the train between Copenhagen and Malmö in order to explore the potential adaptive capacities of the system.

Together these methodological approaches complement each other and contribute to novel understandings of the topic under investigation. The conceptual historical discussions and ideographic historical analyses support the more social scientific approaches to the case study by contextualizing contemporary thinking and practice. The specific papers describe the specific methodologies applied in detail.

State of the field: from Risk to Resilience

Many approaches to and definitions and interpretations of resilience exist (see, for example, Bhamra et al. 2011, Walker & Cooper 2011, Alexander 2015, Weichselgartner & Kelman 2015). Understandably, some academics, decision-makers, and practitioners have recently turned away from this contested concept, which some claim to be "just another" buzzword with hollow meaning and only temporary relevance (Davoudi 2012, Hussain 2013, Barrios 2016). The present thesis, however, embraces and challenges the concept, acknowledging that resilience appears to resonate remarkably well with the understandings and needs of practitioners in emergency and disaster management. At the same time, it lacks clear meaning and consensus on its application. This section delineates the author's theoretical and practical points of departure, outlines some contemporary challenges to emergency management from a resilience approach, and positions this study in the literature, current research, and practice trends. The following is, however, not meant as a review of the literature on risk and resilience. For this, see Papers I and II.

Three interpretations of resilience reached the author in 2014, shortly after the introduction of the concept in an emergency management context in Denmark: "In a certain sense, then, resilience is the obverse of risk", states sociologist Kathleen Tierney in *The Social Roots of Risk* (Tierney 2014: 7). Political scientist David Chandler put it differently: "Resilience is the discursive field in which we negotiate the governance of complexity" (Chandler 2014: 13). And Lauren Alexander Augustine, Director of the Program on Risk, Resilience, and Extreme Events at the US National Academies, proclaimed in a lecture in Copenhagen: "… we need to build resilience to the uncertainties that lie ahead", linking resilience to uncertainty (Augustine 2014). In different ways these three interpretations inspired and guided the work leading to the present thesis. They therefore merit a special introduction and contextualization.

Tierney's main argument is that risks are always socially constructed; i.e., vulnerabilities arise not from hazards, such as flooding, earthquakes or volcanic eruptions, but rather human exposure to such hazards produced by gender inequality, bad land-use planning, low social capital, etc. (Tierney 2014: 4-5). This is in line with the "vulnerability tradition" in disaster research, first and foremost characterized by US sociologists standing on the shoulders of one of the "founding fathers" of disaster research, Samuel Henry Prince (Scanlon 1988). Tierney's social approach to disasters also reflects the European/UK tradition of understanding disasters as intersections of hazard and vulnerability, pioneered in the 1960s by Allen Barton and, perhaps most famously, visualized by a group of authors in their book *At Risk* as the Pressure and Release model (Blaikie et al. 2004, 1st ed. 1994). To Tierney, social networks, economic equality, and political transparency are important aspects of building resilience to counter risk.

What caught the author's attention when reading David Chandler's 2014-book on resilience was his use of the concept as a governance/managerial approach to complex socio-economic systems. This resonated well with a tradition in safety science that can be traced back to organizational sociologist Charles Perrow's seminal book from the mid-1980s on *Normal Accidents* (Perrow 1999, 1st ed. 1984). There he argued that unavoidable "normal accidents" characterize complex systems. Instead, the system must be able to absorb unexpected perturbations and employ barriers to avoid cascading effects. This line of thinking underlies much of the work in safety science in recent decades, and "resilience engineering" reflects this thinking (Hollnagel et al. 2006). This field also became a useful source of inspiration for this thesis (see Paper II), while the basic linking of resilience to complexity resonated well with the original problem statement in the project description.

Last, Lauren Alexander Augustine represented a very practical approach to resilience and became a great source of professional as well as personal inspiration. In her interpretation, resilience is not an elusive theoretical concept coined by academics sitting at desks, but rather a very practical approach to societal security and disaster and emergency management. Building strong social networks in local communities, empowering citizens to take responsibility for their own safety in co-operation with the authorities, and creating flexible organizations able to learn, adjust, and adapt is not necessarily an academic quest but rather a practical problem. Being an embedded doctoral student with the Danish Emergency Management Agency (and having promised to come up with concrete recommendations during the project period), this practical approach to resilience seemed a reasonable guiding principle.

The map and the territory

The Danish disaster and emergency management system is well organized and based on a number of sound principles, routines, and organizational values that guide practices in ordinary as well as extraordinary times (for an introduction to the Danish system, see Eydal et al. 2016: 65-84). Modern emergency management, however, faces a number of challenges that require novel approaches. One challenge is external to emergency management: the ever-increasing complexity of society due to the interconnectedness of things, the massive amounts of available data about everything, and the unpredictability of socio-technological systems

(Alexander 2016: 1). Another challenge is internal: an apparently firmly rooted belief that risk is measureable and can thus be calculated to form the basis for societal risk management (Aven 2010, 2014). This raises the question of risk modeling – of the difference between the map and the territory.

In 2002 the Danish parliament passed legislation regarding the municipal fire/rescue services. It stated that the local preparedness level should in the future be dimensioned, based on specific risk analyses instead of general national-level principles (Beredskabsstyrelsen 2004: 5). This required Danish municipalities to carry out risk analyses consisting of (i) a scenario analysis and (ii) a capacity analysis, so that all local risks would be mapped and cross-checked with available resources to reveal vulnerabilities in the preparedness system. The Danish Emergency Management Agency (DEMA) issued a handbook to guide municipalities in their work with risk-based dimensioning, and among the models and tools offered in this handbook was the "risk matrix": a simple diagram with "consequences" on the X-axis and "frequency" on the Y-axis, designed to "provide an overview of different risks" (ibid. 28).

There is no doubt that risk-based dimensioning of the Danish municipal fire/rescue services was a big leap forward, compared to the traditional approach. That approach basically stated that, for every 10,000 inhabitants, a municipality had to employ so many fire engines, ladders, water tenders, etc. Now it became possible (and necessary) to adjust the local level of preparedness according to specific circumstances, such as high-risk industry, tall buildings, high population density, etc. But while this calculative approach signified a more advanced and "modern" way of managing risks, it also created new vulnerabilities. Inherent in models such as the risk matrix is a certain way of thinking about the world—an underlying interpretation of society as *understandable* and therefore *manageable*. It implies that it is in theory possible to map all risks and plan accordingly. While accepting that all identified risks may not be managed properly, the potential fallacy of the approach is attributed to the political process that determines the level of service, not the analytical process itself (ibid. 25).

The major weakness of such an approach to societal risk management is that it may create a false sense of security among decision makers. This is not a critique of the method itself, but rather of the overall interpretation of risk as something that can be mapped and calculated precisely. The methodology suggested by DEMA in the 2004 guidelines for risk-based dimensioning is sound and practical, advising municipalities to include a broad variety of stakeholders in brainstorming and workshops, while at the same time acknowledging the limitations involved. The problem is, rather, that these reservations are sometimes lost in translation when the results of the process are presented in the final report to the strategic and political level. Thus, the map becomes the territory, but without all the inherent uncertainties and the imperfect knowledge that is part of reality.

Managing uncertainty

"The classic response to uncertainty is to recognize the limitations of the existing system and to broaden the scope of actors, agents, and knowledge that can be marshaled for action, as needed", writes Louise K. Comfort (2005: 347), while Michael Power argues that risk should be understood as *organized uncertainty*: "Uncertainty is (…) transformed into risk when it becomes an object of management, regardless of the extent of information about probability" (Power 2007: 6). He even goes so far as to state: "Organizing and managing are fundamentally about individual and collective human efforts to process uncertainty," and that there "is a long normative, theoretical, and explanatory history in the fields of economics and organizational sociology in which risk management and organization are almost the same thing; managing and uncertainty are two sides of the same coin" (ibid.: 8,11). Jens O. Zinn also understands risk as a "specific form of managing uncertainty – it is about the way uncertainties are (rationally) managed, and the theories vary regarding the degree of rationality, from a calculative practice to any form of purposeful management of uncertainty" (Zinn 2008b: 173).

Following Luhmann, we can also say that uncertainty is closely interlinked with decision-making, and uncertainty is therefore of great importance to emergency managers, as they typically are unable to postpone decisions (a preferred strategy for government officials and politicians when facing uncertainty) due to imminent threats to life, health or property (Handmer 2008: 232). Historically, we can also agree with Power that disaster and emergency management have been related to interpretations of risk, uncertainty and decision-making. The early modern shipowner who began sharing risk with other shipowners "took responsibility for the success or failure of his project (…) and this self-attribution of consequences of decisions is a key feature of modernity" (Zinn 2008b: 81). First came the concept of insurance in the Renaissance, then the first European fire brigades in the 1600s as a consequence of urbanization. However, disaster and emergency management on a larger scale did not evolve until the middle of the 18th century. The Great Earthquake of Lisbon in 1755 was the pivotal moment. This catastrophe claimed more than 20,000 lives in one of Europe's most flourishing capitals. It fueled scientific approaches to the concept of disaster in particular as well as the process of secularization in general (Dynes 2000, Lindell 2013).

Modern emergency management has its roots in civil defense organizations. These organizations date back to the first aerial bombardments in the United Kingdom from zeppelins during the First World War. In the interwar period, many European countries created civil defense organizations, especially after German military aircraft bombed Guernica in 1937 during the Spanish Civil War. Civil defense organizations were tasked with constructing and operating shelters, distributing equipment, like gas masks, fire fighting, and search and rescue equipage during the Second World War. In the following decades these organizations focused on preparing for the protection of populations in case of nuclear war. After the end of the Cold War, many countries reorganized civil defense organizations into governmental emergency management agencies and state-approved volunteer organizations. They had much broader briefs than before that included disaster preparedness, assistance in large-scale emergencies, and, most recently, additional homeland security tasks.[7]

Uncertainty thus always accompanied the development of modern emergency management. Societal uncertainty can manifest itself in positive as well as negative ways—as opportunities for creation, innovation and entrepreneurship, but also as the risk of possible loss (of life, health or property). This resonates well with Emanuel Derman's good advice: "The best you can do with unquantifiable uncertainty is to be aware of it and aware of your inability to quantify it, and then to act accordingly" (Derman 2011: 154).

Emergency management deals with "residual risk". This is the risk remaining after dealing with all manageable risks (Handmer 2008: 231-234). This is the kind of risk that is known or at least knowable, but very difficult or impossible to predict precisely—the "known unknowns". Then there are "unknown unknowns" that do not *exist* before they happen. This means that people can only respond to them, depending on their level of preparedness. The "unknown unknowns" especially require emergency managers and management organizations to be more adaptive and flexible (Aven 2014: 12).

Adaptation and flexibility

Traditionally, the fields of emergency and disaster management have not focused on adaptation and flexibility. Agencies owe their preoccupation with plans and procedures to the civil defense paradigm coming out of the Second World War that matured during the nuclear scare of the Cold War. A militaristic command-and-control mindset characterized this paradigm (Helsloot and Ruitenberg 2004, Hamilton & Toh 2010, Boersma et al. 2014). Such organizations do not thrive on chance. On the contrary, incident command systems, hierarchical or-

[7] This section builds on the entry for "Civil Defense" in Dahlberg & Rubin 2016.

ganizations, and plans and procedures are tools meant to *counter* uncertainty, ambiguity and individuals' attempts to improvise, adapt, and overcome when faced with the unexpected.

Today, a self-image of top-down management still often characterizes the heirs of civil defense organizations even if "the 'command and control' model was always more aspirational than descriptive." (Power 2007: 36). With its origins in the military system, command-and-control ensures direction and execution as fast as possible during a crisis. In a national emergency, the commands are typically released by a government authority and then passed down to lower state levels or other external organizations for implementation. Denmark manages this through the national crisis management system (see Eydal et al. 2016: 70-77).

Infrastructure protection exemplifies how disaster and emergency management reveals its roots in command-and-control mindset. Preparedness planning concerning infrastructure has traditionally focused intently on physical protection of built structures (Brown 2006). Since the 1990s, however, infrastructure has increasingly been understood to comprise technical as well as organizational, social, and economic components (TOSE) (Semaan & Mark 2011: 2, Kozine et al. 2015). Around 2000, anthropologists became interested in the human aspects of infrastructure. They focused on the social arrangements that affected people adopt in times of disruption (Star 1999). Much research focused on role improvisation and emergent behavior in the response phase of crises following the 9/11 terrorist attacks in the United States (Webb 2004, Rodriguez et al. 2006, Kendra & Wachtendorf 2016). Since then, increasing interdependency in TOSE systems, and especially the use of digital systems (e.g., computer networks), has challenged traditional thinking within the field of Critical Infrastructure Protection (CIP), just as recent work on emergence in crisis and emergency management has focused on the role of Information and Communication Technologies (ICTs), like digital social media (Boersma et al. 2014).

"Through the approach known generally as 'command and control' emergency management organizations have attempted to manage uncertainty by controlling and containing it," writes Australian EM expert John Handmer (2008: 237). Such a "respond-to" strategy is well-suited for small-scale incidents, but "the model becomes less appropriate due to the need for flexibility and adaptability in decision-making and of securing full cooperation from numerous groups" as scale and complexity increases (ibid. 237-239). Plans and procedures, so important to the command-and-control paradigm, work well for routine incidents, but may hinder the flexibility of emergency management organizations when dealing with highly uncertain situations. In the beginning of the 21st century, risk and emergency management has, in practical terms, become uncertainty management.

Towards resilience

Studying emergent behavior during disasters is a prerequisite for integrating adaptation or flexibility into preparedness planning, which are important elements in a resilience approach (Rodin 2014). Such interest can be traced back to Samuel Henry Prince, who wrote his dissertation about the social behavior of the affected inhabitants of Halifax, Canada, in the aftermath of the explosion in the harbor in December 1917 (Prince 1920). The literature suggests that more research has been done on the role of "ordinary people" or "zero responders" in the response phase than on prevention, preparedness and recovery. The reason is that during the acute phase immediately following an accident or major disruption, the interfaces between professional responders and volunteers, bystanders, and other groups are most visible (Scanlon et al. 2014, Helsloot and Ruitenberg 2004, Drabek and McEntire 2003).

Preparedness planning from a resilience perspective suggests a change in mindset from the military-inspired command-and-control approach to coordination-and-cooperation. This perspective acknowledges the resources and competencies residing in citizens, companies, and civil society as a whole. In this perspective, authorities engage in partnerships with other actors, showing the way and providing the tools, rather than viewing citizens as lemmings that—if not instructed—will either behave irrationally or even obstruct the efforts of professionals to mitigate the effects of adverse events. Resilience with regard to response addresses the flexibility and adaptive capacity of emergency management organizations to deal with the unexpected. An example is the Danish police's quick reaction patrol concept, introduced after the Breivik terrorist incident in Norway in 2011. The concept designates specific teams of specially armed and trained officers who—in emergencies—will be immediately detached from daily duties to respond. This is a simple, yet effective, very flexible and adaptive, concept. The Copenhagen Fire Department's recent introduction of fast-response flexible units to some extent, mirrors this concept. The fire department's units are small vehicles with light fire-fighting equipment manned by only two fire fighters. Between call-outs, they can perform other duties.

The numerous and diverse definitions of and approaches to resilience, discussed in Paper II, all add up to a mindset or paradigm accepting the unpredictable behavior of complex socio-technological systems. In addition, they apply new operational and managerial tools and doctrines exactly embracing this complexity and unpredictability rather than trying to control it.

In this way, the three sources quoted at the beginning of this section framed the meaning of resilience well. They are not mutually exclusive, but rather interpret resilience from three different approaches. They thus provide us with complementary views that together form a broad framework for further investigating the concept.

A premise of this thesis is that the concept of resilience applies meaningfully to contemporary disaster and emergency management, providing a conceptual approach to the management of uncertainty. The findings of Paper IV feed especially into this discussion, which is currently high on the agenda in Denmark.[8] Although the size and the quality of the sample limits the power of the qualitative study of adaptive capacities perceived by travelers on the Øresund Bridge, it provides a key insight presented in this thesis: The fundamental notion that preparedness planning should be seen (and communicated) as a collaborative effort shared among agencies, operators and users rather than as solely an obligation for the authorities.

The following section introduces each of the four papers, with special emphasis on their contributions to the investigation of the shift from risk to resilience as well as their limitations.

[8] For example, on 2 February 2017, DEMA published its new strategy for national preparedness. It strongly emphasizes the role of citizens, volunteers, and civil social organizations and institutions (DEMA 2017).

Papers' contributions and reflections

The guiding principle for the papers included in this thesis is understanding the foundations and conceptual content of resilience as a mindset for disaster and emergency managers. These actors concern themselves with managing social risks by governing complexity and preparing for uncertainties lying ahead. This thesis naturally consists of papers that are written, submitted, and even accepted or published during the project period. This is beneficial to the learning process, but may challenge the overall coherence of the final product. The following sections reflect on the contributions and limitations of each paper.

Paper I: "The Roots of Risk"

This paper explores the history of some important components of the concept of risk: uncertainty, probability and predictability from a very broad perspective. It contributes to the thesis by tracing the origin of these concepts to obtain an understanding of the foundations of modern risk thinking. The paper argues that these foundations date back to the Age of Enlightenment and the transfer of insights and methods from natural science to the social sciences in the 1800s. Risk is broadly understood as the product of likelihood and impact, and the conceptual history focuses on the measurement of the former. Inspired by the notion of a "predictability horizon", the paper argues that life in the "Risk Society" requires us to acknowledge the limits of prediction. This argument is in line with current understandings of a resilience approach to disaster and emergency management and societal security. Thus, the paper links the history of uncertainty, probability, and predictability to the contemporary discussion.

While one can argue that risk, especially in disaster studies, is often defined as the intersection of hazard and vulnerability, this paper approaches the topic from a historical point of view. The paper acknowledges that likelihood through the centuries has played a more influential role in the theoretical development of the concept than vulnerability. A limitation of the paper, however, is the very broad and general nature of the discussion that aims at approaching the concepts from a variety of disciplines. At the same time, it risks unjustified comparisons, simplifications, and omissions. In retrospect, the paper could have benefitted from a narrower focus and a more structured argument, including the concept of vulnerability.

Paper II: "Complexity and Resilience"

This paper continues along the same line of thought as Paper I, exploring the history and contents of "complexity" and "resilience". It links the two into a common framework. Paper II emphasizes their relationship with regard to designing and managing socio-technological and socio-economic systems with the ability to recover from sudden impact. Methodologically, the paper approaches the two concepts from a pragmatic discourse theory perspective, connecting them to the history of risk presented in the previous paper. It also introduces other aspects, like economic theory (especially Hayek's). Resilience is seen as a property of complex adaptive systems that are not as predictable as complicated, mechanistic systems. The paper emphasizes ecology's contribution to the development of the concept, which is interpreted as synonymous with Taleb's concept of "anti-fragility". The paper introduces the Cynefin Framework for Sense-Making as a useful model for disaster and emergency managers.

This paper was written at an early stage in the project process. In retrospect, it has a number of limitations even though it was peer-reviewed and published in an academic journal. The discussion of the shift from a descriptive to a normative interpretation of resilience indicates incomplete knowledge of the multidisciplinary historiography. Furthermore, establishing 1973 as a paradigmatic pivotal moment in the development of the concept reveals insufficient familiarity with the progress in anthropology and psychology in the preceding decades. Looking back, the paper also lacks a clear and concise definition of central theoretical concepts within the field of ecology, such as homeostasis. In addition, it probably overstates the importance of Holling and the relevance of Taleb.

This attempt to conjoin the two contested concepts of resilience and complexity was perhaps too ambitious for a newcomer to the field and should have been subjected to more thorough discussion with fellow scholars in the field before submitting it to a journal in a discipline not typically concerned with resilience thinking. Still, the paper contributes valuable unpacking of central concepts and lays out the foundations for the theoretical framework in the case study.

Paper III: "Bridging the Gap"

This paper delineates the concept of infrastructure, describes the proceedings of the Work Group for Øresund Preparedness 2014–2016, and discusses the findings presented in the final report to the Danish and Swedish transport authorities while drawing upon experiences from two recent comparable cases of infrastructure disruption. The methods employed include a literature review, participatory observational studies during the proceedings of the Work Group for Øresund Preparedness, and a policy analysis of the report resulting from the work. The main contribution of the paper is its application of some of the insights from Papers I and

II to a case study in contemporary disaster and emergency management. The paper exemplifies how a traditional quantitative approach to risk thinking (for example, the very low estimated probabilities for long-term disruptions of the Øresund Bridge) can be accompanied in practice by a different approach that dispenses with the interpretation of risk as the product of likelihood and impact and instead focuses solely on a "possibilistic" approach.

In retrospect, the author would consider exchanging the introduction of Larkin's definition of infrastructure with a theoretical framework based on the theory of cascading disasters (Pescaroli & Alexander 2016). Unfortunately, at the time of writing, the author was not familiar with this particular approach. Nor did colleagues or discussants at the 2016 Dynamics of Disaster conference recommend it. Nor did the editors of the published proceedings.[9]

Paper IV: "Do you have a Plan B?

Developing further the findings from Paper III, this paper specifically explores adaptive capacities in preparedness planning, using the Øresund Bridge as a case. First, the paper establishes a theoretical framework framing adaptive capacity in a more general resilience discourse with regard to infrastructure protection and preparedness planning. Then, the paper discusses the findings from a small qualitative study of travellers' perception of their own adaptive capacities and presents some recommendations on how authorities and infrastructure owners and operators can integrate this into preparedness planning. In addition, the paper provides examples of a resilience approach to contemporary disaster and emergency management with special regard to infrastructure. The main contribution of the paper is the notion that many travelers perceive themselves as competent actors willing and able to take responsibility for solving problems in case of a long-term disruption. Thus, the case study provides useful knowledge of how users think they might behave should the highly unlikely happen one day. This allows the integration of otherwise unknown adaptive capacities into preparedness planning.

Limitations of this paper are the relatively small sample size of the survey and the fact that the interviews were all carried out on the same day. This necessitates acknowledging that the sample was a convenience sample with limited representative value. The paper could have more heavily emphasized that the study aimed more at addressing the question of how to approach the role of citizens and their adaptive capacities in preparedness planning than at providing an answer to this question.

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[9] It is also worth noting that the anecdotal reference to Donald Rumsfeld on page 53 lacks a reference to a more scientific discussion of the concept of "unknown unknowns". For this, see for example Aven (2014: 12).

Conclusion

Reflecting on the research question presented in the introduction, we can say that this thesis shows that the concept of resilience first and foremost manifests itself in contemporary disaster and emergency management as a reluctance to rely on a classic interpretation of risk as a quantifiable and analyzable entity. Rather, an interpretation of risk more in line with the ISO 31000-definition ("The effect of uncertainty on objects") is applicable in this new mindset. A resilience approach involves a shift from command-and-control thinking to coordination-and-cooperation. The latter requires authorities and operators to acknowledge and accept some degree of uncertainty and unpredictability due to the complexity of most contemporary socio-economic systems. While the former aimed at reinstalling control through structures and hierarchies, the latter seeks to utilize the inherent adaptive capacities of complex systems by integrating them into preparedness planning and response plans—for example, by embracing citizens' willingness and ability to help themselves and each other rather than treating them as passive bystanders.

Paper I showed how the concept of risk originated with early insurance thinking, and came to dominate the Western industrialized world. In fact, sociologists at the end of the 20th century coined the term "Risk Society" to describe it: a form of late-modern society preoccupied with risk and the distribution and management of it. Mathematicians and philosophers, obsessed with solving the fundamental problems in probability and game theory, developed the theoretical foundations of risk in the 16th, 17th and 18th centuries. The Western states then incorporated these insights in the 19th century, so that "governing by numbers" became the new standard. This transition from theory to practice continued in the 20th century, with the development of risk management, seeking to control the uncertainties that multiplied with increased complexity.

As stated in Paper II, resilience is, and has been for decades, a concept with many different meanings and interpretations, depending on disciplines, tradition, and political agenda. Originating in literature and law and moving through mechanics and psychology to ecology and social science in general over the last half millennium, the concept was only recently introduced in the Danish disaster and emergency management context. Here, resilience has been quickly and widely accepted as a broad umbrella term for a variety of novel approaches to the field. However, central to the concept are adaptation and flexibility as a means to cope with uncertainty, as discussed in Paper III. Increased awareness of the limitations of predictability and certainty in risk assessment has characterized the turn from risk towards resilience in contemporary disaster and emergency management thinking.

The thinking of the Work Group for Øresund Preparedness, as described in Papers III and IV, is a good example of this trend: Even though the risk of a long-term infrastructure disruption has been estimated as extremely low, the work group examined its potential consequences and outlined different possible mitigation strategies—however, without detailed planning. Instead, in case of an actual disruption, coordination would become the responsibility of various crisis management staffs in Denmark and Sweden, while freight companies and individual travelers would be responsible for solving many problems on their own, with information and assistance from transport companies and the authorities to guide and encourage them. This approach is in line with the concept of resilience presented in Paper II. Instead of looking at traffic flows, built infrastructure, and response capacity as a machine that needs to be made robust in order to withstand unforeseen perturbations, the view is rather that the entire system is more like an ecosystem able to switch from one mode of behavior to another without pre-designed top-down instructions.

The turn towards resilience was born in the 1970s, grew up in the early 2000s, and moved away from home in the 2010s. Then the concept became so mainstream in many disciplines that some scholars began to reject it. But it is only now, as this thesis argues, that resilience has become an increasingly accepted mindset. It indicates a rejection of man's ability to analyze and predict everything, given enough time and resources. Paper I described how the so-called "predictability horizon" eventually undermined the rational belief in the power of prediction, and Paper II argued that the concept of resilience offers a language for speaking about managing uncertainty. This mindset was then applied in Papers III and IV.

These concluding remarks relate to the Cynefin Framework for Sense-Making, introduced in Paper II. A resilience approach denotes a complex process with new insights emerging bottom-up from the sharp end of the system. Citizens enjoy a different role as participants rather than mere bystanders, and metaphors of organizations shift from hierarchical machines to complex organisms and ecosystems. Command-and-control is giving way to coordination-and-cooperation as the focus shifts from risk to resilience, and this creates new agendas, possibilities, demands, and challenging tasks for disaster and emergency managers in the future.

Epilogue

Looking back at the past three years' work, resilience has transformed in the author's interpretation from a rather elusive theoretical concept mentioned in policy documents and national agendas to a very practical set of practices and principles that disaster and emergency management organizations can implement. As part of this PhD project, the author contributed to the introduction of this mindset to analysts and practitioners, for example with DEMA's new concept for a Forward Looking Cell in crisis management: The Pandora Cell (DEMA 2016, Dahlberg 2017). This concept describes a simple process, based on sense-making theory, which enables the members of a crisis management staff to think outside of the infamous box and prepare mentally and practically for different versions of the immediate future during a crisis situation. The Pandora Cell offers a simple solution to a complex problem, adding to the organizational resilience of the crisis management staff in question.[10]

Perhaps the most "naturally" resilient emergency management organization encountered during the project was the HDMS *Knud Rasmussen* and her crew of 19. The author spent three weeks together with the crew in the Autumn of 2016 in Northeast Greenland. This 1,750 t Danish naval inspection vessel navigates the most remote waters in the world, performing scientific missions, fishing control, coast guard duties, and power projection in the Arctic.

Being a military platform, the *Knud Rasmussen*, of course, has a strict formal hierarchy onboard, but adaptation and flexibility is found at all levels of both the formal and the informal organization. One evening, after a courtesy lecture in the officer's mess, where the author presented the key insights from this thesis, a crewmember responded by saying that Donald Rumsfeld's distinction between "known knowns", "known unknowns" and "unknown unknowns" (discussed in Paper III) was obvious to them: The *Knud Rasmussen* travels at full speed in charted territory, at reduced speed in uncharted waters inside the fjords of Greenland – and they *always* keep a lookout on the conning bridge, even while at anchor, just in case something unforeseen happens. An experienced seaman knows the limits of predictability.

If uncertainty is the challenge – then resilience is at least part of the solution.

[10] David Snowden, creator of the Cynefin Framework for Sense-Making (presented in Paper II), proclaimed in a public lecture in Copenhagen in 2015 that many problems today are caused by attempts to solve complex problems with complicated tools and presupposing that the world is analyzable and the future predictable. Complex problems sometimes require a multitude of simple solutions instead of a few grand, complicated plans.

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Appendix: Papers I-VI

Paper I: "The Roots of Risk: A Brief Conceptual History of Predictability, Uncertainty and Statistics." Solo authored working paper. Presented at a COPE seminar October 7 2016 (revised version). This paper is currently being developed into a book in Danish about the history of risk, entitled *When I met Florence Nightingale and other Improbable Stories* (transl).

Paper II: "Complexity and Resilience: Conjoining the Discourses of Two Contested Concepts", *Culture Unbound*, Vol. 7 (2015): 541-557. Solo authored article in a peer-reviewed journal. Published with open access.

Paper III: "Bridging the Gap: Preparing for Long-Term Infrastructure Disruptions", in Kotsireas, I., Nagurney, A. and Pardalos, P.M (eds.) (2016): *Dynamics of Disaster: Key Concepts, Models, Algorithms, and Insights. Kalamata, Greece, June-July 2016.* NYC: Springer: 37-56. Solo authored contribution to conference anthology. Published.

Paper IV: "Do you have a Plan B? Integrating Adaptive Capacities into Infrastructure Preparedness Planning." Solo authored article for a peer-reviewed journal. Accepted for publication later in 2017 in a special issue on "Citizens in Disaster" in the *Journal of Contingencies and Crisis Management*.

The Roots of Risk

A Brief Conceptual History of Predictability, Uncertainty and Statistics

Working Paper

Presented at a COPE seminar on October 7, 2016. Revised version.

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Contents

Acknowledgements

I wish to thank my co-supervisor Henning Boje Andersen for inspiring me to embark on this investigative journey into the history of risk, not least by providing me with book titles and names of influential writers in the field. I am also grateful for the useful comments provided by my colleagues from COPE at our article seminar.

Abstract

This paper explores the history of some important components of the concept of risk: uncertainty, probability and predictability. Risk is broadly understood as the product of likelihood and impact, and the analysis focuses on the former aspect: the measurement of uncertainty. Taking as its point of departure the first attempts at spreading risk through insurance, the paper investigates the historical development of probability from Pascal and Fermat in the middle of the 17th century, focusing on early game theory. The birth of statistics is described through the works of de Moivre, the Bernoullis and Leibniz, while Bayes' theorem from the mid-1700s, together with the genius of Laplace, represents a pivotal moment in what has been called a "truly Copernican revolution". The outcome was the incorporation of statistical methods into social science and governance in the 19th century, exemplified by the emergence of statistical bureaus in most European countries. The end of the 1800s also witnessed, apart from the apex of a Western fascination of "governing by numbers", the end of scientific determinism. This was followed by another scientific revolution, which finally provided the field of statistics with a theoretical foundation instead of mere "sophisticated tricks." The Pearsonian revolution shifted scientific focus from the measurement of empirical data to the estimation of distributions, thus providing quantitative scientists with a new set of powerful tools, such as correlation and regression. In 1921 Knight separated risk from uncertainty, creating a fundamental division between the measurable and the unmeasurable that would influence the debate on risk for the rest of the 20th century. Risk management developed in industrial societies, especially in the high-risk petro-chemical and nuclear industries in the 1900s. Here, all the insights and tools originating in probability theory, risk thinking, and statistical method came together to empower analysts and decision makers facing uncertainty in ever-increasing complex socio-technological systems. The 1970s was the climax of scientific belief in prediction; after that, the so-called "predictability horizon" became more and more visible to those looking into the future. Later, "aleatory" and "epistemic" uncertainty entered the vocabulary of probabilistic risk assessment, linking modern risk theory to early notions of duality in probability as well as the Knightean distinction between risk and uncertainty. Lastly, the paper argues that life in the late modern "Risk Society" requires us to acknowledge the limits of prediction and accept the existence of "Black Swans": the impact of the highly unlikely. Such an approach is compatible with current understandings of a resilience approach to emergency management and societal security.

Keywords: risk, probability, uncertainty, statistics, prediction, emergency management

Introduction

What is risk? This question has engaged philosophers, lay thinkers, mathematicians, lawyers, scholars and thinkers from many other disciplines for centuries. Risk is an elusive concept with many different connotations, depending on discipline, tradition and context. This paper aims at delineating the concept by providing a brief conceptual history of some of its main components: uncertainty, probability and prediction. The approach is deliberately broad and comprehensive in order to obtain an overview, based on academic ruminations as well as practical applications although the study is culturally and geographically limited to the Anglo-Saxon tradition, with some excursions into the Soviet sphere.

Risk, perhaps more than any other concept, permeates our society, science and everyday lives (Taylor-Gooby & Zinn 2006: 1-8). A classic interpretation of risk defines it as the product of likelihood and impact, and this definition outlines the two axes that most analyses of risk follow: one that focuses on probability, and one that looks at the potential consequences of whatever might happen. The former aspect of risk is of particular interest in this paper, which aims at describing the historical development of a number of components of risk, such as predictability and probability. Methods for impact assessment, etc., are thus excluded from the present analysis.

Attempts at predicting the future are a very human activity that has been part of our culture for thousands of years. “The ability to define what may happen in the future and to choose among alternatives lies at the heart of contemporary societies,” writes Peter Bernstein in his eminent history of risk, and continues: “Risk management guides us over a vast range of decision-making, from allocating wealth to safeguarding public health, from waging war to planning a family, from paying insurance premiums to wearing a seatbelt, from planting corn to marketing cornflakes” (Bernstein 1996: 2). Only the methods have changed over time. When man thought that God or the gods were behind everything, prediction sought to figure out what plans the divine being(s) had made for us – and, if possible, to nudge these in a more favorable direction. Later, the predictive power of scientific models became the goal of generations of geniuses standing on each other’s shoulders. Throughout history, prediction has been seen as something very special: “Since ancient times, the ability to predict was believed to be a divine right of sages and one of the main goals of development of science” (Malinetskii 1993: 75).

The history of insurance, which can be understood as the first institutionalized application of the concept of risk, can be traced back to the ancient Babylonians and the Chinese marine traders, who as early around 3000 BC shared risk by dividing their merchandise into smaller equal shares so that no merchant would go bankrupt in case his ship sank. This practice resurfaced after the Middle Ages, with the first modern insurance underwriters going into business in Genoa in the middle of the 1300s. Like in ancient China, insurance first expanded in marine trade, but from the 16th century, onshore buildings and companies also found their way into insurance contracts, especially in England, where the Great Fire of London in 1666 fueled the process. In colonial America, the insurance business also expanded – with Benjamin Franklin (1706-1790) co-founding the first successful fire insurance company in 1759. Some scholars have argued that this "insurance society" marked the transition to modernity (Powers 2012: 94-95, Zinn 2008b: 9).

From the earliest times, risk and insurance has been concerned with an uncertain future and estimates of the likelihood of loss, linking the concept to prediction and forecasting. Prediction ("foretelling") is known from the middle of the 16th century, while the term forecasting has its origins in the Germanic roots of the English language and is historically linked to Protestantism and to planning under conditions of uncertainty. As such, forecasting is related to the Weberian idea of the Protestant work ethic, which laid the foundation for capitalism and industrialism – man's greatest attempt at becoming master of Nature and of his own fate (Silver 2012: 5).

However, the road from acts of God to scientifically based prediction and planning was long and winding. A prerequisite for moving from prophecies based on mere readings of signs and mysticism towards scientific forecasting and prediction was the introduction of mathematics as the primary language for endeavors to tame chance.

The birth of probability

In the opinion of Ian Hacking, perhaps the most prominent philosopher and historian of probability, in the 1650s, Blaise Pascal (1623-1662) initialized the process that has led to the modern understanding of risk with his discussion of the choices facing the atheist in a Christian world. Together with Pierre de Fermat (1601-1665), Pascal laid the foundations to modern quantitative probability theory as the answer to a fairly simple question about betting in a game of dice. Actually, Luca Paccioli, the monk who posed the question 200 years before, already knew the answer from experience. He just did not know why, but that question was resolved by the renaissance geniuses (Hacking 2006, Bernstein 1996: 3, Attenwell 2008: 85-86).

Most of early probabilistic theory was applied to astronomy, a rapidly developing scientific field at that time. Stephen Stigler, a historian of statistics, also describes the importance of these contributions: "The role of probability theory in the historical development of statistics was far more extensive than simply that of a refinement to the already developed combination of observations in astronomy." Stigler's argument is that while simpler combinations of observations of previous times resulted in errors cumulating, the new methods grounded in probability theory evened them out in the long run. Thus, scientists from the middle of the 17th century possessed still more efficient tools for the quantification of uncertainty (Stigler 1986: 28-30)

There was, however, a duality to probability already in its infancy, argues Hacking. One version was concerned with facts about the relative frequency with which events occur, another with the degree of confidence that observers attribute to something they are not sure about. This distinction has always been difficult for both scholars and practitioners of probability theory to make. "This suggests that we are in the grip of darker powers than are admitted into the positivist ontology", as Hacking eloquently puts it (Hacking 2006: 13-15).

However, not all of the giants of the natural scientific revolution were interested in the new ways of thinking about chance. The schematism of René Descartes (1596-1650) left little room for probability, and it seldom engaged the great Isaac Newton's (1643-1727) attention. This underlines the fact that even the simplest techniques in probability were unknown to most people before 1650, when "most people could not observe an average because they did not take averages" (Hacking 1990: 3, Hacking 2006: 45, 92, 164).

But then things accelerated. Already in the late 1600s, physician John Arbuthnot (1667-1735) published the first test of significance of a statistical hypothesis (Hacking 2006: 168). The normal distribution can be traced back to Abraham de Moivre (1667-1754) even though it was Carl Friedrich Gauss (1777-1855) who eventually got his name associated with it. (Bernstein 1996: 5, Salzburg 2001: 15-16). Long before that, the Dutch mathematician Christiaan Huygens (1629-1695) had published a book on games of chance, which became the first printed textbook on probability (Hacking 2006: 61). However, it fell to members of the gifted Bernoulli family, first and foremost Jacob Bernoulli (1655-1705), Nicolas Bernoulli (1687-

1759) and Daniel Bernoulli (1700-1782), to come up with the notion of expected utility in the first half of the 18th century, one "of the most powerful and important models of human decision making", which provides a "comprehensive and consistent approach to decision making in the face of uncertainty" (Powers 2012: 79). That was the very beginning of decision theory – "the theory of deciding what to do when it is uncertain what will happen", which in due time would be interpreted as closely related to the concept of risk itself (Hacking 2006: 64).

Uncertainty can be seen as a fundamental prerequisite for risk thinking. If uncertainty is expressed as a number between 0 and 1, where 0 denotes total uncertainty and 1 total certainty, then the concept of risk is only relevant for values between 0 and 1. For total uncertainty, the notion of risk is meaningless, and for total certainty, it is irrelevant. The notion of (un)certainty was already employed by the earliest thinkers in probability theory. Both Jacques Bernoulli and Gottfried Wilhelm Leibniz (1646-1716) thought of probability as the degree of certainty, and in the opinion of Ian Hacking, Leibniz envisioned probability as a new kind of logic that in the future would enable men to end any disagreement by picking up pencils and shout "Let us calculate!" (Hacking 2006: 134-135, 145).

Frequentism vs. Bayesianism

It is not too much to claim that the theory of probability developed in the historical period from Pascal in the 1650s to Laplace in the early 1800s (i.e., just a century and a half). Already in the early 1700s, when de Moivre published his book on the doctrine of chance, the "mathematics of probability was recognized as an? independent discipline in its own right" (Hacking 166). The main contributions were made at the height of the Age of Enlightenment: "All the tools we use today in risk management and in the analysis of decisions and choice, from the strict rationality of game theory to the challenges of chaos theory, stem from the developments that took place between 1654 and 1760, with only two exceptions [Galton's regression in 1875 and Markowitz's diversification in 1952]" (Bernstein 1996: 6).

But many other great thinkers contributed to the thinking of early modernity. One of them, David Hume (1711-1776), argued in *A Treatise of Human Nature* (1739) for a skeptical view of the future. Hume doubted that "any known facts about past objects or events give any reason for beliefs about future objects or events" (Hacking 2006: 176). In other words, prediction in the form of deduction from past experience or general theory to the particular was impossible.

This became known in philosophy as the problem of induction, an important notion that we shall return to in the last part of this brief history of risk and uncertainty.

Probability theory adds to the inductive argument a quantitative statement about the strength of the induction. In the 1700s, early statistics branched out into a so-called frequentist approach, which applies techniques from probability theory to data series of repeated occurrences, for example, of tosses of dice or results of the roulette in order to make statements of the distribution of future outcomes, and a Bayesian approach, owing its name to the Rev. Thomas Bayes (1701-1761). Bayes, an amateur mathematician, formulated a theorem that today bears his name, even though his works were only published after his death. Bayes' "Essay toward solving a Problem in the Doctrine of Chances" (1764) attacked the probabilism of de Moivre, using a geometrical Newtonian method, and laid the foundation for a very different way of thinking about probability (Powers 2012: 32, Stigler 1986: 98).

Bayesian inference distinguishes itself from frequentism in that it incorporates prior information about probability, which is then updated with information from a data sample (Attenwell 2008: 86). This "a priori" probability is subjective and can be based on personal judgment, expert opinion or, in principle, a wild guess, which of course influences the "a posteriori" probability. But even if frequentism is sometimes interpreted as more objective than Bayesianism, this approach also requires subjective decisions crucial to the outcome, such as selection of a reference class (i.e., delineation of the range and resolution of the historical time series that predictions will be based upon) (Hájek 2008: 96). Also the "issue of whether previous data come from trials identical to the situation of interest is a subjective question" (Winkler 1996: 128).

Bayesian probability is applied to many real-life situations. Michael R. Powers provides the following example. When an insurance underwriter talks about the probability of someone stealing the Mona Lisa while on loan to another museum from the Louvre, it is not probability in the frequency interpretation, because of the (fortunate) lack of previous occurrences of theft, but rather "purely cognitive metaphor or degree of belief" – a subjective interpretation of probability as opposed to frequentism, which requires a large number of repeated trials (Powers 2012: 30-32). Nate Silver emphasizes the qualitative aspect of Bayesianism: "In accordance with Bayes's theorem, prediction is fundamentally a type of information-processing activity – a matter of using new data to test our hypotheses about the objective world, with the goal of coming to truer and more accurate conceptions about it" (2012: 266).

When Bayes and Laplace together although in intellectual spirit, never in person, in the last part of the 18th century finally solved Jacob Bernoullis problem of how to infer from tickets drawn from a an urn, it was a "truly Copernican revolution" in Stephen Stigler's words: "His [Jacob Bernoullis] conceptual stance, his mathematics, his discrete urn model, and his lack of a yardstick for the measurement of uncertainty all had conspired to deny him a satisfactory solution to his problem" (1986: 122-123). But the geniuses of the late 18th century succeeded in providing exactly that yardstick – and one of them went even further in his scientific ambition.

"A mad answer to an impossible question"

French mathematician and statistician Pierre-Simon marquis de la Place (1749-1827) – the "Newton of France" – wrote in the foreword to a book on probability, first published in French in 1814, that:

> We ought then to regard the present state of the universe as the effect of its anterior state and as the one which is to follow. Given for one instant an intelligence which could comprehend all the forces by which nature is animated and the respective situation of the beings who compose it – an intelligence sufficiently vast to submit these data to analysis – it would embrace in the same formulae the movements of the greatest bodies of the universe and those of the lightest atom; for it, nothing would be uncertain and the future, as the past, would be present to its eyes. (Laplace 1902: 4)

With those words la Place expressed the Enlightenment vision of total predictability with his "little demon" – the "intelligence" with complete knowledge of all laws of nature, enabling it to make precise predictions in a perfectly deterministic universe.[1] The Laplacian demon, as it has become known, lived in a linear world where the future could be predicted as easily as the behavior of a straight line in a two-dimensional coordinate system – not unlike the line that could be drawn from Euclid to Laplace: "The belief in such a theory [of everything] and the search for it has deep roots in our cultural history. It is a dream or a foundation myth for our culture going all the way back to the ancient Greeks" (Malinetskii 1993: 75, Byers 2011: 53).

A number of great discoveries proved the applicability and accuracy of deterministic methods. The astronomer Edmund Halley (1656-1742) predicted in 1705 that a comet, later to be named after him, would pass close to Earth in 1758. It did, proving the understanding of pre-

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[1] In his presidential address in 1978 the philosopher Wes Salmon argued that the epistemic abilities of such a demon would actually undermine the quest for explanatory power in science, because "why ask why" if you already know the future? (Salmon 1978, Douglas 2009: 452)

vious times of comets as the unpredictable work of the Gods obsolete (Silver 2012: 447). And the planet Neptune was found in 1846 by pure mathematical prediction by John Couch Adams (1819-1892) and Urbain le Verrier (1811-1877), who independently calculated its location using only the laws of gravitation and geometrical analysis. They never observed this new celestial body, but nevertheless proved the predictive power of their analytical tools (Byers 2011: 134).

However, determinism did not rule out the acknowledgement of randomness[2]. The Laplacian demon dreamt of knowing everything, but experimental science became sophisticated enough at the end of the 19th century to show clearly that not all of the observations could be explained with classical physics (Buckman 2008: 72). "Europe began to understand concepts of randomness, probability, chance and expectation precisely at that point in its history when theological views of divine foreknowledge were being reinforced by the amazing success of mechanistic models," writes Hacking (2006: 2). Laplace, for one, believed in the perfection of Nature, but was at the same time convinced that human beings were unable to live up to this perfection – hence, probability theory was needed to describe human behavior, etc. (Silver 2012: 113)

The contribution to science by Laplace was tremendous. He started thinking probabilistically in 1811-1812, and, by his death in March 1827, his error distribution had synthetized with Gauss' normal distribution and matured into textbook material (Stigler 147, 157). Together with Bayes, he represented the climax of the Enlightenment in mathematics:

> The intimate connection between probability, prediction, and scientific progress was thus well understood by Bayes and Laplace in the eighteenth century – the period when human societies were beginning to take the explosion of information that had become available with the invention of the printing press several centuries earlier, and finally translate it into sustained scientific, technological, and economic progress. (Silver 2012: 243)

At the beginning of the 18th century, most scientists believed that a few fundamental laws of nature could describe reality and predict the future. All that was needed was a complete set of precise baseline measurements and a thorough understanding of the laws that govern nature.

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[2] Randomness is a fascinating and elusive concept. It was not defined until the 1960s as a sequence of integers of a given length that cannot be encoded into another sequence of integers substantially shorter than the original ("incompressibility"). Also, most people find it difficult to acknowledge true randomness. For example, Apple had to reduce the randomness in the iPad's random playlists to make them seem more random to the users (Powers 2012: 180, Gerstein 2008: 54-55, Taleb 2001).

This was, of course, ambitious, but Laplace was no stranger to scientific ambition. When Napoleon asked him about the role of God in his version of the universe, Laplace answered dryly: "I had no need for that hypothesis." (Salzburg 2001: vii)

So, Laplace and his contemporaries dreamt of perfect prediction based on total knowledge adjusted for observation errors with a little probability. For a creature capable of such computations, nothing in the future would be unknown. "What would be needed to make us able to understand the risks that face us?" we could ask with a quote from a late modern cultural risk theory. The answer reads laconically: "Nothing short of total knowledge (a mad answer to an impossible question)" (Douglas & Wildavsky 1982: 3).

Into the social sciences

What Hacking has called "the avalanche of printed numbers" that followed after the Napoleonic era made possible the rise of the social sciences and eventually eroded determinism: "A new law came into being, analogous to the laws of nature, but pertaining to people" (Hacking 1990: 1). This development actually began as early as the middle of the 1600s in the form of a systematic study of quantitative facts about the state. One of the pioneers, John Graunt (1620-1674), estimated the population of London at 384,000 based on data about the number of births, the fertility of women, etc. (Hacking 2006: 102, 106). In 1693 the British mathematician and astronomer Edmund Halley (the same Halley who 12 years later would predict the comet) published the first comprehensive mortality table, which made it possible for the British government to offer the first life annuity products that were based on actuarial calculations. The first statistical results to be taken seriously, however, did not surface until the 1780s when the Welsh philosopher and preacher Richard Price (1723-1791) published his Northampton tables, which set the standards for insurance companies for the next century (Power 2012: 7, Hacking 2006: 113-114).

The new field of statistics got its very name from a German scholar who collected remarkable facts about the state, and statistics quickly became the preferred method for modern governance, especially in the European nation states that emerged after the Napoleonic era. Prussia founded Europe's first statistical bureau by decree of the king in 1805, with France and most other western countries to follow. To begin with, these bureaus simply counted everything that could be counted, people, property, animals, etc., and categorized the results into social classes, gender, age groups, etc. However, the statistical tools available were still fairly primitive, often limited to averages and other descriptive calculations. That did not prevent some early scholars in the field from becoming almost obsessed with employing these new "magic" explanations (Hacking 1990: 24, 27-34).

The first to use probability theory to examine social data in the modern sense was Adolphe Quetelet (1796-1874), who made two important contributions to the development of applied probability theory: the concept of the average man and the fitting of distributions. His aim was to create a discipline of "social physics", able to do for the study of society what physicists and astronomers had done for the study of Nature and the universe in the previous century: discover the fundamental laws governing everything. Even if Quetelet failed to solve the main problems in the early social sciences, his contributions laid the foundations for modern statistics that Galton, Pearson and Fisher would later build upon (Stigler 1986: 169-170, 219).

The 19th century became the era of early Big Data. Siméon Denis Poisson (1781-1840), the heir of Laplace in France, formulated the Law of Large Numbers in the late 1830s, stating that if some event has a given probability, and if identical trials are run over and over again, the proportion of times that event occurs will get closer and closer to that probability (Stigler 1986: 185, Salzburg 2001: 112). The vision was, that "the regularity of statistical phenomena could reveal the laws of society, just as the regularity of physical phenomena had revealed the laws of nature to an earlier generation. The principle was the same. The vast statistical compilations of the nineteenth century could make social physics a reality" (Stigler 1986: 227). The aspiration and inspiration from natural science was evident, even a century later: "The ability to predict events within its field indicates that a science has reached a high level of development" (Kaplan 1940: 492).

In the introduction to a new edition of his excellent history of probability, Ian Hacking writes in Kuhnean language about a "second scientific revolution" in the beginning of the 19th century, but then he states that the "emergence of probability, however, was a change more fundamental than any revolution. A new thinking cap" (Hacking 2006: introduction to the 2end edition). However, living in a world whose models are inspired by natural science has its downside. "The similarity of physics and finance lies more in their syntax than their semantics", as Emanuel Derman puts it. "In physics you're playing against God, and He doesn't change His laws very often. In finance you're playing against God's creatures, agents who value assets based on their ephemeral opinions" (Derman 2011: 140).

The problem was that in "physics you can travel a very long way before you run into uncertainty" as Derman nicely puts it (ibid., 149). This created a false sense of confidence in the social sciences:

> The aura that science provides – precision and objective truth – migrates over into the field of finance. However, economics and finance cannot realistically expect to have the exactitude of the physical sciences. If the claims of absolute certainty in physics and mathematics can be disputed (…), how much more so can these claims be disputed in "softer" disciplines, which deal with human behavior. (Byers 2011: 61)

A group of Russian scientists, writing on the limits of predictability only a few years after the fall of the Soviet Union, history's most grandiose and ill-fated attempt at social engineering, reflected on the fundamental differences between the natural and "soft" sciences: "(E)ven in those cases where we can write equations for the social and economic phenomena, it should be borne in mind that those equations have certain distinctive properties, with no analogies to be found in natural science" (Kravtsov 1993c: 200).

The cause of the inappropriateness of applying laws similar to those in natural science to social science was human behavior, as one of the contributors to this volume noted: "(P)eople typically violate probability theory in various ways, often spectacularly so (although sometimes they may fruitfully be modeled as obeying it)" (Hájek 2008: 97). John Stuart Mill (1806-1873) recognized that "the complexity of human behavior impedes the development of causal explanation." He was merely aiming at an "inexact" science of human behavior (Salmon 1989: 384). Later, the philosopher Carl Gustav Hempel (1905-1997) sought to describe the general laws that govern history although his explanatory claims did not imply that "because the act can be explained in terms of laws and initial conditions, that these laws and initial conditions could have been discovered before the act occurred"[3] (Hempel 1942, Salmon 1989: 393).

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[3] Interestingly, Hempel deleted this sentence in the 1965 reprint of an article from 1948: "It is this potential predictive force which gives scientific explanation its importance: only to the extent that we are able to explain empirical facts can we attain the major objective of scientific research, namely not merely to record the phenomena of our experience, but to learn from them, by basing upon them theoretical generalizations which enable us to anticipate new occurrences and to control, at least to some extent, the changes in our environment." Apparently, he initially did seek some ultimate predictive power with his theory of general laws in history (Douglas 2009: 450).

After just a century, the "clockwork universe" had deteriorated. In the decades following Laplace, still more signs of the shortcomings of determinism surfaced. For example, Ludwig Boltzmann (1844-1906) came up with the idea of "entropy", a concept in thermodynamics that expresses a measurement of disorder or uncertainty in a system. The law of entropy states that a system becomes more and more disordered over time. This was opposed to classical determinism, in which there is "little room for uncertainty" (Byers 2011: 35). The problem was not so much what determinism did – more what it failed to do: "A classical, deterministic science is a science of stasis. It misses the essence of life, namely dynamic change" (ibid.). After all, the laws of nature (and economy, sociology, etc.) were not so easy to discover, and the old ones had eventually revealed their shortcomings as mere approximations. Instead, most scientific fields moved to statistical models around the turn of the 20th century (Salzburg 2001: viii).

Governing by numbers

Meanwhile, as the nation states of Europe were founded on statistical principles during the 19th century, the strict determinism in natural science eroded gradually. The philosopher C.S. Pierce concluded that process when he wrote in 1892: "I believe I have thus subjected to fair examination all the important reasons for adhering to the theory of universal necessity, and shown their nullity" (quoted from Hacking 1990: 11, who uses Pierce as a witness to the end of determinism). In less than 100 years, from Laplace's vision of total knowledge and perfect prediction, nature and society had become truly statistical with probability theory replacing classical mechanics as the mainstays of the scientific paradigm. Now the tools became much more advanced.

The evolution of the theory of probability, which grew out of studies of games of chance as shown above, produced a set of what David Salzburg calls "sophisticated tricks" that worked well in many disciplines at the end of the 19th century, but the field still lacked theoretical foundations (Salzburg 2001: ix). This would, however, change in the first decades of the 20th century, when the concepts of correlation and regression, so central to the statistical method, matured from Sir Francis Galton's early studies of heredity in the late 19th century into a comprehensive and coherent framework through the work of Karl Pearson, R.A. Fisher and others (Stigler 1986: 360). In Hacking's words, probability was "*the* success story of the first half of the twentieth century" (Hacking 1990: 4).

The Pearsonian revolution effectively ended determinism. From the 1920s, the measurements of science were no longer considered of interest. The probability distribution of those measurements was, as the purpose of scientific investigation shifted towards estimating the parameters of such distributions. In the 1960s, this interpretation of science had reached a level where a US professor could claim that proven scientific facts did not exist, only "statements, about which people who call themselves scientists associate a high degree of probability". In David Salzburg's view, the fall of determinism at the end of the 19th century followed the pattern of a Kuhnean scientific revolution: more and more signs that the "normal science" could not hold eventually made the paradigm shift (Salzburg 2001: 129, 133, 291, 293).

Modern managerial ideals embedded in industrialism and especially mass production have their historical roots in these developments, and with quality control and optimization came the success of the risk concept, "with the application of techniques of probabilistic risk calculation in a range of societal domains" (Zinn 2008b: 9). Michael Power simply defines risk analysis as "an overlapping family of methods for the calculation and measurement of risk based in the statistical sciences" (Power 2007: 13). He links his understanding of the concept directly to the developments in statistical science: "Practices [in risk management] remained intuitive and mathematically underdeveloped until probability theory came to be applied to practical issues of quality control in fields such as agriculture and munitions" (ibid. 12).

If statistics were associated with the present, risk was concerned with the future: "(C)alculative rationality belongs to the historical project of bureaucracies collecting numbers for processing, enterprise belongs to the logic of risk-taking for gain, an idea with a very long history" (Power 2007: 22). This raises the central question of prediction and forecasting. For classic problems, prediction error was characterized by a single value: the standard deviation of the error function (Sadovskii and Pisarenko 1993: 166). To reduce error, you had to increase the amount of information that your prediction was based upon. In frequentism, uncertainty in statistical problems results from collecting data from a sample of the population, not the whole population: "It views uncertainty as something intrinsic to the experiment rather than something intrinsic to our ability to understand the real world. The frequentist method also implies that, as you collect more data, your error will eventually approach zero…" (Silver 2012: 253).

One major problem with statistical analysis, which Nassim Taleb, who we will become much more acquainted with later, addresses, is the so-called "statistical regress argument" or the “circularity of statistics”: When analyzing data, you need to know what kind of probability distribution describes it, and you need to estimate how much data you will need to make sure that you are right. But it is the probability distribution that tells you how much data you need. This is a circular argument, which, Taleb argues, is often solved by simply assuming that your data is normally distributed. This is “quetelesmus” or “queteletismus”: the practice of seeing bell curves everywhere, named after the above-mentioned Adolphe Quetelet (Taleb 2008: 241, 269, see also Hacking 1990: 131).

The separation of risk and uncertainty

“Risk connotes the *possibility* of harm, and so financial theory is intimately bound up with the mathematical theory of probability, which originated centuries ago in connection with the attempt to estimate gambling odds,” Emanuel Derman writes, ushering us into this part of the story (Derman 2011: 49). Just as statistical science was taking off, 1921 turned out to be a pivotal year in the history of risk and uncertainty as it saw the publication of two important books that both dealt with the topics in question. Frank H. Knight (1885-1972) was an economist, but he had a background in philosophy, and his 1921-book *Risk, Uncertainty and Profit*, based on his doctoral thesis, was the first scholarly work to investigate decision-making under conditions of uncertainty (Bernstein 1996: 218-219). The same year, his fellow economist, John Maynard Keynes (1883-1946), published *A Treatise on Probability*, in which he attacked the classical probabilistic views represented by Gauss, Pascal, Quetelet and Laplace.

The questions raised by Keynes and Knight were very different from what the classical economists (and physicists) had been asking and answering. Keynes and Knight were interested in the kind of decision-making under uncertainty that might lead to a result that was not even contemplated in the initial set of probabilities. Low-probability outcomes that seem to occur more frequently than they should had also caught the attention of these two economists, who even questioned whether patterns of the past would always reveal the path to the future – a frontal attack on determinism. Knight and Keynes shared a common distrust of classical theory and certainty and total knowledge as guiding principles in decision-making. Economist John Maynard Keynes went so far as to reject the entire notion of the universal applicability of measurement in *The General Theory of Employment, Interest and Money* from 1936. He argued that it was nonsense to believe that events would happen in the future just because they have been observed to behave in a certain pattern-like way in the past. Keynes thus connects modern economic thinking to David Hume's inductive fallacy of the 1700s (Bernstein 1996: 217-223).

Knight and Keynes disagreed on many things, especially the quality of each other's work, but they shared a fundamental skepticism towards prediction based on past events. Knight "considered reliance on the frequency of past occurrences extremely hazardous" because "no event is ever identical to an earlier event – or to an event yet to happen" (Bernstein 1996: 220-221). Society is far more complex than a game a dice, and therefore economics cannot attain the same level of exactness as probability in its purest sense or classical Newtonian physics.

What made Knight's contribution pivotal was his clear-cut distinction between risk and uncertainty, which deserves a lengthy citation:

> But Uncertainty must be taken in a sense radically distinct from the familiar notion of Risk, from which it has never been properly separated. The term "risk," as loosely used in everyday speech and in economic discussion, really covers two things which, functionally at least, in the causal relations to the phenomena of economic organization, are categorically different. (…) The essential fact is that "risk" means in some cases a quantity susceptible of measurement, while at other times it is something distinctly not of this character; and there are far-reaching crucial differences in the bearings of the phenomenon depending on which of the two is really present and operating. (…) It will appear that a *measurable* uncertainty, or "risk" proper, as we shall use the term, is so far different from an *unmeasurable* one that it is not in effect an uncertainty at all. We shall accordingly restrict the term "uncertainty" to cases of the non-quantitative type. (Knight 1921: 19-20)

Thereby, Frank Knight effectively differentiated risk and uncertainty in way that would permeate the entire field of risk thinking far beyond the boundaries of economic theory – with great implications for scholars as well as practitioners (Derman 2011: 154-55). Michael Power argues that, to a large extent, "what we today call risk management is 'uncertainty management' in Knightean terms, i.e., "efforts to manage 'risk objects' for which probability and outcome data are, at a point in time, unavailable or defective". In addition, Power states that Knight's distinction between risk and uncertainty should be seen as the starting point for definitional anxieties about risk (Power 2007: 13, 26).

It is not an exaggeration when Peter Bernstein calls Knight a "creature of the twentieth century" (Bernstein 1996: 220).

“All models are wrong”

Risk thinking and risk management became an important characteristic of human activity in the Western world in the 20th century. “The application of statistical models to questions of public policy have spawned a new discipline called ‘risk analysis’,” writes David Salzburg, but also points out that the new journals of risk analysis that surfaced during the century tended to ignore the work of mathematical statisticians (Salzburg 2001: 296). The history of risk thinking indicates that Knight’s separation of risk of uncertainty meant that what he termed risk became confined to the quantitative realm, while uncertainty – at least for a while – dissipated into the foggy territories of qualitative enquiry. “Risk”, writes Jens O. Zinn in the introduction to an edited volume of social theories on the subject, “implies that an uncertain future can be made available to human action foremost with the help of positivist science and technique” (Zinn 2008b: 10).

The laws of nature devised by Galileo and Newton in the 1600s and 1700s existed in perfect worlds without friction or other kinds of error-inducing parameters – somewhat similar to Knight’s qualitative notion of risk. And just as the laws of gravity and motion still work very well in many real-world settings, Knightean risk provided risk managers with powerful tools that could be applied with success to many real-world problems, allowing quantification and development of models with strong predictive power. But, as statistician George P. Box famously reminded us, “Essentially, all models are wrong, but some models are useful” (Box & Draper 1987: 424). The difficult part is remembering only to apply the useful models to reality.

Nonetheless, risk thinking in the 20th century became deeply grounded in the building of models – with an explicit aim: “Deep inside, everyone recognizes that the purpose of building models and creating theories is divination: foretelling the future, and controlling it,” so that the world can be made invariant and the present and future become one – to paraphrase Laplace in modern language (Derman 2011: 5, 7). But this requires continuous calibration of the models: “In the absence of a feedback process you look at models and think that they confirm reality” (Taleb 2008: 268) and constant reminders that a “model is a metaphor of limited applicability, not the thing itself” (Ibid. 54). The problem is that different mathematical models will give rise to different conclusions, resulting in disputes and, eventually, fundamental doubt in the ability to derive probabilities without ambiguity (Salzburg 2001: 304).

Making a model of a part of the world is fundamentally a reductionist process, because models always "project multidimensional reality onto smaller, more manageable spaces where regularities appear and then, in that smaller space, allow us to extrapolate and interpolate from the observed to the unknown" (Derman 2011: 58). The problem is that any "reduction of the world around us can have explosive consequences since it rules out some sources of uncertainty" (Taleb 2008: 16). Ortwin Renn, one of the leading experts in social risk, reminds us in this context that it is "essential to acknowledge in the context of risk assessment that human knowledge is always incomplete and selective, and, thus, contingent upon uncertain assumptions, assertions and predictions" (Renn 2008: 75).

The obvious consequence is that an outcome model can never be better than the input. As Renn puts it: "It is obvious that the modeled probability distributions within a numerical relational system can only represent an approximation of the empirical relational system that helps elucidate and predict uncertain events" (ibid., 76). This creates inherent imprecision in model-based prediction, for example, in meteorology: "Because weather systems are vastly complex and because meteorological theories are imprecise, these models are imperfect estimators" (Fine 2010: 8). This is even truer in earthquake prediction (Hough 2010).

As statistical methods came to influence nearly all other scientific fields during the first half of the 20th century, the models that economists, sociologists and other social scientists employed became more and more advanced. Franklin D. Roosevelt's New Deal policy in the early 1930s was a showcase of model application, with the hordes of young men and women fresh out of university resembling an invasion force converging on Washington, DC, with quantitative models under their arms, and governance by numbers also became the preferred *modus operandi* of the European welfare states that matured during the 20th century. The new predictive paradigm soon began to reveal the first cracks in the concrete, but, as Nassim Taleb argues, when "an economist fails to predict outliers he often invokes the issue of earthquakes or revolutions, claiming that he is not into geodesics, atmospheric sciences, or political science, instead of incorporating these fields into his studies and accepting that his field does not exist in isolation" (Taleb 2008: 155).

Forecasting and feedback

In Hacking's words written in the mid-1970s, probability theory has only recently "been hardy enough to create its own problems and generate its own programmes of research. The stimulus used to come from other disciplines." Those stimuli originated in insurance in the 1600s, astronomy in the 1700s, biology in the 1800s and agriculture in the beginning of the 20th century (Hacking 2006: 4). But forecasting was the finest application of the statistical models of the 20th century. "We need models to explain what we see and to predict what will occur", as Emanuel Derman phrases it (2011: 43).

A prime example of prediction using scientific models is weather forecasting, which is based on knowledge about the natural laws governing the meteorological system, long time series of previous data and meticulous measuring of present variables. Meteorology is a scientific field where experts actually have become much better at prediction over the last half century, thanks to the increase in computing power and enhanced understanding of the laws of nature. Today, for example, meteorologists are able to predict the landfall of hurricanes on the US coasts a week ahead, whereas people in affected areas 30 or 40 years ago would perhaps get only 24 hours' notice. "By colonizing the future", writes Gary Alan Fine, a sociologist of weather forecasting, "they shape our approaches to risk management as well as our routines of life" (Fine 2010: x). Nonetheless, it is still impossible to predict the weather more than approximately one week ahead because of the complexity involved. British meteorologist once said, tongue in cheek: "It is easy to predict the weather – as long as it doesn't do anything unexpected" (Stewart 1989).

This is because, as with any model, a "weather model's equations are a limited and partial representation of a limitlessly complex system" (Derman 2011: 47). Weather forecasts have improved so much partly because meteorologists have a strong understanding of the relatively simple laws of physics that govern their field, partly because millions of daily forecasts have been compared to how the weather actually unfolded, providing an abundance of feedback that most other scientific fields can only be envious of. But what "makes forecasts fail is when our concern only extends as far the method, maxim, or model" (Silver 2012: 386, 403).

A leading Russian expert on prediction asserts that, in the 40s, 50s and 60s, it was "maintained that scientific forecasting had limitless opportunities", and that hardly any actors in the field back then accepted that "prediction is limited in principle" (Kravtsov 1993b: 1). Especially the second half of the 1960s saw a "prognosis boom" in the West as well as in the East with hundreds of research centers employed in technological forecasting (Bestuzhev-Lada 1993: 207). Nate Silver exhibits an interesting diagram in his book *The Signal and the Noise,* showing the use of the words "predictable" and "unpredictable" in academic journals from 1900 to the

2010s. In the beginning of the 20th century, the two terms were used equally often, but then in the middle of the 1920s the use frequency of "unpredictable" surged ahead, coinciding with the emergence of quantum mechanics and Heisenberg's uncertainty principle (Buckman 2008: 73-74). However, in the middle of the 1950s, the usage again shifted dramatically, and in the 1970s the use frequency of "predictable" peaked, marking the decade "when we thought we could predict everything, but couldn't", as Silver puts it (2012: 453-454).

In science, however, the shifting of paradigms in a Kuhnean sense has often brought about not only new insights but also limitations on the ability of scientists to attain a certain kind of knowledge. The new insight in this case was that many relatively simple mechanical, physical, and ecological systems seemed to be inherently unpredictable over long periods (Malinetskii 1993: 76).

The predictability horizon

Around 1960, the American mathematician turned meteorologist Edward Lorenz (1917-2008) was attempting to create a statistical method for weather forecasting because the numerical charts of the 1950s for short-term forecasts had proved inefficient, when he discovered that a butterfly flapping its wings in Brazil could set off a tornado in Texas due to the coupling and complexity of the weather system (Monin & Piterbarg 1993: 12). Even though the honor for describing how small perturbations in the initial conditions can cause huge variations in the final state of a dynamical process ultimately went to Lorenz, Russian mathematician Kolmogorov had suggested a similar insight several years before his American colleague announced his Lorenz became known as the father of nonlinear dynamics or "Chaos theory" (Monin & Piterbarg 1993: 18).

This was not exactly news, as the French mathematician Jules Henri Poincaré (1854-1912) "introduced nonlinearities, small effects that can lead to severe consequences, an idea that later became popular, perhaps a bit too popular, as chaos theory" as early as the 1880s. His three-body problem showed that "near precision [in prediction] is not possible since the degradation of your forecast compounds abruptly – you would eventually need to figure out the past with infinite precision." However, it was not until Lorenz applied this way of thinking to meteorology that it caught the attention of the international scientific community (Taleb 2008: 176-177).

Nonlinear dynamics created, so to speak, a "third way". They bridged the traditional two classes of objects divided into predictable deterministic and stochastic (random) ones, for which probability theory had to be employed in order to forecast. The new class behaved predictably in the short term and unpredictably in the long term, prompting scientists to slowly acknowledge that "it is beyond any doubt that there must be predictability horizons not only in physics but also in all other fields of knowledge" (Malinetskii 1993: 76-77, Kravtsov 1993b: 2).

Still, it surprised scientists in the 1970s that the continuous development of more powerful computers did not really increase their ability to forecast the weather in terms of days ahead – the predictability horizon was still looming in the distance, remarkably unchanged. It also dawned upon scientists that increasing the number of predictors (independent variables) in general did not improve their forecasts. In some cases, the predictive power of their mathematical models even deteriorated when the number of predictors increased (Monin & Piterbarg 1993: 22, 36).

However, accepting the inherent unpredictability of complex natural systems, such as the weather, was one thing. It was even more difficult to increase the accuracy of prognoses in the social sciences, particularly in sociology, because "any prognosis can itself affect, directly or indirectly, the measures taken either to implement it or to prevent it from happening" (Kravtsov 1993b: 2). This is the so-called "Oedipus effect" in forecasting, which denotes the paradox of trying to predict the behavior of systems comprising entities that are capable of changing their behavior on the basis of the forecast, thus rendering it useless. Otherwise, the lives of these entities would be meaningless (Bestuzhev-Lada 209). A firm believer in the power of social science to predict regretted this: "One of the difficulties is that knowledge about human beings at once changes them" (Kaplan 1940: 496). Ian Hacking, as always, describes this dilemma eloquently: "The human sciences display a feedback effect not found in physics" (Hacking 1990: 2).

Complex adaptive human ecosystems (societies) share some remarkable characteristics with nonlinear dynamic systems and mechanical systems that behave according to the principles of quantum mechanics at the sub-atomic level, while abiding to the laws of classical physics on the surface. Many social processes are predictable in the short term, but totally unpredictable in the long term on the far side of the predictability horizon, and many social processes may be unpredictable on the micro level (an example is Durkheim's investigation from the 1890s of who will commit suicide) while surprisingly predictable on the macro level (the number of people in Paris committing suicide annually) (Perez 2008: 148). Oscar Kaplan compares the ability to predict the behavior of a group without predicting the behavior of all the individuals in it with the interest in net effects known from the gas laws (Kaplan 1940: 496).

When Laplace and his contemporaries were dreaming of total predictability, they were first and foremost thinking about simple systems that resemble ideal games of billiard with perfectly even, frictionless surfaces, straight lines and right angles and balls that always obey Newton's laws of motion without the slightest error. Nonetheless, Laplace's demon is still alive and kicking – especially among social scientists and civil servants. "We do not know enough" is a popular tactic to oppose a certain decision or path (Kasperson 2008: 339-340).

The predictability horizon seems not to have been acknowledged by those who apply probability theory to matters of state and call it statistics. I.V. Bestuzhev-Lada, of the Institute of Sociology at the Russian Academy of Sciences, claims that all ideological trends through history, both Marxist and non-Marxist, have maintained that the future is predictable in principle: "That certainty, ingrained in the public mind and still giving quite a few fortune-tellers a chance to earn a living, is shared by virtually all decision-makers, from heads of families to heads of state, in the entire world" (Bestuzhev-Lada 1993: 205).

Aleatory and epistemic uncertainty

The rise of nuclear power prompted the development of probabilistic risk assessments (a whole new scientific field) in the US in the 1960s and 1970s. This was the ultimate application of risk in the Knightean sense. The quantification of uncertainty became the standard for risk management in high-risk settings with WASH 1400, a safety study report published by the US Nuclear Regulatory Commission in 1975 (Parry 1996: 119). The underlying assumption was that every risk could be quantified, and that meticulous calculation would allow for total prediction of the behavior of the complex systems involved in nuclear power. Some scholars go so far as to claim that the confidence of the official American scientists "came to be interpreted as arrogance" (Ravetz 2008: xiii).

There is an important distinction between aleatory and epistemic uncertainty needs. With its origins in philosophical approaches to risk and uncertainty, the distinction did not enter the field of probabilistic risk assessment until the 1990s. These new categories were defined in a special issue of *Reliability Engineering and System Safety* in 1996:

> The aleatory aspect of uncertainty is that addressed when we characterize the events or phenomena being modeled as occurring in a "random" or "stochastic" manner, and adopt probabilistic models to describe their occurrences. (…) The epistemic uncertainty is that associated with the analyst's confidence in the predictions of the PRA model itself, and is a reflection of his assessment of how well his model represents the system he is modeling. (Parry 1996: 120)

In other words, aleatory uncertainty has its roots in inherent random processes of a system, while epistemic uncertainty derives from deficiencies in the models used to describe the system or in the tools applied to gather data. According to the author, the source of confusion was that probability theory traditionally had been employed to parameterize and quantify both types of uncertainty if any distinction at all had been made: "It has not been uncommon for analysts to avoid addressing the issue by claiming that the distinction is irrelevant."

Aleatory and epistemic uncertainty is somewhat analogous to the duality of early probability theory that Hacking described (see the section on "The birth of probability"), and they also relate to the distinction between risk and uncertainty that Knight made in 1921. The difference in wording is that while Knightean risk excluded uncertainty, the aleatory/epistemic dichotomy implies that both kinds of uncertainty must be taken into account (Renn 2008: 70-71). Newton's law of gravitation is an example of a deterministic model with a very high degree of predictive power due to low epistemic uncertainty, while some probabilistic (aleatory) models based on quantum mechanics also have great predictive power although for average behavior of populations of events rather than particular events (Parry 1996: 120-21).

Any model is only an approximate representation, as argued above, and therefore it follows that some epistemic uncertainty necessarily must be associated with them as well as any predictions made on basis of the model (Parry 1996: 120). But there are ways to decrease the two different kinds of uncertainty: "By collecting more information we can indeed decrease our epistemic uncertainty with respect to parameter values and modeling issues, within the context of the structure of the model, using Bayes theorem as a basis. However, to decrease the aleatory content requires restructuring the model itself" (Ibid. 124).

With the quantification of risk in the 20th century came a preference for uncertainties that could be expressed numerically. One could even speak of a certain seductiveness of the quantitative risk analysis (Taleb 2008: 275). “Mathematics is a powerful means to win arguments because people have a strong feeling that mathematics is objective, that ‘figures cannot lie’”, writes William Byers. “The truth is that it is easy to mislead and obfuscate a situation through the use of mathematical and statistical models that are inappropriate, whose assumptions are simplistic or just wrong” (Byers 2011: 63-64). One of the strongest critics of quantitative risk assessment, Lee Clarke, takes the argument even further: “The problem with probability is that over time it has come to be equated with rationality itself, rather than as a form of rationality, and this has stunted imaginations” (Clarke 2008: 673).

This fondness for numbers had huge implications for risk thinking in general. “While it is well known in both theory and practice that risk calculation depends at critical junctures on human judgement”, writes Michael Power, “a technical ideal of risk understood as a product of the likelihood and impact of an event has been at the centre of the risk management collective imagination, defining a broad community of specialists united in the belief that managing risk demands measurement” (Power 2007: 70). However, not even the experts always understand their own numbers. Marc Gerstein provides a horrifying example of misinterpretations of quantitative risk assessments regarding flood risks in New Orleans (especially) before and after Hurricane Katrina in 2005 (Gerstein 2008: 50-58).

Life in the Risk Society

Michael Power’s assessment that “(p)urely calculative, machine-like solutions to technical problems only work well in situations where there is a very high level of agreement about knowledge and a high degree of organizational and political consent about the issue” (Power 2007: 14) resonates well with the findings of Douglas and Wildavsky, who presented what they call the “Four Problems of Risk” in their influential book on *Risk and Culture* from the early 1980s. They represented this as a two-by-two matrix that lists the four possible combinations of knowledge and consent with regard to risk. Certain knowledge and complete consent produce technical problems that can be solved with calculation, while certain knowledge and contested consent create problems of (dis)agreement with either coercion or discussion as the solution. The combination of uncertain knowledge and complete consent produces information problems requiring further research, while uncertain knowledge and contested consent result in what the authors call the “contemporary dilemma of risk assessment” that has no obvious solution. (Douglas & Wildavsky 1982: 5-6)

After the climax of quantification in the 1970s, it became clear that new approaches to risk were necessary. We see again the underlying distinction between aleatory and epistemic uncertainty, most obvious in the technical problems that, in theory, can be solved with calculation. Kahneman and Tversky's studies of risk perception from the 1970s onwards took an adaptive approach to individual and collective risk management although the heuristics they described could also lead to bias in the way people assessed risks, undermining the rational actor models that much of the risk thinking of the 20th century was based upon (Power 2007: 14, Pidgeon 2008: 351). For an interesting collection of applications of heuristic biases to disaster thinking, see Gerstein 2008). This was the beginning of a very different way of looking at risk that brought about theoretical concepts in the 1980s and 1990s, such as risk perception (Slovic 2000) and the Risk Society (Beck 1992).

When describing the Risk Society, German Sociologist Ulrich Beck's (1944-2015) main argument is that the risks faced by people in pre-modern periods were visible (as were the causes of these risks), the risks that the people of late modernity also faced were something completely new. This new category of risk was symbolized by the nuclear disaster at the Chernobyl power plant, which coincidentally happened shortly before the publication of the German edition of Beck's work. While risks in modernity materialized in the class struggle, etc., the risks of late modernity were able to "escape perception" as they hid within chemical formulas and in the confined spaces of nuclear power plants, ready to be released into the atmosphere (Tulloch 2008: 146).

Also Beck distinguishes, in a Knightean way, between risk and uncertainty when he describes risks as "statistical predictions of the future", while defining uncertainty as consisting of other systematic forms of organizing humans' experience to predict (professional judgment, ordinary foresight, rules of thumb, etc. Beck's problem with the late modern risks is the impossibility of managing them using only modern strategies of probabilistic calculation. Beck argues that "*new risks* become problematic because there is not enough knowledge available from science and technology to control their occurrence or to deal with their negative outcomes by insurance" (Beck 1992, Zinn 2008c: 177, 184).

To sociologist Niklas Luhmann (1927-1998), also German and also writing about risk in the 1990s, the concept of risk implies the possibility of decision making about the future and a corresponding allocation of responsibility, which is not the case with the concept of danger. (Luhmann 1993, Luhmann 1995, Power 2007: 5). Luhman argues that human behavior can only be understood by investigating the so-called contingencies (the options available to them in decision making). Acknowledging that contingencies are real, as opposed to a deterministic view of human life, means that adverse effects may result from decisions. It follows from this that "Luhmann's theorizing involves a high level of skepticism regarding the possibilities of steering a society or making an exact prognosis of the future" (Zinn 2008c: 169-170).

This leads us to the problem of complexity, which is also inherent in Beck's treatise on the Risk Society, just as Luhmann's "contingencies of interconnectedness may be cumulative in unforeseen ways" (Power 2007: 9).

Black swans

Complexity is difficult to define, but relatively easy to recognize when you see it. It is a property of systems characterized by a high degree of interconnectedness and interdependence that produce nonlinear interactions, emergent phenomena and – in practical terms – unpredictable behavior (Heylighen et al 2007, Mitchell 2011, Taleb 2012: 7, Renn 2008: 181). The potential for cascading effects characterizes complex systems: "Because everything is interconnected – a massive system of systems – a single disruption often triggers another which exacerbates the effect of the first, so that the original shock becomes a cascade of crises" (Rodin 2015: 5). Silver also notes that complex systems "seem to have this property [of cascading effects], with large periods of apparent stasis marked by sudden and catastrophic failures," produced by processes not literally random, but so irreducibly complex that they in practice are impossible to predict (2012: 172), while Michael Powers relates the concept of complexity to the Laplacian demon: "Inherent failure is a particular kind of uncertainty produced by large scale human organizations, and provides a counterweight to technocratic dreams of perfect control" (Power 2007: 9).

With his infamous 2002-quote, then US Secretary of Defense Donald Rumsfeld underlined the problem. We have a tendency to navigate the world and assess risks based on the "known knowns" and the "known unknowns" – the things that we know that we know and those that we know that we don't know (youtube.com 2007, Aven 2014: 12). These two domains of knowledge are manageable within the classical approach to modeling the world, contrary to the third domain in the Rumsfeld taxonomy: the "unknown unknowns" – the things that we do not know that we do not know, also known as "Black Swan events". Until 1697, Europeans knew only of white swans because that was the only color of swans they had ever observed.

But then a Dutch explorer travelled to Australia and found black swans, thus falsifying the hypotheses that "all swans are white". Europe had fallen victim to the inductive fallacy. The skepticism of David Hume had proved itself right. If you have built your entire worldview upon the notion that all swans are white it can be devastating to observe just a single black one.

The Black Swan concept has been described most recently by American-Lebanese intellectual Nassim Nicholas Taleb with inspiration from John Stuart Mill and Karl Popper among others. In broad terms, the term covers events that 1) are unforeseen, 2) have great consequences, and 3) in retrospect look like something we should have seen coming (Taleb 2008). "Fat tails" is a technical term for Black Swans and denotes events with probabilities that are not scientifically measurable" or so low that they are dismissed or neglected, based on a classic normal distribution approach to risk (Taleb 2012: 133). Michael R. Powers, a professor of risk management and insurance, states that heavy tails "defy intuition" and tend to be interpreted as "pathological", which means that people shy away from them (Powers 2012: 45).[4] This can have severe consequences because although "unpredictable large deviations are rare, they cannot be dismissed as outliers because, cumulatively, their impact is so dramatic" (Taleb 2008: 236).

One of the causes of the Black Swan is the so-called "Lucretius problem", that describes how humans tend to learn from repetition – at the expense of rare events or events that have not happened at all before: "People in risk management only consider risky things that have hurt them in the past (given their focus on 'evidence'), not realizing that, in the past, before these events took place, these occurrences that hurt them severely were completely without precedent, escaping standards" (Taleb 2012: 46, 334).

Taleb is a harsh critic of what he calls "Epistemic arrogance" (overestimating certainty while underestimating uncertainty) and finds it scandalous that "in spite of the empirical record we continue to project into the future as if we were good at it, using tools and methods that exclude rare events. Prediction is firmly institutionalized in our world" (Taleb 2008: 78, 135). But accepting the existence of Black Swans can be rather depressing: "The manner in which we attempt to control risk increases the probability of catastrophic events", writes

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[4] In insurance a catastrophe is defined as an "event whose severity is so far out on the loss distribution that its frequency is necessarily low", and from this point of view the problem with catastrophes is their rarity: It is difficult to make reasonable forecasts based upon few historical observations. Highly specialized catastrophe risk-analysis firms offer nonetheless predictions, but often in the form of black-box forecasting where the "details of the underlying methodologies remain unpublished because of proprietary business concerns" (Powers Acts 45, 206, 213, 180).

Byers. "This shows us that there is something fundamentally wrong. It is not just that people do not understand the math and apply it inappropriately. If that were so, then we could just produce a better model. The problem is that the new model will have its own black swan (highly improbable) events, that uncertainty is so intrinsic to the situation that it will inevitably appear" (Byers 2011: 65). But there *is* hope—although the future is uncertain.

The effect of uncertainty on objects

As shown, probabilistic thinking began as an epistemological paradigm, assisting scientists in grasping the universe when they thought it was just their observational tools that were inadequate, not the universe itself that behaved indeterministically (Salzburg 2001: 15, 24). Not until quantum mechanics in the first half of the 20th century did science concede the notion that it actually might be Nature itself that behaved probabilistically (Silver 2012: 113). According to Werner Heisenberg's uncertainty principle from 1927, it was impossible to measure both the position and the movement of a sub-atomic particle at the same time. Impractical and unimportant for everyday life though the principle was, it killed the Laplacian demon. At the theoretical level, quantum mechanics was also a Kuhnean revolution in science (Lindley 2008). Einstein's reluctance to believe that God would play dice with the universe just proved Max Planck's old notion that the opponents of a new scientific truth do not triumph by convincing their opponents and making them see the light, but rather because they eventually die, and a new generation more familiar with the new truth grows up.

The ISO 31000 standard for risk management from 2009 defines risk as the "effect of uncertainty on objects" – a philosophically sound reminder that risk is not the same as aleatory uncertainty alone. While aleatory uncertainty is generated by randomness and is thus irreducible (although calculable using frequentist probability), epistemic uncertainty is caused by lack of knowledge about the behavior of the system under investigation. If we know that the dice are fair, we may construct a useful model of the distribution of results in a long series of tosses even if we cannot predict the result of the *next* toss. But if we do not know much about the system's design or behavior, our model of it will be flawed. Perhaps the dice are loaded? Do we know what's on the other side of them? And could they be affected by the outcomes of other random games?

It might be that the Laplacian demon is dead, but its ghost is apparently still around. "When limits of calculability occur, they are rather interpreted as a lack of knowledge which can overcome in principle by further research and better scientific analysis", writes social risk expert Jens O. Zinn (2008b: 5), and Nate Silver also addresses this point: "They [economic forecasters] don't estimate it [uncertainty] accurately, making assumptions that lower the amount of uncertainty in their forecast models but that don't improve their predictions in the real world. This tends to leave us less prepared when a deluge hits" (2012: 177). The problem is that many risk thinkers and practitioners are still trying to resolve issues quantitatively without accepting that risk consists of more than aleatory uncertainty.

"(S)tatistics alone (and frequencies) can characterize only randomness", writes Elizabeth Paté-Cornell. "They are helpful when a phenomenon is relatively stable, the sample size sufficient, and dependencies well understood. But they fail to represent epistemic uncertainties when new or poorly known factors are at play." For such situations, Bayesian probability is needed to quantify and combine uncertainties of both the aleatory and the epistemic kinds (Paté-Cornell 2012: 1826). British statistician Dennis Lindley represents an extreme point of view at the other end of the scale when he firmly states that "(p)robability is the only sensible description of uncertainty and is adequate for all problems involving uncertainty" (quoted from Powers 2012: 33).

Nassim Taleb aims to erode the foundations of predictability when he, building on Popper, states that "to understand the future to the point of being able to predict it, you need to incorporate elements from this future itself" – which is another impossible answer to a mad question in the history of risk and uncertainty (Taleb 2008: 172). He concedes that many people accepted his Black Swan idea but reports that most "could not take it to its logical conclusion, which is that you cannot use one single measure for randomness called standard deviation (and call it 'risk'); you cannot expect a *simple* answer to characterize uncertainty" (ibid. 262).

The traditional response to deep uncertainty is to reduce the level of uncertainty by improving knowledge and understanding of the hazard at hand. The aim is to convert uncertainty into manageable risk (Kasperson 2008: 339). But to reduce uncertainty in complex adaptive systems is impractical. Instead scholars in the field suggest tolerance and acceptance as more pragmatic strategies (see Perez 2008). If we draw an analogy to society, tolerance and acceptance point our attention towards notions, such as absorption and flexibility; core aspects of the concept of resilience.

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Culture Unbound
Journal of Current Cultural Research

Resilience and Complexity
Conjoining the Discourses of Two Contested Concepts

By Rasmus Dahlberg[1]

Abstract

This paper explores two key concepts: *resilience* and *complexity*. The first is understood as an emergent property of the latter, and their inter-relatedness is discussed using a three tier approach. First, by exploring the discourse of each concept, next, by analyzing underlying relationships and, finally, by presenting the Cynefin Framework for Sense-Making as a tool of explicatory potential that has already shown its usefulness in several contexts. I further emphasize linking the two concepts into a common and, hopefully, useful concept. Furthermore, I argue that a resilient system is not merely robust. Robustness is a property of simple or complicated systems characterized by predictable behavior, enabling the system to bounce back to its normal state following a perturbation. Resilience, however, is an emergent property of complex adaptive systems. It is suggested that this distinction is important when designing and managing socio-technological and socio-economic systems with the ability to recover from sudden impact.

Keywords: Resilience, robustness, complexity, emergency management, Cynefin Framework.

Dahlberg, Rasmus: "Resilience and Complexity: Conjoining the Discourses of Two Contested Concepts", *Culture Unbound*, Volume 7, 2015: 541-557. Published by Linköping University Electronic Press: http://www.cultureunbound.ep.liu.se

Introduction

Resilience has gained remarkable popularity over the last decade, after the 2005 Hyogo Framework for Action adopted the concept as a core element in its strategy for global disaster risk reduction (Dahlberg et al. 2015). Countries adopt "resilient strategies" in emergency planning and disaster preparedness (Cabinet Office 2011; National Research Council 2012; Rodin 2015) to a degree that in just a few years has elevated 'resilience' to buzzword-status. For instance, following the 2004 national plan in the USA, even critical infrastructure (CI) was subjected to resilient strategies meant to imbue CI "with a particular agency that literally breathes life into what was once deemed inanimate" (Evans & Reid 2014: 19). Resilient communities and cities are wanted and needed everywhere (World Bank 2008; Ungar 2011; Walker & Cooper 2011: 144). Further, corporations as well as individuals need to be resilient, and able to not only accept but also cope with the stress and shocks of modern-day society (Kupers 2014; Rodin 2015). Resilient citizens thus become subjects who "have accepted the imperative not to resist or secure themselves from the dangers they face (Evans & Reid 2014: 42). Unsurprisingly, a Google Ngram search shows an increase in the use of the word 'resilience' in English-language publications during the last two decades.[2]

Figure 1. Google Ngram showing the percentage of publications in English with the occurrence of "resilience" (case sensitive) 1800-2008.

The term resilience has been widely used over the last decade to describe man-made systems' ability to recover from sudden impact. This widespread use has in fact led to the concept's origins in ecological systems theory to be sometimes forgotten. A basic distinction that is both useful and necessary when working with the concept of resilience is the distinction between what one of the founding fathers of the concept, Canadian ecologist Crawford Stanley Holling, has termed *engineering* and *ecological* resilience (Holling 1996). On the one hand, engineered ecological, economical, or technological systems are governed by an equilibrium steady state, and in such systems resilience denotes the ability to "bounce back" to this steady state after a shock. On the other hand, in natural ecosystems and complex adaptive systems, instabilities can flip the system into new stable domains with very different inner functions: “There is strong evidence that most ecosystem types can exist in alternative stable regimes, for instance lakes, coral reefs, deserts, rangeland, woodlands, and forests” (Brand & Jax 2007).

The meaning of resilience has been transformed over the last decade and a half. Before the early 2000s resilience was primarily defined as a descriptive concept that in itself was neither perceived as good nor bad. An ecosystem may be highly resilient, but unwanted by humans, and some of the most feared and hated social systems such as terrorist networks and organized crime can be extremely resilient and therefore difficult to eradicate. Brand and Jax (2007), however, identified a general movement towards a more normative view of resilience that followed the introduction of the concept into a much broader spectrum of disciplines around the turn of the millennia. They suggested that resilience was becoming a “boundary object”, rather than a well-defined scientific concept, providing scholars from many disciplines with a crosscutting theme with common vocabulary that could enhance cooperation and coordination. This however happened at the cost of losing the practical value in a more precise ecological definition. More recently, Davoudi updated this analysis by asking in the title of a paper if resilience was “a bridging concept or a dead end” (2012).

How to measure resilience is a question that has occupied researchers from many disciplines over the last several decades, and one which continues to do so. With regard to measurement, the above-mentioned distinction also proves useful: while engineered resilience can be thought of in terms of *elasticity* – resilience is exactly what provides such systems with the ability to absorb a shock and return to their steady state, and that which can be observed and measured – ecological resilience is more difficult to grasp. Holling states of ecological resilience, “In this case the measurement of resilience is the magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behavior” (1996: 33).

In other words: if an engineered resilient system bounces *back*, an ecological resilient system bounces *forward* to a different state. These introductory remarks on the concept of resilience lead into a more historical approach to its development.

A Brief History of Resilience[3]

Resilience is a contested concept with a long and winding history, and numerous definitions or resilience exist – scholars have identified as many as 46! (Tierney 2014: 162). It is not my aim to provide the reader with an exhaustive conceptual history of resilience (for such reviews, see Folke 2006, Brand & Jax 2007, Walker & Cooper 2011, Davoudi 2012 and Alexander 2013), rather I wish to highlight important milestones and definitions.

First of all, resilience must be differentiated from resistance, which is "the extent to which disturbance is actually translated into impact" (Adger 2000: 349). While a system's resistance protects it from an agent of threat by deflecting the shock, resilience is what enables the system to absorb and bounce back from the impact. In his etymology of resilience, David Alexander demonstrates that the concept originates from Latin (resilire, "to bounce"), and that resilience was first used in a somewhat modern sense by Francis Bacon in 1625. Historically, the term developed from literature and law through scientific method in the 17th century, and entered the language of both mechanics and child-psychology in the 19th century. The engineers of the Industrial Revolution thought in terms of resilience when they added redundant strength to structures such as buildings and bridges. In general, the concept retained the original core meaning of "bouncing back" regardless of the system being mechanical or psychological. It was not, however, until the second half of the 20th century that resilience found its way into ecology and the social sciences (Alexander 2013).

Overall, resilience denotes a system's ability to withstand shock through absorption and adaptation. Traditionally, engineering, economy, and ecology viewed technological, financial, and natural systems as being able to return to equilibrium (a "normal state") after subjection to a sudden, violent disturbance. From this ability arose robustness of such systems. The turning point came in 1973 when C.S. Holling in a seminal paper defined resilience as "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables" (Holling 1973: 14). This idea of "resilient homoeostasis" (dynamic equilibrium) became highly influential in the following decades of integration of the concept into social science and climate studies, even if it was debated if it could be "transferred uncritically from the ecological sciences to social systems" (Adger 2000; Gallopín 2006: 299). Holling's original ideas eventually matured into the Resilience Alliance, established in 1999 as a multi-disciplinary research organization providing advice for sustainable development policy and practice.

The modern multidisciplinary understanding of resilience also has its foundations elsewhere. In the middle of the 20th century, Austrian economist Friedrich A. Hayek laid out the foundations for the Austrian school in Neoliberalism with his thoughts on self-organizing economies. Hayek "understood that shocks to economic systems were caused by factors beyond our control, hence our thinking about such systems required systems of governance that were premised upon insecure foundations" (Evans & Reid 2014: 31). Rejecting the stable equilibrium sought by Keynesian economists, Hayek argued that markets exhibit such complex behavior that no government or other regulating body could ever hope to predict or control them. At the same time, markets themselves "have proven to be among the most resilient institutions, being able to recover quickly and to function in the absence of government" (ibid.: 35-36). Walker and Cooper point out that Holling and Hayek worked in very different fields and were inspired by very different political concerns, but that their contributions nevertheless "have ended up coalescing in uncannily convergent positions" (2011: 144).

Around the time Holling wrote his 1973-paper, the term resilience was also picked up by psychologists (via anthropology) as the discipline's substitute for robustness (Kolar 2011). By the turn of the millennium the term continued its transformation, when the relationship between social and ecological resilience was developed into a broader understanding of community resilience (Adger 2000). The Hyogo Framework for Action (an UNISDR-initiative), adopted by 168 UN members in 2005, placed resilience on the international agenda by focusing on the concept of *resilient communities* – such as cities, neighborhoods, and networks – as a corner stone in future humanitarian development. And in recent years both the UK and US governments have taken on a "resilience approach" to Disaster Risk Reduction/emergency preparedness (Cabinet Office 2011; National Research Council 2013).

Although different disciplines and traditions still disagree on the exact meaning of the concept of resilience, a broad and commonly accepted definition today would be along the lines of "the capacity of an individual, community or system to absorb and adapt in order to sustain an acceptable level of function, structure, and identity under stress". Note the emphasis on adaptation: what makes a complex adaptive system resilient is it's learning and transformational capabilities, not its ability to merely resist a shock. As phrased by Folke: "[R]esilience is not only about being persistent or robust to disturbance. It is also about the opportunities that disturbance opens up in terms of recombination of evolved structures and processes, renewal of the system and emergence of new trajectories" (2006: 259).

Complexity

As with resilience, 'complexity' has permeated the scientific and, to a lesser degree, public discourse over the last few decades, addressing the still tighter coupling and growing interdependencies of modern societies: "As technological and economic advances make production, transport and communication ever more efficient, we interact with incrementally more people, organizations, systems and objects" (Heylighen et al. 2007: 117).

Pioneered in the 1880s by Henri Poincaré, who showed that deterministic systems need not be predictable, the understanding of complexity was propelled forward by Edward Lorenz and his famous "Butterfly Effect" in the 1960s. Complexity science in its purest form originated in general systems theory and cybernetics in the second half of the 20th century. Complexity science is, however, "little more than an amalgam of methods, models and metaphors from a variety of disciplines rather than an integrated science" (ibid.), but it nevertheless offers fundamentally new insights into the properties and functions of man-made as well as natural complex systems.

Central to complexity science is an anti-reductionist approach. Contrary to the basic approach in Cartesian, Newtonian, and Laplacian science, complex systems cannot be fully understood by taking them apart and studying each of their parts individually. This is due to the "emerging properties": synergies that are created through interactions and interdependencies within the system in an unplanned way. An aircraft or a cruise ship is a highly complicated, but predictable system, where you can tell exactly what will happen if you press a button or pull a lever. Insert operators and place the system in an environment with fuzzy boundaries (e.g. an airspace with other planes or a busy shipping lane), and performance variances that no designer ever thought of are bound to happen eventually. Emergence is thus key to understanding complex systems (Perrow 1999; Dekker et al. 2011).

Unpredictability is not only a property of complex technological systems. Large social systems such as organizations, communities, and institutions also exhibit complex behavior due to many interactions between agents and subsystems. Such systems are therefore unpredictable and uncontrollable – something that often comes as a total surprise to economists, city planners, legislators, and regulators. Consequences are usually expensive and often also fatal. The failure of risk management in the late Industrial Age may be seen as the outcome of continuous application of linear predictive methods on unpredictable complex systems. Such misinterpretations and misapplications have produced disasters such as Bhopal, *Challenger, Deepwater Horizon* and *Costa Concordia* (Dahlberg 2013b).

In the Industrial Age, accidents and failures were understood as "a disturbance inflicted on an otherwise stable system" (Hollnagel et. al. 2006: 10), exemplified by Heinrich's Domino-model (1931) representing the linearity of a technical system with chains of causes and effects. From this perception of systems came the hunt for "The Root Cause Effect" and an overall reductionist focus on broken/weak components. The late Industrial Age saw the rise of complex linear accident models such as James Reason's Swiss Cheese Model (1990), adding more contributing factors in the form of "holes" in the barrier layers – but still based in error-trajectory.

A much more non-linear approach to understanding performance and safety in complex systems was taken by the Resilience Engineering movement founded in 2004 by Erik Hollnagel, David D. Woods, and other safety researchers. While Charles Perrow's Normal Accident Theory (first published in 1984, see Perrow 1999) represents the pessimist approach to complexity and adaptive systems, Resilience Engineering took from the outset an optimist's stand, assuming that "an adaptive system has some ability to self-monitor its adaptive capacity (reflective adaptation) and anticipate/learn so that it can modulate its adaptive capacity to handle future situations, events, opportunities and disruptions" (Hollnagel et al. 2011: 128).

Resilience and Complexity

The Resilience Engineering movement investigates socio-technological systems in which predictable technological processes interact with unpredictable human behavior. Together they form complex adaptive systems that are dynamic (ever changing) and able to adjust to conditions that cannot be built into the system at the design-phase. The movement's definition of resilience reads: "The essence of resilience is therefore the intrinsic ability of an organization (system) to maintain or regain a dynamically stable state, which allows it to continue operations after a major mishap and/or in the presence of a continuous stress" (Hollnagel et al. 2006: 16). David D. Woods, however, noted in the same publication that *all* systems adapt, even though some adaptation processes are very slow. Therefore, resilience in his view could not simply be the adaptive capacity of a system, prompting him to reserve the term to a system's broader capability of handling performance variations. Failure, either as individual failure or performance failure on the system level, was seen by the founding fathers of Resilience Engineering as "the temporary inability to cope effectively with complexity" (ibid.: 3). Following from this, David D. Woods argues that "organizational resilience is an emerging property of complex systems" (ibid.: 43), thus connecting the two concepts explicitly.

It follows from the above that an up-to-date understanding of resilience is more or less synonymous with what Nassim Nicholas Taleb, author of *The Black Swan*[4] (2007), recently has termed "the antifragile": systems that not only survive disturbance and disorder but actually develop under pressure. In his usual eloquent style, Taleb in a footnote addresses the relationship between his antifragility concept and resilience: "the robust or resilient is neither harmed nor helped by volatility and disorder, while the antifragile benefits from them" (Taleb 2012: 17). But in this he confuses the terms in viewing resilience and robustness as synonymous: "Antifragility is beyond resilience or robustness: The resilient resists shocks and stays the same; the antifragile gets better" (ibid.: 3).

Taleb's understanding of resilience is pre-Holling, and therefore somewhat undermines Taleb's otherwise interesting aim to "build a systematic and broad guide to *nonpredictive* decision making under uncertainty in business, politics, medicine, and life en general – anywhere the unknown preponderates, any situation in which there is randomness, unpredictability, opacity, or incomplete understanding of things" (ibid.: 4). He sees complex systems as weakened, even killed, when deprived of stressors, and defines the fragile as "what does not like volatility" in the form of randomness, uncertainty, disorder, error, stressors, etc. (ibid.: 12). However, he underlines that complex systems are only 'antifragile' up to a certain point. If the stressor is too powerful, even the most resilient system will be unable to absorb and adapt. The result, then, is catastrophic (ibid.: 69).

If the resilience of complex systems cannot be designed (as it is an emerging property), it can, however, be exercised and cultivated. The principle of "hormesis", known by the ancients and (re)discovered by modern scientists in the late 19th century, states that a small dose of poison can stimulate the development of an organism (ibid.: 37). Hormesis, on the social scale, means "letting people experience some, not too much, stress, to wake them up a bit. At the same time, they need to be protected from high danger – ignore small dangers, invest their energy in protecting themselves from consequential harm. […] This can visibly be translated into social policy, health care, and many more matters" (ibid.: 163). Hormesis can be likened to what Evans and Read call "endangerment" of agents in social systems which "is productive of life, individually and collectively" (Evans & Reid 2014: 64). Erik Hollnagel and David D. Woods also note the need to provoke complex systems in their epilogue to Resilience Engineering movement's first publication: "Resilience requires a constant sense of unease that prevents complacency" (Hollnagel et al. 2006: 355-56). This exact formulation also connects the resilience discourse with High Reliability Organization theory, as formulated by Karl Weick et.al, with its emphasis on chronic unease, fear of complacency, and attentiveness to weak signals (Weick & Sutcliffe 2007).

The point is that for complex systems, disturbances, performance variations, etc. are beneficial. As Taleb points out: "machines are harmed by low-level stressors (material fatigue), organisms are harmed by the *absence* of low-level stressors (hormesis)" (Taleb 2012: 55. He also lists the most important differences between the mechanical (non-complex) and the organic (complex) (ibid.: 59). While the mechanical needs continuous repair and maintenance, dislikes randomness, and ages with use, the organic is self-healing, loves randomness (in the form of small variations), and ages with disuse.

While fully accepting the need for constant endangerment of agents in complex systems in order to cultivate resilience, Evans and Reid also deliver a critique of what they identify as a Neoliberal strategy of governance:

> Rather than enabling the development of peoples and individuals so that they can aspire to secure themselves from whatever they find threatening and dangerous in worldly living, the liberal discourse of resilience functions to convince peoples and individuals that the dream of lasting security is impossible. To be resilient, the subject must disavow any belief in the possibility to secure itself from the insecure sediment of existence, accepting instead an understanding of life as a permanent process of continual adaptation to threats and dangers which appear outside its control. (Evans & Reid 2014: 68)

In their view, the Neoliberal discourse, stemming from the theories of Hayek and Friedman, has been the main force driving resilience to its current omnipresence: "'Resilient' peoples do not look to states or other entities to secure and improve their well-being because they have been disciplined into believing in the necessity to secure and improve it for themselves", they write. "Indeed, so convinced are they of the worth of such capabilities that they proclaim it to be fundamental 'freedom'" (Evans & Reid 2014: 77).

Another characteristic of complex system is “hysteresis” – a consequence of emergence among entities connected by nonlinear relationships. If a linear, predictable system shifts from one stable state to another, it can be switched back by reversing the process, Newtonian-style. This is what happens when you change gears back and forth in your complicated, but (usually) predictable car. In complex systems, however, “if a system is to return to its original configuration, it must take a different path” (National Research Council 2007: 26).

A complex system, however, not only depends on its current inputs, but also on its history. Hysteresis contributes to the irreversibility of complex systems, and renders the “Best Practice”-approach to problem-solving in organizations and societies virtually useless, as the multitude of historical factors in any socio-economic system create vastly different initial states, even if they look similar on the surface. The path-dependency of complex systems forms the basis for what could be called the mantra of the turn towards resilience in emergency management: “Stop planning – start preparing.” We may predict that catastrophic events will unfold in the future, but it will always be different from last time. A resilient approach to emergency planning and crisis management is based less on rigid contingency plans than on heuristics and adaptability.

Introducing the Cynefin Framework

Complexity is not absence of order – rather it is a different form of order, of un-order, or emergent order. While ordered systems are designed, and order is constructed top-down, un-ordered systems are characterized by un-planned order emerging from agents and sub-systems to the system as a whole. The Cynefin Framework developed by David Snowden offers a useful approach to sense-making by dividing systems and processes into three distinct ontologies: (1) Order, (2) un-order and (3) chaos. Order and un-order co-exist in reality and are infinitely intertwined. Separation of the ontologies serves only as a sense-making tool at the phenomenological level, as assistance in determining the main characteristics of the situation you find yourself in, thus guiding you towards the most useful managerial and epistemological tools for the given ontology (Snowden & Boone 2007; Renaud 2012).

In the ordered ontology, there is a correct answer, which may be reached through observation or analysis. In un-order, multiple right answers exist, but their nature defies observation and analysis. The three ontologies are divided into five domains. Two of them are in the ordered ontology: while the *simple* domain is characterized by obvious causalities that may be immediately observed and understood, the *complicated* domain requires expert analysis – yet still yields an exact answer after reductionist scrutiny. The un-ordered ontology is home to the *complex* and *chaotic* domains in the Cynefin Framework. In the complex domain, analysis fails due to feedback: any diagnosis is also an intervention that disturbs the system. Emergent order may be facilitated, but is difficult to design, and impossible to predict. The chaotic domain is characterized by the lack of perceivable causality rendering any form of planned intervention useless – here you can only act and hope for the best, because chaos has no right answers at all as there is no relationship between cause and effect. There is also a fifth domain, namely that of disorder which is impossible to label and make sense of (Kurtz & Snowden 2003: 468).

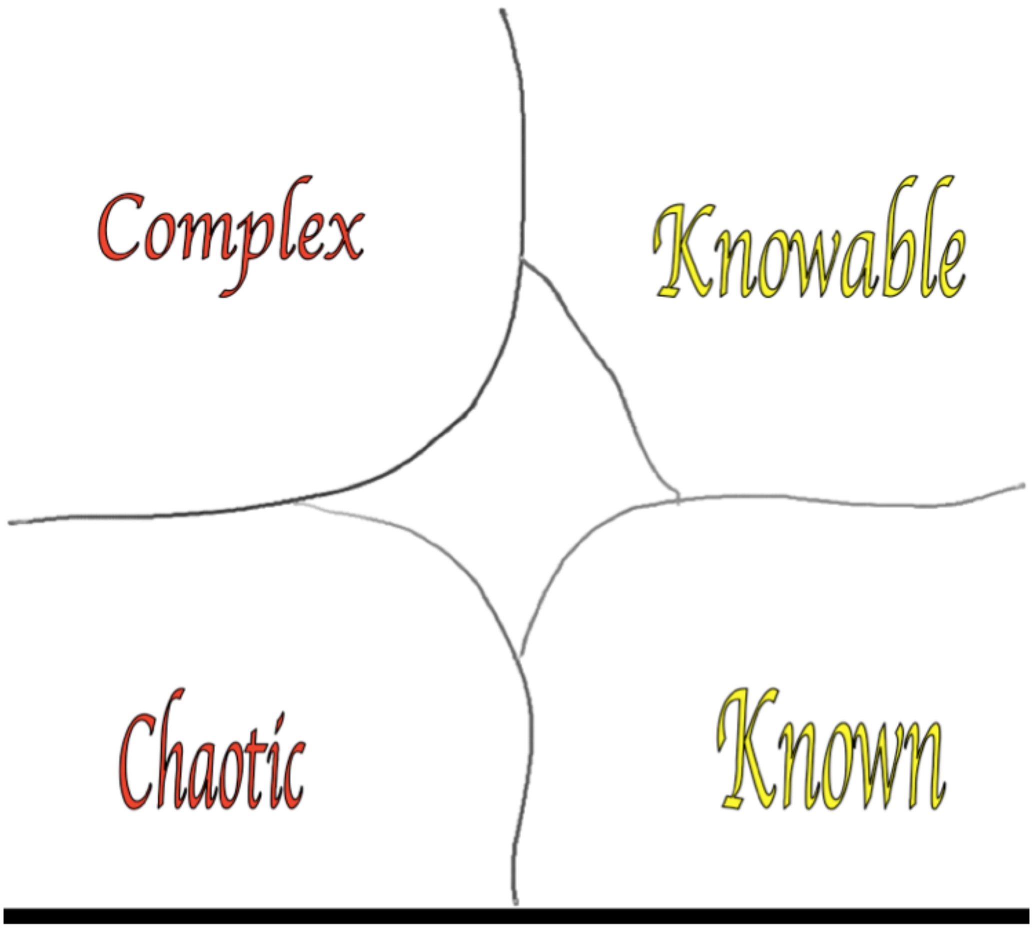

Figure 2. The Cynefin Framework, reproduced by permission from Cynthia Renaud. The known/simple and knowable/complicated domains are in the ordered ontology while the complex and chaotic domains belong to the un-ordered ontology. The domain of disorder is found in the middle.

The complex domain is characterized by weak central connections and strong distributed connections (ibid.: 470), meaning that agents interact directly instead of being controlled by an omniscient puppeteer like in the ordered domains. Lacking the common traits of order (i.e. structures, procedures, rules), the complex domain is governed primarily by co-operation between agents, mutual goals and interests, and competing forces. It is from these infinite interactions and dependencies that un-order emerges. “Most crises arise as a result of some form of collapse of order, most commonly from visible order” (Snowden 2005: 51). The boundary between the ordered and the chaotic domains is strong, meaning that after a “fall” from order to chaos there is no easy way back other than moving through complexity. Falling over the boundary is also known as “Asymmetric Collapse”:

> Organizations settle into stable symmetric relationships in known space and fail to recognize that the dynamics of the environment have changed until it is too late. The longer the period of stability and the more stable the system, the more likely it is for asymmetric threats or other factors to precipitate a move into chaos. (Kurtz & Snowden 2003: 475)

Right at this boundary we find catastrophes such as the *Deepwater Horizon* incident, a disastrous sudden transition from order to chaos produced by the “atrophy of vigilance” (Freudenburg & Gramling 2011). When the offshore semi-submersible drillrig exploded on April 20 210, a delegation from the company was on board to award the rig management a certificate for being the safest installation in the Mexican Gulf because seven years had passed without Lost Time Incidents on the *Deepwater Horizon* (Dahlberg 2013). A strategy of resilience may be seen as a countermeasure to exactly this fallacy: “To be resilient is to insist upon the necessity of vigilance in relation with one’s surrounding” (Evans & Reid 2014: 16).

The Cynefin Framework does not imply a differentiated value between the domains. Some systems perform very well in the ordered domain, while other systems benefit from operating (perhaps only momentarily) in the un-ordered domain. Only in the ordered domain, however, does a focus on efficiency through optimization of the separate parts of the system make sense. The reductionist approach to a complex system will never bear fruit. Likewise, traditional command and control-style management approaches are impossible to implement in the complex domain. Instead, complex systems are best managed by setting boundaries and adding or removing path-forming attractors (i.e. fixed points in the time-space of possible states). Constant monitoring and probing through small-scale experiments facilitate continuous development of the complex system towards a desired outcome (Snowden & Boone 2007). This resonates well with Holling’s comments on how to manage resilient ecological systems (Holling 1996: 38-41).

Taleb identifies two separate domains: one where prediction is to some extent possible, and one where it is not (the Black Swan domain): “Social, economic, and cultural life lie the Black Swan domain, physical life much less so” (Taleb 2012: 137-38). These are more or less comparable to the ordered and the un-ordered domains in the Cynefin Framework: “There is, in the Black Swan zone, a limit to knowledge that can never be reached, no matter how sophisticated statistical and risk management science ever gets” (ibid.). The unpredictability of the complex domain is primarily produced by human collaboration. The “superadditive functions” of people working together to innovate and create is impossible to forecast (ibid.: 233), just as complexity arises in complicated systems when “they are opened up to influences that lie way beyond engineering specifications and reliability predictions” (Dekker et al. 2011: 942). Erik Hollnagel also notes the limits to prediction in the complex domain: “It is practically impossible to design for every little detail or every situation that may arise, something that procedure writers have learned to their dismay” (Hollnagel et al. 2006: 16).

The ordered domain is home to Gaussian curves and “statistical confidence”, while the complex domain is haunted by black swans and fat tails. In the ordered domain, normal distributions of height, for example, enable us to predict how tall the next person is likely to be – if we have a large enough sample for measuring the mean. Fat tails are someshat synonomous with Black Swans in the sense that they constitute “high impact, low probability events”.

The so-called fat tail distributions found in the complex domain defy prediction: instead of convening around a mean, these samples consist of large numbers of not-very-surprising cases and a few extreme outliers: “In the past decade or so, it seems like fat tails have been turning up everywhere: in the number of links to Web sites and citations of scientific papers, in the fluctuations of stock-market prices, in the sizes of computer files” (Hayes 2007: 204).

The Italian economist Vilfredo Pareto discovered fat tails in the distribution of wealth in the early, industrialized societies, where a limited number of very rich people were balanced by a huge number of workers with a modest income. Paradoxically, a larger sample size provides less useful information about the distribution among the majority of the cases, as the probability of including additional outliers increases.

> The shape of a probability distribution can have grave consequences in many areas of life. If the size and intensity of hurricanes follows a normal distribution, we can probably cope with the worst of them; if there are monster storms lurking in the tail of the distribution, the prospects are quite different. (Hayes 2007: 204)

Taleb even argues that the famous 80/20 rule coined by Pareto in the beginning of the 20th century (that 80 % of land in Italy was owned by 20 % of the population) is outdated: Today, in the network society, we are “moving into the far more uneven distribution of 99/1 across many things that used to be 80/20” (Taleb 2012: 306). Such a development towards increased complexity constitutes an ever-growing challenge to the epistemological strategies we apply. History seems to drive a clockwise drift in the Cynefin Framework, while the Future exercises a counter-clockwise force upon the systems in question. It seems to be natural for people to seek order, for societies to convene towards the simple domain: “This phenomenon of grasping at order is common in people, governments, academia, and organizations of all shapes and sizes” (Kurtz & Snowden 2003: 476). And then disaster strikes and sends us plummeting over the fold into chaos.

Concluding Remarks

The Cynefin Framework was designed by Snowden to be a sense-making device, and as I have demonstrated in this paper, it is an effective lens to view and understand the concept of resilience through. The framework offers an arsenal of useful dynamic strategies that may be executed in the different domains. Many negative performance variances in our modern societies may be seen as the result of people, agencies, and governments trying to solve complex problems with solutions from the ordered toolbox – or vice versa. Instead, we should perhaps focus our efforts on *planning for the predictable* and *preparing for the unpredictable*. And this is exactly what the turn towards resilience in emergency planning and management is about.

Resilience is the ability of a complex system to adapt to disturbances and changing conditions, and resilience should be understood as an emergent property of the complex domain. This complies with recent developments in safety science according to which safety itself is "an emergent property, something that cannot be predicted on the basis of the components that make up the system" (Dekker et al. 2011: 942). Instead of looking for broken components in the causal chain that leads to an accident or disaster, a complex approach to safety science accepts competing truths and multiple explanations. From this follows that an accident might very well be no-one's fault – but merely a negative outcome of unpredictable behavior among tightly coupled interdependencies.

Resilience enables the system to cushion the effects of unforeseen disturbances by absorbing the shock and adapting to changing conditions, thus bouncing not back but forward to a more advanced level better suited for future hazards. Instead of focusing on the vulnerability of a socio-economic or socio-technological system, resilience addresses its potentials (Gallopín 2006: 294). Emergent order does exactly this: Distributed agents of change work together to solve problems and face challenges, and out of their combined efforts emerges a new un-order capable of coping with the perturbation in question. But cultivating resilience means stopping clinging to plans and beliefs in predictive capabilities:

> Disasters do not follow preordained scripts. Even in situations where there is extensive disaster experience, those seeking to respond invariably confront unforeseen situations. One counterproductive way of dealing with the unexpected is to adhere to plans and procedures even when they are ineffective or offer no guidance in the face of unfamiliar challenges. (Tierney 2014: 208)

Should all planning then be abandoned? No. Many processes and systems, technical as well as socio-economic, exhibit complicated or even simple behavior, and for those we should develop and rehearse plans which can be executed in case of emergencies. But at the same time we must accept the unpredictability of complex systems and prepare for the unknown future by cultivating resilience.

For instance, a well-rehearsed method in emergency planning is scenario-building. Most agencies tasked with national emergency preparedness create and maintain registers of risk framed as most-likely scenarios, i.e. earthquakes, flooding, train crashes, industrial accidents (European Commission 2014). While scenario-building and comparable methods work well in the ordered domain with its knowable facts and right answers, they are of limited value when dealing with complex systems. Complexity is the realm of “unknown unknowns”, to paraphrase Donald Rumsfeld, and here the shortcomings of methods developed for the ordered domain become evident. How would it, for instance, be possible to construct a scenario to prepare for an emergent calamity that has not yet revealed itself? How can one assess the probability of an event that has happened only once or perhaps never before? No analysis, no matter how thorough, will be able to identify the pattern of such a hazard before it actually manifests itself – because a pattern does not yet exist.

A consequence of such applications of ordered epistemological tools on un-ordered ontologies is 20/20 hindsight, which – unfortunately – doesn’t lead to foresight. Taleb calls this the “Lucretius problem”: humans have a tendency to prepare for the future by reviewing the past, but are not expecting anything worse than has already happened to happen (Taleb 2012: 46). Improvisation, creativity, and imaginative capacity are key elements in resilient strategies: “The challenge is understand (sic.) when a system may lose its dynamic stability and become unstable. To do so requires powerful methods combined with plenty of imagination” (Hollnagel et al. 2006: 17). The understanding of risk is challenged by complexity as no other concept. Defining risk as likelihood × consequences” of a future event, presupposes our ability to predict and assess the probability of the event in question, but this is much easier to do in the ordered domains than in cases of un-order. Uncertainty must be re-installed in the concept of risk from where it has been largely absent since Frank Knight established the distinction between uncertainty and risk (seen as measurable uncertainty) in 1921 (Jarvis 2011).

Resilience cannot be created – and it does not have to be, as it is already present as an inherent, emerging, property of all natural as well as engineered complex adaptive systems. But it may be facilitated, nudged, exercised, and cultivated, unleashing strengths and resources hitherto hidden from linear-minded planners, controllers, and predictors. Even when faced with clearly complex problems that undergo fundamental changes while being solved (“diagnosis equals intervention”), these heirs of the Enlightenment insist on reductionist thoroughness in hope of full knowledge and perfect prediction. But, as Evans & Reid note (2014: 201): “Reason imagines nothing. It cannot create and thus it cannot transform. [...] It is not made for opening up new worlds, but enabling us to survive present ones.”

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Notes

1. I would like to thank my colleague Suhella Tulsiani and my supervisor Peter Kjær Mackie Jensen, both also at COPE, for useful comments. I also thank Helene von Ahnen A.S. Haugaard for comments and proof reading.

2. Note also the historic increase in usage of "resilience" in books published during the 1880s. This is probably due to the many publications on engineering, shipbuilding, bridges, etc. of this time - which was the apex of the age of engineering: "The first serious use of the term *resilience* in mechanics appeared in 1858, when the eminent Scottish engineer William J.M. Rankine (1820-72) employed it to describe the strength and ductility of steel beams" (Alexander 2013: 2710).

3. This section is an elaborated version of Dahlberg (2013a).

4. The "Black Swan" is a metaphor for unforeseen events with great consequences that in hindsight look like something that could have been predicted (i.e. the 9/11 terror attacks in the U.S.). The origins of the concept can be traced to Roman antiquity, and the term was common in London in the 1600s as an expression of something most unlikely. In western discourse only white swans existed until 1697 when a Dutch explorer found black swans in Australia. Later, John Stuart Mill used the Black Swan metaphor when he described falsification in the 19th century: If we observe 1,000 swans that are all white and from these observations state that "all swans are white", we fall victim to the *inductive fallacy*. The observation of a single black swan would falsify our claim. Lately, the Black Swan metaphor has also entered professional risk discourse (Aven 2014).

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Bridging the Gap

Preparing for Long-Term Infrastructure Disruptions

Rasmus Dahlberg

Abstract The fixed link between Denmark and Sweden connects two busy cities and a large international airport with many of its travelers and employees. 18,000 vehicles and 160 passenger trains transport each day more than 70,000 people across the combined road and rail Øresund Bridge and through the Øresund Tunnel, approximately 25,000 of them critical to the regional work market. Even though the risk analysis states that the likelihood of a long-term closure (100+ days) is very low Danish and Swedish transport authorities have demanded that the infrastructure operator conducts a survey of the preparedness plans already in place and map possible alternate travel routes for people and freight in case of long-term disruptions. This paper (a) delineates the concept of infrastructure, (b) describes the proceedings of the Work Group for Øresund Preparedness 2014–2016, and (c) discusses the findings presented in its final report to the Danish and Swedish transport authorities while drawing upon experiences from two recent comparable cases of infrastructure disruptions: The Champlain Bridge (2009) and the Forth Road Bridge (2015).

Keywords Infrastructure • Disruption • Resilience • Contingencies • Preparedness • Transport • Possibilism

1 Introducing Infrastructure

A bridge or a tunnel connecting two areas of land across a stretch of water is in daily speech an “infrastructure,” as it allows people and goods to cross. A disruption of the infrastructure may occur in the shape of a low frequency, high-impact event such as a ship collision or plane crash that damages the bridge and renders it unusable for a prolonged time. However, demand for the service provided by the infrastructure remains, as people and goods still need to cross the water. After a

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I.S. Kotsireas et al. (eds.), *Dynamics of Disasters—Key Concepts, Models, Algorithms, and Insights*, Springer Proceedings in Mathematics & Statistics 185,
DOI 10.1007/978-3-319-43709-5_3

while the infrastructure is (hopefully) repaired, and the service is restored to its previous state. Now, people and goods may again cross the bridge or pass through the tunnel unobstructed.

From a research point of view, however, an infrastructure has a certain duality to it in that it is at the same time a tangible technology built of concrete and steel or other materials *and* an intangible process involving flows of people, goods, energy, or information. In his 2013 paper, anthropologist Brian Larkin distinguished infrastructures from technologies by stating that "infrastructures are matter that enable the movement of other matter," and when they do so they become systems that "cannot be theorized in terms of the object alone." Systemic operation, in Larkin's terms, means that they are objects that "create the grounds on which other objects operate" (Larkin 2013, p. 329). Applied to a bridge or a tunnel this notion is self-evident: without traffic it is merely a technology, with it, is an infrastructure.

An often-repeated assumption is that infrastructures are by default "invisible," and that they only become visible when they break down (Star 1999; Chang 2009). Seen from an everyday point of view this makes sense as nobody notices the bridge or the tunnel until it fails—but then it will be all over the news. Larkin argues, however, that this notion is only a partial truth: "Invisibility is certainly one aspect of infrastructure, but it is only one and at the extreme edge of a range of visibilities that move from unseen to grand spectacles and everything in between" (Larkin 2013, p. 336). When working with long-term disruptions that have very low probabilities, but potentially huge consequences, Larkin's idea about a scale of visibility is relevant. By addressing the vulnerability of the infrastructure it might be possible to decrease its opaqueness just a little, thus enabling owners, users, and policy makers to better prepare for a contingency.

A subset of the broader concept of infrastructure is the so-called critical infrastructures (CI). These are assets or systems that are critical for the maintenance of vital societal functions, providing services that citizens rely on in their daily life—i.e., power and water supply, healthcare, transport, electronic communication, and banking (Kozine et al. 2015). In other words, a vital societal function delivers a service needed (or at least valued) by society while an infrastructure is a system that enables or supports the delivery of that function. It follows from this definition that a specific vital societal function may be delivered by multiple infrastructures, i.e., a number of power plants all producing electricity to a city interchangeably or two bridges crossing the same body of water. If a vital societal function relies on an infrastructure that has no alternatives, that infrastructure is per definition a CI.

While infrastructure itself has its conceptual roots in the Enlightenment idea of a "world in movement and open to change where the free circulation of goods, ideas, and people created the possibility of progress" (Larkin 2013, p. 332), protection of critical infrastructures only became an important task for the modern industrial state (Brown 2006, p. ix). Traditionally, Critical Infrastructure Protection (CIP) has been very focused on physical protection, but increased interdependency and use of digital systems, especially networks, has since 2000 prompted a turn towards resilience (Chang 2009; Biringer et al. 2013, p. 75; Dahlberg et al. 2015a, b). A resilience approach to CIP acknowledges that all threats from either natural hazards or intentional man-made attacks cannot be avoided or deflected, and therefore, CI must be able to some extent to absorb unexpected perturbations without losing functionality (Boin and McConnell, p. 52). This approach to infrastructure is informed by complexity theory and focuses on the interdependencies of many nodes and actors (Vespignani 2010, p. 984).

Biringer et al. identify three "lines of defense" in CIP: (1) absorptive capacity, (2) adaptive capacity, and (3) restorative capacity (Biringer et al. 2013, pp. 117–123). The first line of defense describes the ability of a system to cushion the effect of an unforeseen impact through endogenous features such as robustness, redundancies, and segregation (de-compartmentalization of vital functions). The second adaptive defense line utilizes alternative ways of maintaining overall performance by substituting, reorganizing, or rerouting processes—or by exploiting basic human ingenuity that can contribute to the adaptive capacity of CI, although in unpredictable ways. The third line of defense seeks to decrease the time and money needed to restore a disrupted CI by installing early warning and monitoring systems in advance as well as prepositioning supplies in key locations.

The acute response phase of critical infrastructure disruptions has been covered elsewhere (for a review of the literature with special emphasis on information sharing, see Petrenj et al. 2013). This paper focuses on what Biringer et al. term "Adaptive Capacity" in CIP: the ability of an infrastructure system to change the way it functions in case of a disruption so the societal function that it delivers is interrupted the least.

2 Crossing the Øresund

The narrow strait of Øresund separates Denmark from Sweden and provides, together with two other Danish straits, access to the Baltic from the Atlantic Ocean. Until 1658 both sides of the water were under the rule of the Danish king, who controlled the passage with fortresses and demanded dues from foreign ships. In modern times Øresund has developed into one of the busiest waterways in the world. Ferries have crossed the strait for centuries linking Copenhagen, the capital of Denmark, with Malmö, the third largest city in Sweden. However, a fixed link comprised of the Øresund Bridge and the Øresund Tunnel was inaugurated in 2000, rendering most of these routes obsolete. Only the ferry connection between Elsinore and Helsingborg 40 km to the north, where the strait is very narrow, maintained service after the bridge was opened. The Øresund Bridge, comprising both the bridge itself and the tunnel as well as the artificial island Peberholm in the middle, is owned by the Danish and the Swedish state through the jointly owned independent Øresund Consortium that also operates the fixed link.

On an average day 70,000 travelers cross the fixed link between Denmark and Sweden, traversing the Øresund Tunnel (4 km) and Europe's longest combined road and rail bridge (8 km), dispersed in approximately 18,000 vehicles and 160 passenger trains. Approximately 25,000 daily travels are estimated to be of critical importance to the local work market. Freight, both regional and local, amounts on average to 18,000 tons daily distributed on 1100 trailers and 20–25 freight trains. An estimated 11,600 people commute on a daily basis, the vast majority of them from Sweden to work in Denmark. A traffic forecast puts the yearly increase towards 2025 at approximately four percent (middle estimate) for passengers as well as freight, testifying to the popular success of the bridge and tunnel. The number of train travelers alone more than doubled from 5 million in 2001 to 11 million in 2014.

Following Larkin's definition of infrastructure as "matter that moves matter," there is no doubt that the fixed link between Denmark and Sweden qualifies as an infrastructure—but is it also a *critical* infrastructure? In December 2008 the Council of the European Union issued its Directive 2008/114 addressing CIP in the member states. Here, CI was defined as:

> an asset, system or part thereof located in Member States which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact in a Member State as a result of the failure to maintain those functions (Council Directive 2008/114/EC)

The potential impact of a disruption of such assets, systems, or parts thereof should be estimated with regard to three criteria: (a) casualties, (b) economic effects, and (c) public effects, with any one of these being sufficient to meet the definition. Threshold values were, however, not defined in the directive, but were left up to the member states to decide upon. Each member state was obliged by the directive to identify infrastructures that could be defined as European Critical Infrastructure (ECI), and in 2010 the Øresund Bridge Consortium issued the report *Vurdering af Øresundsbron som Europæisk Kritisk Infrastruktur* (transl. Assessment of the Øresund Bridge as European Critical Infrastructure).

According to this report the Øresund Bridge is *not* an ECI. Using a 100-day total closure of road and rail traffic as the baseline, the report concludes that even in the most pessimistic estimates none of the criteria are met: casualties from increased road traffic on alternate routes would amount to a mere four additional deaths and 59 injured persons, while the economic repercussions would be just 0.03 % of the Danish and Swedish GNP. The potential effects on public trust and societal coherence were also estimated as very low. An important factor for not defining the Øresund Bridge as ECI was the existence of an alternate transportation route (i.e., the ferry link between Elsinore and Helsingborg) that would allow people and goods to keep flowing in case of a closure, although at a higher cost.

Also in 2010 *Länsstyrelsen i Skåne Län* (the regional Swedish authority) published a report on *Beredskapsplanering i samband med ett långvarigt avbrott i den faste Öresundsforbindelsen* (transl. Preparedness planning in connection with long-time disruptions of the Øresund fixed link). This report estimated the necessary means for handling a 100-day total disruption of the fixed link—the scenario that the above-mentioned assessment of the Øresund Bridge as ECI was based upon. The work group behind the report concluded that the available ferry capacity in the region would be insufficient to replace the fixed link in case of a disruption. During the initial phase large build-ups of road and especially rail traffic should be expected on both sides, and in the longer perspective severe disturbances to travel patterns in the entire region would be unavoidable.

With regard to risk assessment, the fixed link is thought to be an extremely safe system. Using the definition from Biringer et al. the absorptive capacity is very high due to the robustness of the bridge and the tunnel, the redundancies and segregation built into management systems and power supply, and the procedures of surveillance and preparedness organizations. The infrastructure operators' Operational Risk Analysis (ORA), revised in 2008, estimates the probability of a closure of the bridge for more than 30 days at 3.7 % for the link's entire expected lifetime (100 years). The probability of a closure of the tunnel that connects the bridge to Denmark is considerably higher (26.3 %) due to the risk of a vessel colliding with the immersed tube tunnel comprised of 20 prefabricated reinforced concrete segments. Overall, however, the risk of a long-term disruption (100+ days) of the infrastructure is deemed very low even though the fixed link altogether, being a tightly coupled system, depends on the bridge as well as the tunnel to function in order to provide its designated service. All probabilities for long-term disruptions caused by either accidents in the tunnel or on the bridge were estimated at below two percent for the link's entire expected lifetime (Fig. 1).

Nonetheless, Danish and Swedish transport authorities called in 2014 for a mapping of preparedness plans and crisis management procedures relevant to short- and long-term disruptions of the fixed link between Denmark and Sweden. To accomplish this the *Arbetsgruppen för Öresundsberedskap* (transl. Workgroup for Øresund Preparedness) was formed and tasked with writing a report that in addition

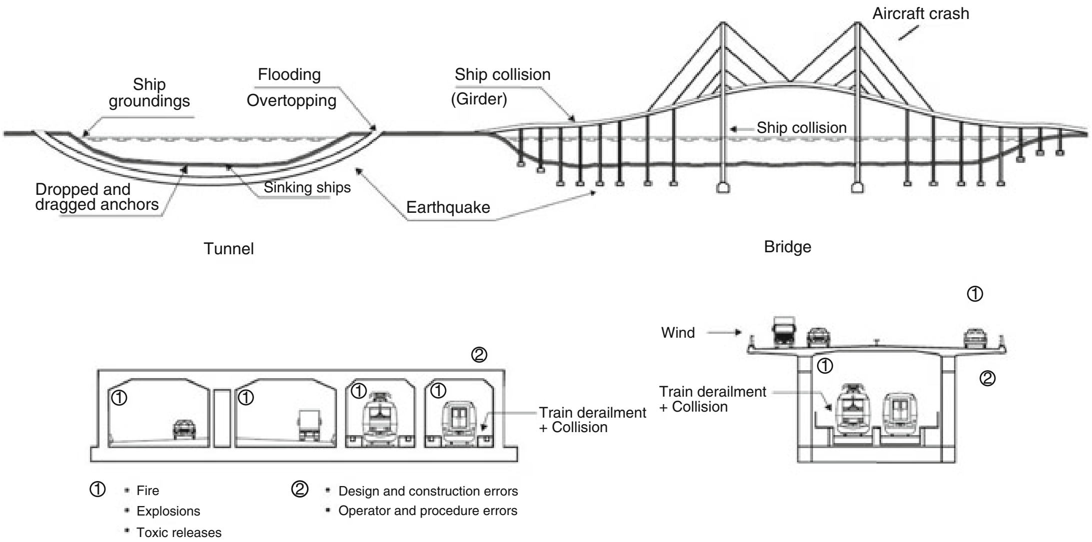

Fig. 1 Cross-section of the Øresund Bridge and Tunnel (not to scale) from the Operational Risk Analysis, revised 2008, with indication of major sources of risk. Copyright: The Øresund Consortium

to mapping the existing plans and procedures would also investigate the possibility of establishing alternate transport routes in case of a disruption.[1]

3 The Impact of the Highly Unlikely

As mentioned above, the likelihood of a total closure of the fixed link due to a ship collision or a plane crash is very low according to the ORA. But so is the calculated likelihood of a closure of the 50-km Eurotunnel that connects England and France—and yet it has already happened twice since its inauguration in 1994. In November 1996 a fire on a train carrying Heavy Goods Vehicles caused a partial closure of the tunnel that lasted until May the following year, and in September 2008 another similar fire resulted in personal injuries and a 5-month partial closure. A third and less severe fire occurred in August 2006.

Such events may be called "extreme" in the sense that the probability of them occurring is very low. They are found in the tail of the normal distribution of probability that governs most modern thinking about risk in general as well as in engineering and social science (Clarke 2008, p. 672, see also Zio and Pedroni 2014 for a more classical risk analytical interpretation of possibilism). The problem with extreme events is that they happen too rarely to allow for meaningful probabilistic risk assessment (PRA)—that is, quantification of occurrences over a time series on which the analyst can apply statistical tools. Lee Clarke proposed in 2006 the so-called *possibilistic* thinking as a complement and antidote to probabilistic thinking. It is an approach that focuses on the consequences instead of the likelihood of a certain event happening and thereby "shifts our gaze away from the center of a normal distribution out to its tails" (Clarke 2008, p. 676).

So, by exposing the potentially huge consequences of a low-probability event the possibilistic way of thinking about risk helps make infrastructure visible to paraphrase Susan Leigh Star (1999). If probability is difficult to determine for infrastructure disruptions, the consequences of such, however, are just as hard to estimate as "too few" have happened in Western societies (Boin and McConnell 2007, p. 51). Clarke advocates for the use of worst case scenarios and points out that thinking possibilisticly does not usually require much "ground truthing" as he calls it—understanding and accounting for all the details of reality. He states that possibilistic or worst case exercises should not try to approximate reality because "their greatest virtue may be their *unreality*" (Clarke 2008, p. 683).

The proceedings of the Work Group on Øresund Preparedness were to a high degree governed by possibilistic thinking. Looking strictly at the ORA, it would

[1]The researcher was allowed to participate in the work of the group as an observer and contributed also to the report with a section on resilience. All data not otherwise referenced in this paper can be found in the final report that was submitted to the Danish and Swedish authorities in Spring 2016 (Arbetsgruppen för Öresundsberedskap 2016).

appear little effort should be invested in preparing for long-term disruptions of the fixed link from a cost-benefit point of view as the likelihood of other kinds of incidents (e.g., traffic accidents, suicide attempts, extreme weather, strikes, and blockades) resulting in short-term closures is probably much higher. But Danish and Swedish authorities nonetheless opted to apply the precautionary principle by establishing the work group so that a thorough mapping and analysis could be carried out. No operational plans, however, resulted from the work; the uncertainties involved are so great that the infrastructure owner, in agreement with the authorities, decided that detailed plans for handling a long-term disruption would be meaningless. Instead, keeping in line with both Danish and Swedish principles for crisis management, an all-hazards approach (focusing on generic capabilities instead of hazard-specific planning) was taken. The group reviewed the procedures for activation of operational staffs and coordination between the responsible sectors as well as mapped the different ways alternate routes could be established in case of a disruption.

A minimum of 30 days of total closure of service was selected as the threshold for long-term disruptions because this time frame would make it necessary to establish temporary alternate means of transportation; at the same time a maximum duration of one year was chosen, as this would be too short a time for a new bridge or tunnel to be built. Rather little attention, however, was paid to the "triggering event" in the long-term disruption scenario during the early meetings in the work group. In the ORA a ship collision with the immersed tunnel was highlighted as the least unlikely scenario, while the risk of a plane crashing into the suspension bridge or a large vessel colliding with the road/rail section was assessed to have extremely low probability. As the waterways in the area are very busy, a large cargo or passenger ship colliding with the bridge's pylons is probably the most likely scenario, but a robust design with underwater barriers is believed to mitigate this risk effectively.

That said, for the possibilistic thinker an extremely low probability is still a probability that needs to be considered. In a study of supply chain flows in and across the Øresund before and after the fixed link was built the following scenario was described:

> There was a heavy fog. A northbound container ship hit one of the protective islands of the high-level bridge pillars. Through the collision some containers fell into the sea, one of them containing carbide. The container, which for security reasons had been placed as far as possible away from the crew and the machine room, was damaged when it fell into the sea. Water came in and acetylene gas was formed, which caught fire through the formation of sparks between the hull, which turned to the north, and the container, which scraped against the side of the hull. A rather powerful explosion followed and fire started in the bow. The bridge pillar was enveloped in flames and it was feared that the concrete would become weakened, so the traffic on the bridge was closed down. (Paulsson 2003, p. 2)

This is a good example of a scenario that utilizes a possibilistic approach to risk. Ask any risk analyst to perform a Quantitative Risk Assessment and calculate the likelihood of exactly this happening using, for example, Fault Tree Analysis, and you will end up with an extremely low probability. But ships with hazardous material *do* traverse the Øresund, so it *could* happen—with potentially huge consequences.

In case of a disruption of the fixed link the response phase will be managed by the standard emergency management organizations on both sides of the bridge. In Denmark the National Operative Staff (NOST) would be activated allowing tight integration between the police, emergency services, the health sector, transport authorities, and other key entities, while the *Länsstyrelsen* (regional authorities) would coordinate the incident on the Swedish side of the Öresund. After the immediate response has been managed, NOST would handover further monitoring and handling of the situation to the *Trafikal genoprettelsesgruppe* (Traffic restoration group), chaired by the Danish transport authorities, which would then be responsible for long-term planning and management of the traffic consequences, in close cooperation with Swedish authorities during the recovery phase.

The traffic restoration group is, however, *not* responsible for restoring the fixed link itself after a disruption; this responsibility rests solely with the infrastructure owner and operator. Reaching back to the before discussed definitions, we may say that the traffic restoration group is concerned with restoring the infrastructure as *process*, while the owner/operator manages the infrastructure as *technology*. This concept, which only is part of the Danish crisis management plan, is aligned with modern resilience thinking in (critical) infrastructure protection as it focuses on adaptive capacities instead of rigid plans and procedures. Overall, contingency planning for the recovery phase resonates with the Biringer et al. concept of second and third lines of defense. Such planning will be the focus of the following two sections of this paper.

4 Contingency Planning

As mentioned above, the fixed link across the Øresund has not been designated as ECI. But such definitions are not wholly independent of politico-economic, but instead depend on context and perspective. Many businesses in the area are to varying degrees dependent on the fixed link. As mentioned earlier, more than 10,000 commuters are traveling daily from the Malmö area in the morning to jobs in Copenhagen, returning late in the afternoon. Some of them will of course be able to work from home or relocate temporarily, but a long-term total closure will have a large impact on many people's daily lives. A disruption will also amplify social inequalities as educated workers will have much more flexibility, for example, to be able to work from home, compared with less highly educated and well-paid workers who must perform their jobs at set locations (e.g., nurses or shop assistants).

Basically, there are two different concerns with long-term disruptions of the fixed link across the Øresund: passengers and freight. Both categories travel on road and rail, and as these means of transportation are tightly coupled, running in the same immersed tunnel and on the same bridge structure, any disruption that could result in a long-term closure is highly likely to affect both travelers and freight. Passengers can be divided into two main groups: commuters and non-commuters, while freight is either local/regional or long-distance (e.g., Volvo cars and spare parts). The work group assumed, based on the findings in *Länsstyrelsens* 2010-report, that the long-distance freight would not be severely affected by a disruption of the fixed link, as there are several rail-ferry connections directly from Southern Sweden to the continent with surplus capacity. These assumptions were confirmed by findings from interviews carried out by the members of the work group with different actors within the sector. Market-driven self-organization is therefore expected to take care of this aspect of future disruptions without interference from the authorities.

The ferries that go between Elsinore and Helsingborg are equipped to carry railcars, but the tracks have been removed from the terminal on the Swedish side, so local and regional freight would have to be reloaded onto lorries. That could result in competition between freight and passengers for the surplus capacity on the ferries, especially during rush hour, so some kind of regulation could be necessary. The 2010-report also describes how the inflexibility of railways very quickly results in build-ups of cars and locomotives in the wrong places, and this is also expected to happen in case of a disruption of the fixed link. However, managing such issues falls outside of the responsibility of the infrastructure operator and the authorities and is a task for the responsible sector and the commercial companies involved. As these actors are professionals with experience in logistics and supply chain management they will, however, quickly adjust to the “new normal” and use the surplus capacity on the ferries to transport goods across the Øresund on lorries.

Individual travelers are the largest challenge, as they are much more difficult to communicate with and do not possess the same tools for coordination and planning as logistics and transport companies. Commuters require special attention, as they rely on the infrastructure service on a daily basis. Some Danish employers are especially dependent on the fixed link as they have many employees residing on the Swedish side: in 2014, Capital Region (Danish regional authority primarily responsible for the health sector), Field’s shopping mall on Amager and Copenhagen Airport, Denmark’s largest workplace, were some of the major attractors for Swedish labor.

Copenhagen Airport also serves many Swedish customers as an important regional hub for international air travel. As many as 10,000 daily travelers on the bridge are going either to or from Copenhagen Airport, 4000 of them on business trips. In total, Copenhagen Airport served 26.6 million travelers in 2015; four million of those came from Southern Sweden (Magnusson 2016). For commuters as well as for travelers, increased travel times would be, at the best, a nuisance. To many as much as five additional hours of daily travel time via Elsinore–Helsingborg would be unacceptable in the long run (Fig. 2).

In case of a long-term disruption, it would be possible for commercial actors such as shipping companies to set up temporary ferry connections between Copenhagen and Malmö ports. Both are large commercial harbors able to accommodate RO/PAX vessels (ships that can carry both vehicles and passengers), although the available parking space for vehicles is limited. Establishment of such a temporary connection

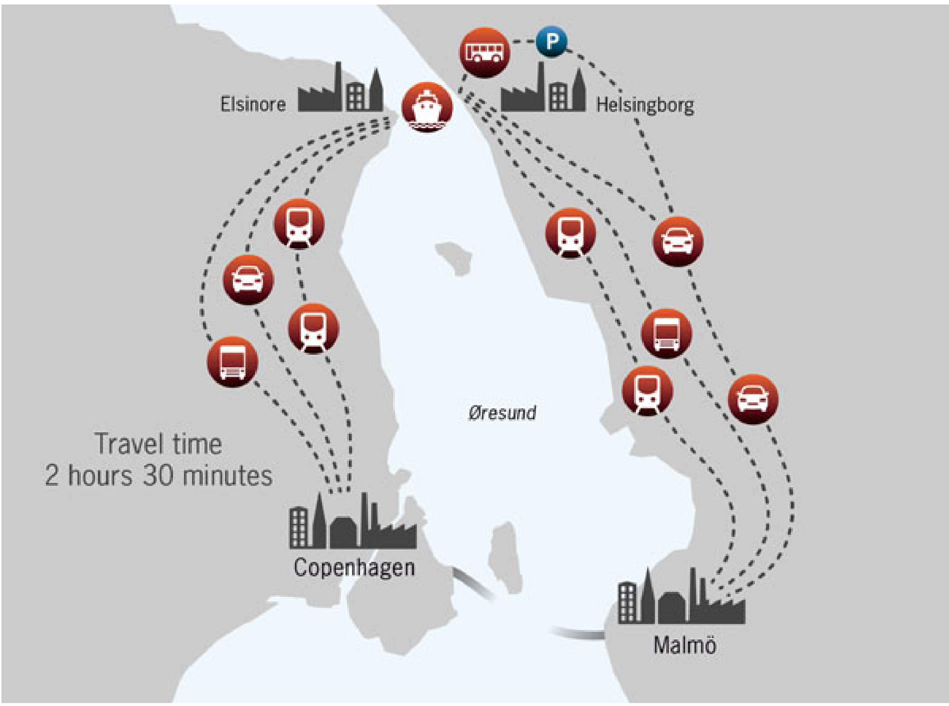

Fig. 2 The alternate route via the ferry connection between Elsinore and Helsingborg increases travel time significantly. And limited rolling stock, congested freeways and lack of parking space close to terminals may create additional bottlenecks during peak hours. Copyright: The Øresund Consortium and BGRAPHIC

is feasible—the authorities state in the report that it would probably take a longer time to identify and negotiate the use of the vessels needed than to obtain the necessary permits. The real challenge, however, is to move vehicles and passengers from the closest train station or freeway through the busy streets of a city like Copenhagen. Many commuters do not live in central Malmö or work in central Copenhagen, adding even more extra travel time to their daily commute, which speaks against setting up a temporary ferry connection between the two ports.

If the closure lasts more than 30 days, the time window from 3 to 6 months will probably pose the most challenges, as this is long enough for workers to wear out the patience of their employers with regard to flexibility but too short to attract commercial actors to a market for alternate transport routes. It is also a challenge that, due to the many daily commutes, there will be an unevenly distributed demand for transportation—if an alternate route, say a high-speed ferry between Copenhagen and Malmö, should be able to accommodate the demands at peak hour, there would be surplus capacity outside of rush hour, which would render such a service commercially problematic unless the carriers were subsidized as part of emergency measures (Fig. 3).

Fig. 3 A temporary ferry connection directly between the ports of Copenhagen and Malmö may seem like a good idea, but travel time still increases significantly due to heavy traffic especially in central Copenhagen. Copyright: The Øresund Consortium and BGRAPHIC

5 The Closure of the Champlain and Forth Road Bridges

After having presented the proceedings and results of the Work Group on Øresund Preparedness it is now appropriate to review two recent incidents that may provide useful insights about disruptions of similar infrastructures. The aim is to investigate the repercussions of two unexpected bridge closures and compare the preparedness plans from the Danish–Swedish context to how those disruptions unfolded.[2]

5.1 The Champlain Bridge

On August 26, 1929, the governor of New York, Franklin D. Roosevelt, cut the ribbon and formally opened the new Crown Point Bridge (known as Champlain Bridge) spanning the big freshwater Lake Champlain. The 2187 ft (666 m)

[2]Unless otherwise referenced, all information about the closure of the Champlain Bridge is taken from the New York State Department of Transportation report about the incident and the new bridge project (NYSDOT 2012), while the description of the Forth Road Bridge closure builds on bridge's official website (accessed February 2016) and Jane Arleen Breed's account of how the events unfolded (Breed 2011).

continuous truss bridge, designed by Charles M. Spofford, connected New York and Vermont, linking communities and people on across the lake. Over time counties started sharing hospitals and fire departments, and farmers grew accustomed to living on one side with their land on the other side. Therefore, although in 2009 daily traffic only consisted of about 3500 vehicles, the Champlain Bridge was an important infrastructure to many locals who lived on one side and worked on the other.

Champlain Bridge was one of only two bridges connecting the two states across the lake, the other one being on US Route 2 more than 40 miles (65 km) to the north. The bridge was toll-free from 1987 onwards, while the two existing ferry routes in the area (Essex, 30 miles to the north, and Fort Ticonderoga, 14 miles to the south) both charged tolls. The bridge had undergone extensive rehabilitation in the 1990s, but by 2009 the now 80-year-old bridge was ready for a new overhaul. A 5-year plan was initiated to survey the structure so the authorities could decide on either a new rehabilitation project or a total replacement.

After the 2007 collapse of the I-35W Mississippi River bridge in Minneapolis, Minnesota, New York officials took no chances when a planned inspection in the fall of 2009 disclosed severe deterioration in the bridge's supporting structure. Experts carried out a number of surveys above as well as below the surface of the lake while traffic on the bridge was restricted to one lane. The condition of the concrete piers was much worse than expected, and on October 16, 2009, the experts concluded that the supports could collapse. On the same day, at 1:30 p.m., NYSDOT closed the bridge to all traffic without any warning—never to reopen it.

The sudden closure of the bridge affected local communities severely. When the lifeline between the communities divided by Lake Champlain were cut, workers, farmers, fire fighters, and paramedics suddenly faced 2 or 3 h increased travel time, and cafes and shops on either side of their crossing lost their customers overnight. The only alternate land route was at least 85 miles (140 km) longer than the direct crossing, and even though the ferries at Essex and Fort Ticonderoga were made free of charge with subsidies from the authorities on October 27, people still had to drive long distances and wait in line to cross the lake. On October 28 a temporary connection for pedestrians was set up using the Basin Harbor tour boat, which ran until November 25, and there were also shuttle bus Park'n Ride services on both sides. From the middle of December, the Ticonderoga Ferry south of the closed bridge only operated sporadically because of the ice conditions on the lake.

The authorities monitored the situation closely. Four days after the disruption the Vermont Secretary of Transportation issued a Declaration of Emergency, and the following day the Governor of New York declared a state of Emergency under an Executive Order. The effects of the disruption were huge. For example:

> The bridge's closure separated residents from employment, medical services, childcare and family members. Farmers with fields and cattle on opposite sides of the lake could not bring in their fall harvests or tend to their livestock. Other residents were leaving home at 3 a.m. to arrive at work on time. (NYSDOT 2012, p. 4)

Exactly as the Work Group for Øresund Preparedness pointed out, the disruption amplified social inequalities. “Hundreds of workers from impoverished upstate New York towns who have low-paying but steady jobs on the Vermont side now face long-distance commutes that add hours to their day and take dollars from their pockets,” wrote one newspaper 2 weeks after the closure. Also dairy farmers, already hit hard by declining milk prices, faced potentially fatal unforeseen expenses driving around the lake to feed and milk cows (Filipov 2009).

Public meetings were held on both sides of the lake in late October, and here people demanded a temporary crossing at the location of the now unusable bridge. The local population was furious, but the NYSDOT and VTrans (the Vermont Transportation authority) found that it would be way too expensive to build a temporary bridge, which in any case would take at least 6 months to complete. Instead the authorities decided to set up a temporary ferry connection right next to the closed bridge so the inland infrastructure could still be used (Yanotti 2011).

Setting up a new ferry connection running between two states in an area with many special environmental as well as archeological conditions proved surprisingly demanding. Coordination among the many involved agencies from the Army Corps of Engineers to the Vermont Department of Fish and Wildlife were, however, successful and resulted in a permission from both Vermont and New York on November 11 to set up a ferry service. Then NYSDOT and VTrans could start building the temporary docks and prepare the service, which would be conducted non-stop by two small vessels capable of carrying approximately 20 cars at a time. Due to harsh winter conditions the construction work was difficult, and the temporary ferry connection did not open until February 1, 2010—three and a half months after the disruption of the fixed link. The average daily cost of operation was $24,240, which was covered by NYSDOT and VTrans. Additional costs were carried by the affected residents and business.

While the mitigation efforts were implemented, the authorities also had to manage the long-term perspective. Only two options were possible: either the bridge could be repaired or a new one had to be built. Reinforcement of the fractured supports was considered, but deemed too costly and inefficient, as more permanent repairs would have to be carried out anyway. By the end of 2009 the span of the Chaplain Bridge was gone—it was demolished with explosive charges on December 28. The contracting process was fast-tracked by state and federal agencies, so the contract for building a replacement bridge was signed with the company Flatiron a mere seven and a half months after the closure. On November 7, 2011, the new Lake Chaplain Bridge opened to traffic after more than 2 years of service disruption.[3]

[3]Interestingly, the special situation surrounding the construction of the new Lake Champlain Bridge meant that the building schedule ended up 4 years shorter than if a traditional design-bid-build method had been used and that millions of dollars were saved (APWA 2013, p. 96).

5.2 *The Forth Road Bridge Closure*

When the Forth Road Bridge, crossing the Firth of Forth near Edinburgh, Scotland, opened on September 4, 1964, it was the longest steel suspension bridge in Europe, with a total length of 8241 ft (2512 m) and a span of 3301 ft (1006 m). It replaced a ferry service that for centuries had transported people and goods back and forth between Quensferry and North Quensferry, complementing the nearby cantilever railway bridge which was inaugurated in 1890. In 2014 approximately 75,000 vehicles crossed the bridge daily on average.

At midnight on Thursday December 3, 2015, the Forth Road Bridge was closed to all traffic after engineers had found a 20 mm wide crack in the supporting structure only 2 days before. An inspection of the bridge in May of that year had not revealed the damage, which was located in one of the most inaccessible parts of the structure. There had been numerous problems with corrosion in the bridge's supporting steel cables over the previous decade, which ultimately led to the decision to build an entirely new bridge adjacent to the Forth Road Bridge, planned to open in late 2016. However, what the engineers had found was actually something completely unrelated: a load-bearing link to the north east tower truss end had fractured. At a media conference one engineer said that an "unprecedented set of circumstances" had forced the Scottish Government's resilience committee to close the bridge to avoid further damage, hoping that repairs could be completed before the end of the year (BBC 2015a).

Already the next morning the bridge closure caused heavy congestion on the alternate routes in the area. Approaching the nearest other bridge spanning the Firth of Forth, the Kincardine Bridge 15 miles (24 km) upstream, were traffic jams over a stretch of 11 miles. The Ministry of Transportation was preparing a full travel plan including busses, trains, and even a temporary ferry (BBC 2015b). ScotRail was treating the closure as a "national emergency," increasing its normal service from 75 to 100 trains a day on the Forth Rail Bridge. Locating enough spare running stock was, however, a challenge, as was manning the many extra trains. This prompted train union leaders to publicly criticize the shortage of capacity now exposed by the current crisis (Carrell 2015).

"We are aware of the potential economic impact for strategic traffic in the east of Scotland and on people living in local communities," said the Scottish transport minister on the first day after the closure, while political opponents called for swift action and full disclosure of Transport Scotland's full contingency plans. A representative of the Scottish Federation of Small Business addressed the need to strike a sound balance between safety and the economy, stating that: "Not only will this closure impact those that use the bridge to bring their goods or services to market, employers of all description will face serious disruption" (Carrell 2015).

Repairs took less time than expected, and, with the exception of Heavy Goods Vehicles, the Forth Road Bridge reopened to traffic on December 23, 2015, after 20 days of total closure. During this period approximately 18,000 seats were added to the local bus capacity, and the police and Transport Scotland worked closely together to ensure that road traffic in the affected areas was managed intelligently so that congestion could be minimized. Authorities engaged in dialogue with communities, business groups, and large employers and encouraged people to use public transportation, consider car sharing and work from home as much as possible.

5.3 Lessons from the Two Cases

Both closure cases serve as examples of how disruptions of infrastructures quite similar to those that are possible with the Øresund Bridge have played out. Even if there are important differences (both were only road bridges, Champlain Bridge had very little traffic compared to Øresund, and Forth Road Bridge was closed for less than 30 days) it is evident that such disruption immediately affects local communities severely, and that swift and affirmative action from infrastructure operators and authorities is required.

What immediately draws attention is that freight is almost non-existing in the documentation of both cases, which could be said to testify to the accuracy of the Work Group for Øresund Preparedness' assumption that professional operators to a large extent will solve the problems themselves. Of course, local/regional cargo transport must have been affected, but long-distance freight is not mentioned in the news coverage. One example of a major actor in this field is Amazon.com, whose biggest UK distribution warehouse is located just north of the Forth Road Bridge. A spokesperson for the major international distributor of books and other items said, when asked by *The Guardian* about the risk of delays of Christmas gift orders, that the company had contingency plans and could cope with the bridge closure by switching operations to its ten other UK fulfillment centers (Carrell 2015). More research is, however, needed to investigate the repercussions of the closures on freight.

The Work Group for Øresund Preparedness has put a lot of effort into meeting with potential stakeholders and partners in order to map where and when and how alternate transportation routes could be established in the event of a disruption. Compared to the apparently rather haphazard process led by the NYSDOT and VTrans in the weeks after the closure of the Champlain Bridge (i.e., having to report complicated information about environmental and wildlife issues in the middle of a transportation crisis) it seems reasonable to at least investigate such matters beforehand.

Lessons learned from the two cases confirm most of the issues identified by the Work Group for Øresund Preparedness: temporary ferry connections are tricky and costly to establish and will likely have to be subsidized heavily by the authorities for many months before they can become commercially feasible to run. Using alternate transportation routes such as existing bridges or ferry connections is preferable, but this requires thorough planning before the event and close coordination and cooperation among the many sectors and actors that will become involved. There are costs associated with these and other adaptive strategies—costs that are borne both by governmental authorities and by residents who are affected. Moreover, negative impacts on residents are likely to fall disproportionately on lower-income and less-well-educated members of the population. Using resilience-related terminology, some groups and sectors of the economy have more adaptive capacity than others and thus will fare better in the event of infrastructure disruptions (Walker et al. 2001; Dahlberg 2015).

One aspect of infrastructure disruption that was present in both cases discussed here, but which the Work Group for Øresund Preparedness only touched briefly upon, is the need for sound public relations and professional crisis communication when disruptions occur. After the Champlain Bridge was closed, local residents gathered in community meeting places and demanded action from the authorities, and after the closure of the Forth Road Bridge, former employees of the Forth Estuary Transport Authority (FETA) went to the press with harsh criticism towards the Scottish transport authorities. This type of outrage, which is understandable, can be mitigated through prompt and forthright communication on the part of authorities, focusing on topics such as how long infrastructure disruptions are expected to last, what options are considered and ultimately chosen to alleviate the impacts of disruptions and why, and how those affected can access information and other resources they need in order to adjust to disruptions (Blom Andersen 2015).

FETA's budget was cut by 58 % in 2011. Subsequently, it was relieved of its responsibilities for the Forth Road Bridge in June 2015, when the private UK company Amey took over as infrastructure operator after winning a 5-year tender from the Scottish government for operation and maintenance of the bridge as well as the new Queensferry Connection that was being built to replace it. Its management had been deeply concerned about handing over the management of the bridge to a private contractor—here expressed by the former convener of FETA:

> There can be no doubt that Transport Scotland were well aware of FETA board's concerns about loss of key staff and the threat that this would have on the future management and maintenance of the bridge (McPherson 2016)

This raises the question of private–public partnerships (PPPs) and their special status with regard to infrastructure protection and disruptions (Dunn-Cavelty and Suter 2009). Since the 1990s many infrastructures have been sold off to or operated by private companies, while the ultimate responsibility for maintaining the vital societal functions still rests with governments. One study suggests that infrastructure resilience should be viewed as an integrated part of Corporate Social Responsibility (Ridley 2011). The Øresund Consortium that owns and operates the fixed link is jointly owned by Denmark and Sweden, but will that information convey well to the public and the media in case of sudden closure?

On a final note should be mentioned that in both of the cases the cause of the closure was NOT the sudden impact from an earthquake, a ship collision or a plane crash, but the result of aging and long-term subtle wear and tear that went by unnoticed by authorities and operators. Another recent case is the combined rail and road Storstrøm Bridge in Southern Denmark (inaugurated 1937), that in October 2011 was closed to rail traffic for a week after the authorities discovered a

25-cm crack in its supporting structure (Rasmussen 2011). Also highly unforeseen socio-political developments with origins far away may severely influence the service of an infrastructure: on January 4, 2016, Swedish authorities introduced identification procedures for travelers going from Denmark to Sweden as a means to control the flow of migrants and refugees, increasing travel time for especially train passengers who were forced to disembark and change trains at Copenhagen Airport (Magnusson 2016).

While the consequences are less sudden and brutal as a ship collision or a plane crash, the root causes of such error trajectories tend to be much more complex and should be sought in the socio-economic-technological systems that surround the infrastructure.

6 Known and Unknown, Knowns and Unknowns

Integrating possibilistic thinking in planning for long-term disruptions of infrastructure should be thought of more as process than an objective. When forced to prepare for low-probability events with potentially huge consequences, the socio-technological system surrounding the infrastructure is exercised on more generic terms, generating awareness, expertise, and knowledge (Boin and McConell 2007, p. 55). A plausible worst case scenario provides excellent opportunities to engage in relevant conversations across sectors and organizations, creating the “chronic state of unease” that is crucial to any High Reliability Organization (Weick and Sutcliffe 2015). Any planning process aimed at catastrophic events at the same time prepares the emergency management and crisis management organizations for more common and trivial events.

No matter how unpopular it might be with quantitative risk experts, possibilistic thinking is a necessary and useful complement to the probabilistic approach. However, there are cognitive limits at work even in possibilistic thinking. Just as Herbert Simon argued that a rational persons rationality is inevitably bounded by the incomplete knowledge he or she possess on which to base decisions (Simon 1955), so is possibilistic thinking limited by our ability to imagine the worst that could happen. In February 2002 then US Secretary of Defense Donald Rumsfeld explained at a Pentagon press briefing that there are “known knowns” (things we know that we know), “known unknowns” (things that we know that we don’t know), and “unknown unknowns” (the things that we don’t know that we don’t know) (youtube.com 2007). Not surprisingly, Rumsfeld found the latter category to be the difficult one.

Applied to risk thinking we may say that PRA is generally well suited to deal with the two first categories—the things that we know we know and those that we know that we don’t. PRA requires a thorough understanding of systems, including knowledge of previous events and states over long periods of time. In order to estimate the probability of a certain event happening in the future it is necessary to know the distribution of similar events in the past.

The quantification of risk addresses *aleatory* uncertainties that may be irreducible, but nevertheless can be calculated using probability. Uncertainty caused by randomness such as the tossing of a coin or throwing dice is manageable as long as we understand the behaviors of the system and have access to sufficient past data to describe the probability distribution. That aleatory uncertainty is irreducible means that no matter how much we know about the probability, we'll never be able to say anything more solid about the *next* toss of the coin. Assessing risks over longer time periods and defining acceptable risks are the aims of this approach.

But other kinds of uncertainty are also at play, unfortunately: *epistemic* uncertainties that stem from lack of knowledge about the system and *ontological* uncertainties that resemble Rumsfeld's "unknown unknowns." Risk assessments are based on "world models" that make assumptions about the real-world system that they represent, and if these assumptions are wrong or too simple the result is epistemic uncertainties with potentially catastrophic consequences. Ontological uncertainties constitute a third category that originates not from lack of knowledge but lack of *imagination*. If a risk assessment is based on a world model and that model lacks important factors, then the outcome is of course flawed and dangerous to use for decision-making. Epistemic and ontological uncertainties are usually understood as more dependent on prior assumptions about the world than aleatory uncertainties, although more conventional risk analyses also are based on "subjective" decisions about system boundaries, interpretations of outliers, etc. Therefore, epistemic and ontological uncertainty is often underrepresented in risk assessments done by analysts with a preference for quantifiable "rational" data.

To prepare for disruption, it is necessary to make infrastructure visible before a disruptive event. One approach to this could be to focus more on the infrastructure as *process* than *technology*: if users are made aware of the service that the infrastructure provides instead of thinking about it as a mere stretch of road or rails across the water, that may prompt contingency planning on the individual level—an important element in improving resilience (Rodin 2015). For authorities and infrastructure owners and operators it's about remembering why people buy quarter-inch drill bits. It's because they want quarter-inch holes (Levitt 1986, p. 128). People also use an infrastructure not (only) because they like the view, but because they want to go to the other side of the water.

Making the infrastructure visible before a disruption enables contemplation of not only aleatory but also the epistemic and ontological uncertainties at play. Is cost cutting or other previously unanticipated processes such as climate change slowly undermining an expected infrastructure lifetime of, for example, 100 years, thereby seriously altering the failure probabilities that conventional risk assessments rest upon? Do we take users' and stakeholders' behaviors and opinions into consideration when planning our recovery phase in case of long-term disruption—and if we do not, how can we estimate the costs involved? And do we make sure that we learn the lessons from similar events that have happened elsewhere and incorporate them into our planning processes?

Acknowledgements The author wishes to thank Professor Kathleen Tierney, Natural Hazards Center, University of Colorado Boulder, Professor Henning B. Andersen, Technical University of Denmark, Head of Division Mads Ecklon and Head of Section Maximilian Ritzl, Center for Preparedness Planning and Crisis Management, Danish Emergency Management Agency, Ulla V. Eilersen, Safety Manager, Øresundsbron, and Strategic Consultant Henrik Andersson, Sweco Society AB, for useful comments to a draft of this paper. A special thanks to Ladimer Nagurney and Leif Vincentsen for directing the author's attention towards the two recent cases of infrastructure disruption.

This research was carried out with funding from the READ-project (Resilience Capacities Assessment for Critical Infrastructures Disruptions), funded by the European Commission DG Home.

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Do you have a Plan B?

Integrating Adaptive Capacities into Infrastructure Preparedness Planning

I don't really have any expectations for the role of the authorities. I would probably just solve the problem myself. I would find a Plan B or a Plan C.
(Man, 50, business traveller, crosses the Øresund twice a month)

Abstract:

This paper explores adaptive capacities in infrastructure preparedness planning from a resilience approach using the bridge between Denmark and Sweden as a case. First, a theoretical framework is established to anchor adaptive capacity in a more general resilience discourse with regard to infrastructure protection and preparedness planning. Then, findings from a small qualitative study (n=45) of the perception of commuters and travellers of the responsibilities and contingencies involved in potential long-term disruptions of the Øresund Bridge are discussed. Finally, a number of recommendations for how such adaptive capacities may be integrated into preparedness planning by authorities and infrastructure owners and operators are presented. Resilience is understood in terms of flexibility and adaptive capacity, acknowledging citizens' ability to interpret information and adjust their behavior without prior planning and training or instructions. The most important suggested recommendation for authorities and infrastructure owners is simply to remind users that an infrastructure is not a given – in other words, to ask travellers if "they have a Plan B", thereby prompting citizens to contemplate their dependency on infrastructure and prepare for a disruption.

1. Introduction

This study has its origins in the proceedings of a work group established in 2014 by the Danish and Swedish transport authorities to review the preparedness plans for long-term disruptions of the Øresund Bridge between Denmark and Sweden. Two recent cases show just how disruptive such changes can be: the sudden closure of the Lake Champlain Bridge in the United States in 2009 after severe deterioration was discovered and the equally sudden closure of the Forth Road Bridge in Scotland in 2015 following the detection of a 20 mm wide crack in the bridge's supporting structure. Both disruptions had a large impact on the surrounding communities, but also showed how citizens cope with unexpected change to the availability of transportation means (Dahlberg, 2016).

The work group, which was comprised of experts from the infrastructure operator, the authorities, the police and other stakeholders, analyzed traffic flows, estimated surplus capacity on alternate routes and calculated the need for temporary ferry connections, bottlenecks on road and rail, and many other factors. But something seemed to be missing from the discussion: people. During a meeting it surfaced that despite 15 years of traffic data and myriads of statistical analyses of traffic data, very little was actually known about the individual users of the infrastructure with regard to their thoughts about the possibility of long-term disruptions. On this basis it was decided to carry out a small-scale qualitative survey to gather information about how individual users think about and plan for potential long-term disruptions of infrastructure that is of great benefit to them in everyday life.

This paper presents and discusses the findings of this qualitative survey. After a short case description, a theoretical framework for the analysis is developed based on a literature review; then, the findings from a qualitative survey are presented and discussed; and, finally, a number of recommendations are presented. The exploration of the adaptive capacities of individual travellers and commuters will be the main focus of this paper. By applying a theoretical concept to the empirical statements collected in the survey, this study contributes to the expanding body of literature on adaptive capacity and provides a useful example of how a better understanding of the adaptive capacities of citizens may enable infrastructure operators and authorities to integrate such knowledge into preparedness planning.

2. Theoretical framework

The concept of resilience originates from the Latin *resilire* and was first used in a modern sense by Francis Bacon in 1625. Historically, the term developed from literature and law through scientific method in the 17th century, and entered the language of both mechanics and child psychology in the 19th century (Alexander, 2013). A resilience approach to disaster and emergency management involves working with networks instead of hierarchies, empowering emergent behavior instead of trying to plan for everything, and acknowledging that actors with no formal training, instructions or organization are willing and able to contribute to all phases of the emergency management cycle (National Academy of Sciences, 2012, Tierney, 2014, Rodin, 2015).

In Critical Infrastructure Protection (CIP) the shift towards resilience acknowledges that all hazards cannot be avoided or deflected, and therefore, infrastructures must be able to absorb some unexpected perturbations without losing functionality (Biringer et al., 2013: 75, Dahlberg et al., 2015, Dahlberg, 2016). A resilience approach, in other words, shifts the focus in preparedness planning from a traditional top-down perspective, where authorities assume responsibility for managing the effects of a disruption, to bottom-up thinking that builds on existing capabilities of the citizens involved. That way preparedness planning can harvest all the insights people have gained from coping with short-term closures and integrate them into a larger framework, enhancing the overall resilience of the socio-technological system incorporating the infrastructure.

Even if much theoretical work has been done on resilience in recent years, resilience remains an elusive and contested concept (Manyena, 2006, Walker and Cooper, 2011, Alexander, 2013, Dahlberg, 2015). Most scholars would, however, accept a broad definition stating that 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 structures and functions" (UNISDR's definition). An important aspect of this definition is "accommodate to", which implies that a resilient system is not only able to resist, absorb and recover, but also *adapt* to the effects of hazards.

Resilience can be broken down into parameters like in the MCEER Resilience Framework that defines four resilience properties (Robustness, Redundancy, Resourcefulness, and Rapidity) and four dimensions of resilience (Technical, Organizational, Social, and Economic) (Bruneau et al., 2003). This matrix helps quantify measures of resilience and has inspired a theoretical framework developed under the auspices of the READ (Resilience Capacities Assessment for Critical Infrastructures Disruption) Project (Kozine et al., 2015). The READ Framework defines a resilience capability as a coherent compound of assets, resources, practices and routines that promotes the achievement of resilience objectives. One entity in this compound is adaptive capacity, defined by READ as the "degree to which the system is capable of self-organizing for coping with the unexpected and to adjust to novel conditions of operations." This concept will be explored further theoretically as it fits the purpose of this paper.

In socio-technological systems, adaptive capacity can be said to exist through "institutions and networks that learn and store knowledge and experience and create flexibility in problem solving" (Resilience Alliance, n.d.), while a recent definition in relation to critical infrastructure reads: "*Adaptive capacity* is the degree to which the system is capable of self-organization and uses nonstandard operating practices in an attempt to overcome disruption impacts" (Biringer et al., 2013: 119). To be adaptive can also be defined as is the capacity to adjust to changing circumstances by developing new plans, taking new actions, or modifying behaviors (Rodin, 2015: 9-42). An important prerequisite for adaptive behavior is trust in abstract systems as well as interpersonal trust: If people do not expect infrastructure operators to work with them towards an overarching common goal in times of crisis, i.e. rapid restoration of service, it will not make sense for them to contribute to the process (Semaan and Mark, 2011: 4).

In climate change literature, the concept of adaptive capacity addresses how individuals, local communities and whole societies adapt to manifestations of change caused by climate change, for example rise in seawater level, increased precipitation, higher frequency of extreme weather events, etc. In this context, adaptive capacity is, broadly understood, the ability of an individual, organization or institution to cope with uncertainty and unpredictability (Staber and Sydow, 2002: 410). In this tradition adaptive capacity is often linked to the concept of social capital, developed in the 1980s and 1990s by Bourdieu, Coleman, Putnam and others (Pelling and High, 2005: 310), describing how individuals and communities adapt to climate change through bridging, bonding and linking capital in social systems.

Trust (in each other, authorities etc.) is an especially important aspect of social capital theory as a means for individuals to make decisions under uncertain conditions (Wachinger et al., 2013). Research on people's risk perception in relation to their own experience with disasters and hazards does not show a coherent picture. The importance of personal factors such as age, gender, educational level and religiousness is equally contested. Some studies find that personal experience from disasters increase risk perception and awareness, while other studies suggest that the outcome is depending on how people interpret their experiences. Trust in authorities and confidence in protective measures, however, has been found to be influential with regard to risk perception (Grothmann and Patt, 2005, Terpstra, 2011: 1659, Wachinger et al., 2013: 1052).

The literature suggests that adaptive capacity is an important aspect of resilience and relevant to the case of infrastructure, and that flexibility and self-organization are key elements in resilient socio-technological systems, while trust enables citizens to plan and act. Based on the review three aspects of adaptive capacity are selected to form the analytical framework for the analysis: "Flexibility," "Self-organization," and "Trust." Flexibility is understood here as the capability to change modes and frequency of travel, relocate home or workplace etc., while self-organization addresses users' ability to act and find solutions without instructions or assistance from authorities. Trust covers how travellers perceive information disseminated by infrastructure owners, expectations for the role of transport authorities etc. These aspects will be applied in the analysis of the empirical data.

3. Case description

The Øresund Bridge between Denmark and Sweden is used as the case study throughout the paper as the researcher was embedded in the Work Group for Øresund Preparedness 2014-16.[1] Risk analyses describe the likelihood of a long-term closure (more than 30 days) as very low, but nevertheless Danish and Swedish transport authorities asked in 2014 the infrastructure operator to review preparedness plans already in place and to map possible alternate travel routes for people and freight in case of disruptions lasting more than 30 days. Calculations suggest that establishing temporary ferry routes across the Øresund between Copenhagen and Malmö will not solve the problem, as traffic bottlenecks will develop in the busy city centers. A ferry with surplus capacity connects Elsinore in Denmark and Helsingborg in Sweden approximately 40 kilometers to the north. Both harbor cities are well connected with Copenhagen and Malmö respectively by rail and road, but the additional travel time to cross the Øresund will be approximately two and a half hours.

Even if it may be an important infrastructure, the Øresund Bridge is, however, *not* defined as European Critical Infrastructure according to EU guidelines, mainly because of the surplus capacity on the nearby ferry connection (for a discussion of this, see Dahlberg 2016). But a long-term disruption could still be perceived as highly critical by individual users. Five hours of daily additional travel time for a prolonged period of time would be devastating to most people's lives as the 2009 Lake Champlain Bridge closure case showed (Dahlberg, 2016). The entire nature of an infrastructure being either critical or non-critical is thus to large extent depending on the level of analysis, for example European, national, community, or individual, and the fact that are entangled in systemic operations

[1] The Øresund Bridge, which opened in 2000, connects Copenhagen, the Danish capital, and its busy international airport on one side of the Øresund and Malmö, Sweden's third-largest city, on the other. 18,000 vehicles and 160 passenger trains transport each day more than 70,000 people across the combined road and rail bridge and tunnel, approximately 25,000 of them critical to the regional work market. About 90 percent of the daily commuters across the Øresund live in Sweden and work in Copenhagen. If not otherwise referenced, all information in this paper is based on the report prepared by this group and published in Spring 2016 (Arbetsgruppen för Öresundsberedskap, 2016).

characterized by a duality of tangible and intangible materials and processes (Larkin, 2013). Criticality is produced by the services provided, not the structure itself. Infrastructures are, as anthropologist Susan Star has famously pointed out, invisible until they break down (Star, 1999).

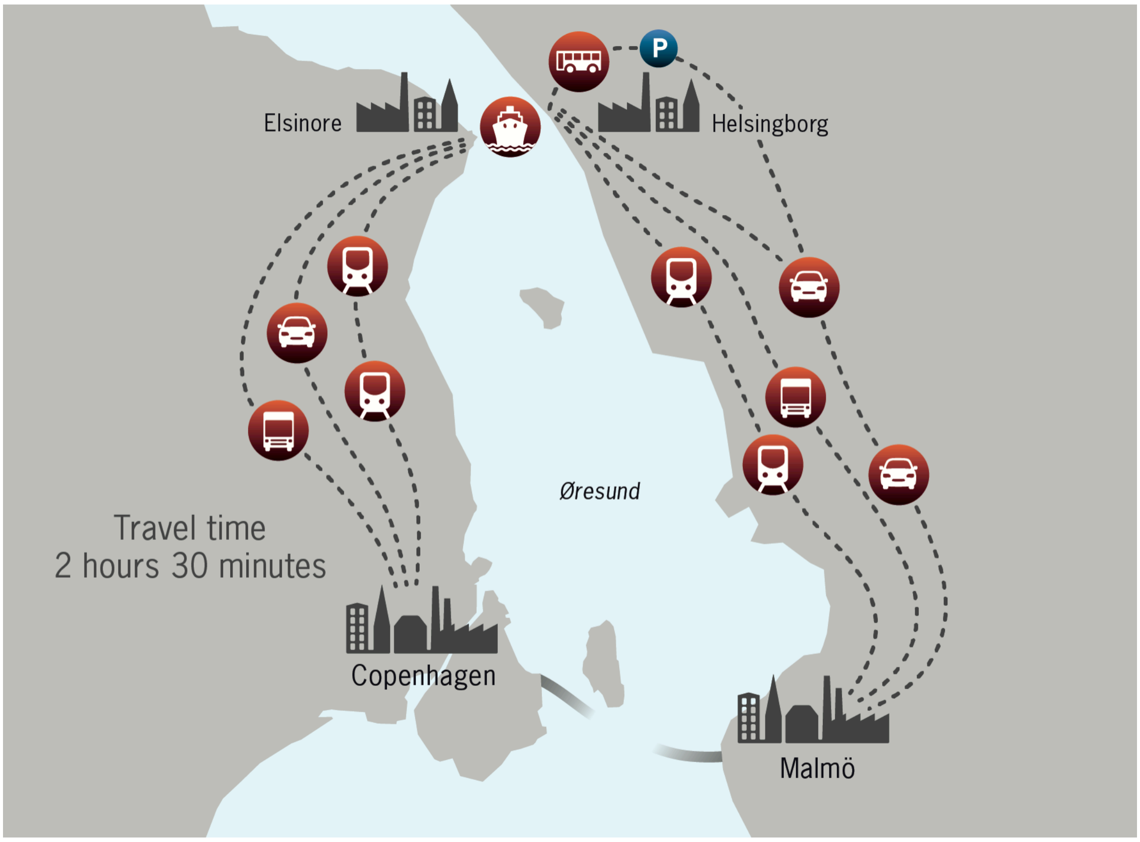

Figure 1. Map of the Øresund Region with indication of the alternate travel route to the north of the fixed link. Copyright: The Øresund Consortium and BGRAPHIC.

As the Øresund Bridge, fortunately, has never been closed for more than a few hours at a time due to extreme weather, the object of analysis is not the actual behavior of users in times of disruption, as this is not known for the particular case, but rather their thoughts about the contingency: What would you do if…?

3. Methodology

In order to explore individual notions of adaptive capacity, the researcher carried out 45 short interviews (each lasting 3-5 minutes) on the trains that run between Copenhagen Airport and Malmö Central Station. The researcher spent a day in June 2015 going back and forth, asking travellers a limited number of very open questions while en route to their destination. Following up with further questions to the respondents would have contributed to the value of the analysis, but that was not possible because the interviews had to be carried out during the short trips across the Øresund (Rubin & Rubin, 2012: 3).

Selection of respondents was deliberately non-random, attempting to reach a broad variation in gender, age etc., but not aiming at any statistical representation. The interviews were carried out in Danish/Swedish or in English and recorded with permission from the respondent for later transcribing and translation into English. All respondents also received a handout with a brief presentation of the research project, a publication disclaimer promising anonymity, and contact information. A few refused to participate, while one respondent allowed the research to carry out the interview, but would not have audio recorded. In this case handwritten notes were taken instead.

After providing the researcher with background knowledge about gender, age and nationality and travel purpose (daily commuter, business traveller or leisure/tourist), each respondent was asked three open questions about their immediate response to three different scenarios:

1. What would you have done if there had been a total disruption of all rail and road traffic on the Øresund Bridge today?
2. What if you had been told that the disruption of the fixed link would last for one month?
3. What if you would not be able to travel across the Øresund on the bridge for a year?

The respondents were also asked about their expectations for the roles of traffic companies, infrastructure owners/operators and the authorities in case of disruptions of the bridge as well as the consequences of a disruption for their personal travel plans and possible changes to their work or personal life.

After transcribing and translating the 45 interviews into English, approximately 200 qualitative statements were identified in the data. The coding method applied was inspired and informed by grounded method theory, focusing on concepts emerging from the data rather than approaching the data with a preconceived set of theoretical concepts (Holton, 2007). In practice, all text was first read through, then cut up into isolated statements with a number representing the respondent attached at the end. The statements were then divided into two main categories: Statements linked specifically to either short-term (1 day), medium-term (1 month) or long-term disruptions (1 year), and statements concerning disruptions of the fixed link in general. Statements belonging to the first category were then grouped into six themes:

Theme	Description	Short-term	Medium-term	Long-term	Total
Frequency	Respondents stating that they would either cancel their travels completely or reduce their need to cross the Øresund.	28	15	8	51
Alternatives	Statements about the intention to use alternative routes.	13	19	16	48
Network	Respondents describing how they would count on friends, family etc. for assistance.	3			3
Employer	Statements about expectations for the respondent's employer to assist.		2	1	3
Relocation	Thoughts about the need for relocating either residence or workplace to the other side of the Øresund.		3	16	19
Uncertainty	Respondents expressing insecurity or ambiguity when faced with the scenarios.	6	36	1	43

Table 1. Thematic codification of qualitative data concerning disruption scenarios based on an explorative reading of the interviews. Note that each respondent is represented in the table with several distinguishable statements on different themes.

Statements belonging to the second category were simply coded into four themes, also based on an explorative reading of the data.

Theme	Description	Occurrences
Responsibility	Respondents expressing any kind of expectation about the role of authorities, traffic companies, infrastructure owners/operators, own responsibility etc.	22
Recovery	Expressions of perceptions of urgency with regard to restoring the fixed link across the Øresund.	6
Information	Statements about expectations for information about duration of closure, alternative routes etc.	15
Compensation	Any mentioning of expectations for economic compensation from infrastructure owners/operators, traffic companies, insurance companies or the authorities.	6

Table 2. Thematic codification of qualitative data concerning disruptions in general based on an explorative reading of the interviews. Note that each respondent is represented in the table with several distinguishable statements on different themes.

In the findings section below, quotes from daily commuters have been prioritized as they would be the most affected by medium- and long-term disruptions of the fixed link. As the empirical data is qualitative and not representative of travellers and commuters in any broader sense the above tables only serve to provide an overview of the thematic composition of the outcome of the interviews. Another important limitation is that only passengers on the train were interviewed – not any of those traveling in the approximately

18,000 road vehicles that cross the bridge daily, so the findings are only valid for the rail part of the infrastructure. Nor were any representatives of the logistics companies that every day use the bridge to transport approximately 18,000 tons of cargo on 1,100 trailers and 20-25 freight trains asked about their contingency plans (for a discussion of these aspects, see Dahlberg, 2016).

4. Findings

Based on the explorative reading of the data and the number of occurrences the following themes were selected for further analysis in order to retrieve as many qualitative statements on each theme as possible: "Frequency," "Alternatives," "Relocation," "Uncertainty," "Responsibility," and "Information." The themes "Network" and "Employer" are neither irrelevant nor uninteresting for the analysis, but due to the relatively low number of occurrences they will require more data to explore. For the same reason, "Recovery" and "Compensation" are not included in the analysis of statements about disruptions in general.

Findings from each of these themes will now be presented using the three aspects of adaptive capacity identified in Section 2 as the structuring principle. "Flexibility" incorporates statements about how citizens think about changing their travel patterns, work routines and general behavior, while "Self-Organization" covers statements from respondents who expressed their thoughts about how they would act without awaiting instructions from the authorities. "Trust" addresses the expectations of citizens towards communication from and behavior of the infrastructure owner, traffic companies etc.

4.1 Flexibility

In the short-term scenario, several respondents stated that they would simply have cancelled their travel plans: "Then I probably would have been forced to work from home today." (02[2]) In general, respondents expected their employers to understand their situation and grant them a day off or allow them to work from home: "I would have called my boss and told him that I couldn't come in today." (10) For disruptions lasting up to a month, decreasing their travel frequency was still the preferred strategy of flexibility for most respondents: "Then I would start going across in the North some days a week, but try to work as much from home as possible. As long as I can connect via my computer…" (15)

[2] Numbers in parenthesis refer to the list of informants, which can be found at http://rasmusdahlberg.com/?page_id=1219

Some would be able to reduce their travel needs significantly even in the one-month scenario, while others estimated that they would be limited to working from home two or three days a week.

In the long-term scenario some would be determined enough to accept the additional travel time: “If I have to reach my goal, I do, even if there is a long detour. But if it was just a pleasure trip, then I would probably cancel or postpone it.” (23) Others expressed the ability to adapt to even a long-term scenario: “Then I would change my work so I could work from home. I have functions that I could do from home.” (32) Another seemed almost positive about the situation: “I work so well from home that I really don’t think it would affect me that much. I don’t think I would quit my job.” (17)

For many respondents the answer to a disruption of the fixed link in the short-term perspective came easy: “I would have gone via Elsinore-Helsingborg. I have traveled this route for eight years so I know it very well.” (43) In the medium-term scenario, only those without other options would accept approximately five hours of daily travel time, more than double the normal: “Then I would go to Helsingborg and take the ferry. Every day. This is my job and it is very, very important. That’s just how it is.” (40) Others were more fortunate: “Elsinore-Helsingborg takes too long. I would not spend that much time on travel. There is nothing to do about it. (…) I work in Denmark as well as in Sweden, so in that case I would just stay at my Danish workspace. I am very flexible.” (22)

Several respondents reflected on the trade-off between importance of their travel needs and the inconvenience involved with changing plans: “I would probably just have called in and said that I couldn’t come to work. If I had extremely important plans I’d possibly have gone via Elsinore-Helsingborg,” explained an independently working respondent whose job as an archeologist nonetheless would force him to sometimes show up in person for excavations etc. (36) Some, however, had no choice at all: “It’s that or no money – I’m self-employed, so if I don’t go to work I don’t have an income,” said a commuter about going on the ferry (20). Especially travels to Copenhagen Airport from Sweden were seen by many as important enough to warrant the extended trip: “I need to get to the airport so I would have gone via Elsinore-Helsingborg on the boats.” (26)

A medium-term disruption of the fixed link would be enough for some to start thinking about relocating: “You can’t just stay home for 30 days in a row. (…) You would either have to move to the other side or find a job here in Denmark. It would be impossible to be a stable employee.” (1) Long-term disruptions require major changes: “I have a job where I have to be present everyday, and that wouldn’t be possible. So I would either have to move to Sweden or get another job, so that would have a large impact," said a commuter. Some were very clear: "Then I would have to give up working in Sweden. Nothing to do about that." (03) "In that case I would probably consider moving my home to Denmark." (43) Many commuters explicitly defined one year as the absolute threshold for considering relocating either their work place or home.

4.2 Self-organization

Many respondents stated that they were counting on their own ability to solve problems: "I probably wouldn't have expected any kind of support from the authorities. I would have known and just made different plans." (42) "There are limits to what DSB [Danish State Railways] can do. If you can't cross the bridge, you can't cross the bridge, and related problems are people's own." (35) One business traveller was particularly self-confident: "I rely on my skills to do it, to rearrange it. Kind of a survival task. [laughs]" (08)

While most respondents did not expect traffic companies, infrastructure owners/operators or the authorities to solve the problem for them (at least not in the short run), many expressed the need for sound and timely information about disruptions – especially if caught on the wrong side of the Øresund: "To get information as soon as possible about the duration and how they can help us to get home." (17) "I would expect to get a lot of information in the papers, television and so. Give me updates on the repairs etc." (26) One respondent likened the disruption scenario to his own experiences from a strike among Swedish railway employees in June 2014: "Like during the strikes last year: frankly, to pretend that they're doing something about it, like repeating 'We don't know how long it will take, but we're working on it'. No radio silence for a week." (15)

Information is seen as a prerequisite for individual action and problem-solving: "I would use the available news and solve the problem myself." (43) "Then I would look into what kind of information was available from the traffic company and the authorities: What would they propose as an alternative?" (20) As many travellers and commuters are not necessarily aware of how to get across the Øresund if the bridge is not available, information about alternative routes would be especially important: "At least tell about alternative options. If you don't know them so well, it would be really helpful if they could provide you with help to get there." (11)

The question of how to receive information from the authorities, traffic companies or infrastructure owners/operators was also brought up by some respondents: "Well, I would like to get the information as soon as possible through an app or some kind of sms."

(41) Some even offered innovative solutions such as car-pooling with colleagues: “We are all from Denmark, so we would be able to group up in one car easily. (…) We wouldn’t do that before a disruption, because we now use public transportation, but it would most certainly be discussed.” (14) Experience with switching to road transportation is primarily based on situations where cars and buses were still able to cross the Øresund on the fixed link, but as the alternate route consists of a car ferry connection this strategy would also apply to full-closure scenario.

4.3 Trust

In general, many respondents were very apologetic towards the authorities: “But what should they be able to do?” (33) “I would think that there is a reason why it is closed today,” said a daily commuter (01), while others expressed almost fatalistic views: “These things can happen, and there is not so much you can do.” (34) “If it is due to natural hazards or war they can’t control it. It won’t help if we stand here and shout,” (22) said a Swedish woman travelling twice a week from Denmark to Sweden. “When traveling you never know if you should expect things to work”, said one respondent (09), while another reflected in depth on this topic: “That’s the risk you run when you choose to use public transportation. (…) A bridge like this is just another kind of service. There was a time before they built the bridge. When it’s there it’s just nice and enables trans-boundary lifestyles as mine, but if it wasn’t there – it wasn’t there, and then I would solve it, perhaps by moving to Helsingborg or something like that. I even might get a job in Elsinore. [laughs]” (20)

Some were expecting temporary ferry connections to be commissioned within the first two or three workdays: “In that case I would expect alternative routes to be established, like a ferry connection from Malmö to Copenhagen. (…) It would require extra travel time until new routines were picked up.” (12) “I am sure that they would insert ferries to maintain the connection,” one respondent stated (22), while another only envisioned temporary ferry connections in the long-term perspective: “If I were informed that the bridge would be closed for an entire year, then I would expect the authorities to do something about it, like establish new ferry routes.” (17) That viewpoint was also interpreted in an regional economic context: “In a 1-year perspective I would not think that it was fair to have to drive all the way to Elsinore to go down to Malmö. In my opinion the relationship between Copenhagen and Malmö is too important for that.” (23)

For long-term disruptions the expectations were quite high: "I would expect both the Swedish and the Danish authorities to bring out everything in their arsenals, because there are so many commuters using the bridge daily, most of them living in Malmö and working in Copenhagen. That would be a lot of wasted money and work time. I am sure that both sides would chip in. Not least because there is this cooperation in the Øresund region and a wish for people to be able to live and work in different places within the region." (12) One said: "To make sure it its not 12 months, because people have become very dependent on the connection" (04), while another simply stated: "To get it fixed as soon as possible." (05)

5. Discussion

The data suggests that people perceive themselves to possess quite strong abilities to adapt to disruptions, especially in the short-term perspective. Respondents employed in jobs allowing them to be flexible about their workplace (especially with the use of ICT) think they would to a large extent be able to maintain their function, while those with on-site work obligations expect quite a lot of flexibility from their employers. They also express an intuitive understanding of the parameters that they would base decisions about alternative routes on: additional travel time and expenses measured against the importance of the trip. This reflects the cost-benefit analysis described by Grothmann and Patt employed as part of the adaptation appraisal process.

The data also suggests that sound and timely information is perceived as important for a swift and efficient response from the affected users. Several respondents expressed the opinion that it would be of much more value to get good information than to be economically compensated in case of a disruption of service. Some even stated that as long as there is good communication about the expected duration of the disruption available, it is not a big problem with additional travel time or inconvenience.

It is also of much higher value to individuals to possess knowledge about alternate routes, delays etc. than to receive economic compensation. Persons and institutions that provide exactly the kind of information that is needed would quickly become central in the formal as well as informal networks, i.e. a private citizen publishing a popular guide on social media or a company succeeding in coordinating car-pooling to combat congestion on the roads to and from Elsinore and Helsingborg. Those individuals and institutions high on social capital would be important actors in self-organization processes where citizens help each other retain the highest possible level of function in times of disruption without assistance from the authorities.

In general, the respondents do not hold the authorities, traffic companies or infrastructure owners/operators solely responsible for disruptions and fast recovery. They seem confident that the infrastructure operators and the authorities are doing what they can and what they should to keep the fixed link open, while at the same time accepting that forces majeure may disrupt the connection. That citizens' trust in the authorities and infrastructure owners/operators to establish alternate means of transportation increase with the expected duration of the disruption probably reflect their individual cost-benefit analyses: the longer the disruption, the bigger the cost and therefore also the benefit of investing in mitigation measures.

A number of respondents stated that they were aware of the fact that the bridge would not necessarily always be operational. But acknowledging that the bridge could close at anytime is not the same as preparing for a disruption. This requires engagement at a totally different level, for example involvement in preparedness planning. People who participate in exercises or are involved in designing and testing emergency plans increase their awareness of "what the authorities are able to perform and what each resident can do to improve protection and crisis management" (Wachinger et al., 2011: 1061). However, it seems unfeasible to actually hold exercises with regard to long-term disruptions of the Øresund fixed link. Instead, other means of motivation for increased risk perception could be suggested such as incentives for adaptation with inspiration from the climate change literature: "Adaptation incentives can play the role of providing additional motivation for adaptation, but can also play the role of being an alternative source of motivation in case there is no risk perception" (Grothmann and Patt, 2005: 205).

In case of a long-term closure of the bridge, the livelihoods of travellers who live on one side of the Øresund and work on the other would be challenged, especially for those not able to switch their mode of work and stay home for a longer period of time. As most people live close to their family and friends, the bonding social capital of close ties would be of limited value, while more loose connections with colleagues residing in the vicinity of the work place would be more valuable. Strong bridging social capital would enable a person to tap into a network of guest rooms etc., allowing for a lower travel frequency in times of disruption.

6. Conclusion and recommendations

The findings from the qualitative study show that the respondents in general exhibit quite strong perceptions of their own adaptive capacities when confronted with short-, medium- and long-term disruption scenarios. They do not see a total disruption of service for one day as a major problem, as most think that they would be able to simply cancel their trip without too much inconvenience, while those with very important travel needs would go via Elsinore-Helsingborg on the ferry. In case of a total closure of the bridge, the ferries on the Elsinore-Helsingborg route will have enough capacity to absorb the expected excess traffic, but the road systems connecting the ports and Copenhagen and Malmö will quickly become bottlenecks, especially with regard to parking space (Dahlberg, 2016). Working with private companies such as GoMore, a very popular Danish online platform for ride sharing, could be a way forward for authorities and traffic companies to utilize the adaptive capacities during a disruption and reduce the overall number of vehicles on the roads.[3]

A very simple recommendation for infrastructure owners/operators and transport authorities based on the qualitative survey could be for them to simply ask their users: "Do you have a Plan B?" in advertisements and information campaigns – even if it may seem counterintuitive for service providers to remind their customers to consider alternatives. Many respondents expressed an immediate gratitude during the short interviews for simply being made aware that they cannot necessarily count on the continued service of the bridge in their everyday lives. Just asking the question might be enough to prompt reflection on personal dependency on the service and possible alternative – knowledge that might come in very handy in the highly unlikely, yet still possible case of a long-term closure of the bridge.

Data from this small qualitative study suggests that when faced with a prolonged disruption of an infrastructure, various strategies will be employed by commuters and travellers to maintain as high a level of function as possible: Some users will reorganize and start working from home, while others will find alternate routes that are acceptable even if they are more time-consuming or costlier as it is only for a limited time period. In the long run people will start relocating either their home or work place to avoid the disrupted infrastructure entirely.

[3] GoMore had 20-30 percent peaks in Danish usage during winter storm Allan in October 2013 and again on 22 December 2013 when – on the busiest travel day of the year – all Danish regional and intercity trains were halted for several hours because of a bomb threat at Odense railway station, a major transport hub in Denmark. Source: CEO of GoMore, Mathias Møl Dalsgaard, in a telephone conversation with the researcher in January 2014.

When it comes to coping with infrastructure disruptions users should be seen as "everyday experts" with experience, resources and strategies that together form a multitude of individual contingency plans that authorities can tap into with a little ingenuity. The field of preparedness include vaguely defined sub-activities such as "willingness to act", "risk awareness" etc. whose exact content depend on discipline and context (Wachinger et al., 2003: 1051). "Willingness to act", understood as an intention, resonates well with the interpretation of preparedness applied in this paper. The empirical evidence provided by this small survey indicates that there indeed is a willingness to act among citizens facing a potential long-term disruption. To integrate the adaptive capacities into preparedness planning authorities and infrastructure owners and operators must first and foremost acknowledge individual users as an integrated part of the infrastructure, equal to built structures, rolling stock and IT systems.

A theoretical insight from the literature on resilience may prove useful for integrating adaptive capacity in future preparedness planning for long-term disruptions of the Øresund Bridge. Since the 1970s, a basic distinction has been made between *engineered* and *ecological* resilience. On the one hand, *engineered* economic or technological systems are governed by an equilibrium steady state, and in such systems resilience denotes the ability to bounce back to this steady state after a shock – like the spring. On the other hand, in natural *ecological* ecosystems and complex adaptive systems, instabilities can flip the system into new stable domains with very different inner functions (Dahlberg, 2015).

Engineered resilience can be a useful metaphor for enabling a socio-technological to bounce back after a shock – for example, by providing travellers with an alternate means of transportation such as a temporary ferry connection set up by the authorities. Ecological resilience, however, is different in that it enhances the ability of the system to change its modes of behavior – i.e. coping with a disruption of infrastructure by assisting travellers with obtaining their individual goals in different ways. While engineered resilience can be seen as part of a traditional top-down approach to preparedness planning with regard to infrastructure, ecological resilience builds more on an understanding of socio-technological systems as ecosystems that are able to adjust, learn and solve many problems on their own.

6. Acknowledgements

The author wishes to thank the members of the Workgroup for Øresund Preparedness, especially Ulla V. Eilersen, Safety Manager, Øresundsbron, and Strategic Consultant Henrik Andersson, Sweco Society AB, for access to their discussions and data. Associate

Professor Olivier Rubin, Roskilde University, Associate Professor Peter Kjær Mackie Jensen, University of Copenhagen, and PhD Fellow Kristoffer Albris, University of Copenhagen, all provided useful feedback on a draft of the paper. Trine Juul Reder read the final draft and made some valuable comments, and Lacy M. Allen was kind enough to edit the text. Lastly, Hardy Olsen, then Head of Preparedness at Danish State Railways, arranged for permissions to carry out interviews on the train between Denmark and Sweden. And of course: thanks to all of the nice people who agreed to be interviewed while crossing the Øresund.

7. Funding

The research for this paper was supported by the READ project, funded by the European Union DG Home. For more information, please visit www.read-project.eu.

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Appendix 1: List of respondents

01 Woman, Danish, 26, daily commuter from Denmark to Sweden.
02 Man, Swedish, 42, daily commuter from Denmark to Sweden.
03 Man, Danish, 77, commutes on average four times a week from Denmark to Sweden.
04 Man, Dutch, 55, lives partly in Sweden, travels across Øresund twice a week on business trips.
05 Man, Montenegrin, 22, pleasure trip, travelling to Copenhagen Airport after a family visit in Sweden.
06 Man, 25, Lithuanian, daily commuter from Sweden to Denmark.
07 Woman, 28, Swedish, pleasure trip, returning from a family visit in Norway, travels across Øresund six times a year.
08 Man, 55, Estonian, on a business trip traveling from Copenhagen Airport to Sweden, crosses Øresund once a year.
09 Woman, 21, Swedish, returning to Sweden from a pleasure trip to Asia with a friend.
10 Man, 24, Danish, commutes every day from Sweden to Denmark.
11 Woman, 30, Australian, living in Malmö, going to Copenhagen for a conference, travels across Øresund six-seven times a year,
12 Woman, 37, Danish, living in Sweden, travels a couple of times every week across Øresund for education purposes.
13 Woman, 24, Indian, traveling from Copenhagen to Sweden for a two-day course.

14 Man, 21, Danish, commutes almost everyday from Denmark to Sweden.
15 Man, 50, Danish, commutes daily from Denmark to Sweden.
16 Man, 39, Swedish, commutes daily from Sweden to Denmark.
17 Woman, 33, Swedish, commutes daily from Sweden to Denmark.
18 Woman, 25, Swedish, commutes three to four days a week from Sweden to Denmark.
19 Man, 23, German, returning to Copenhagen Airport from a family visit in Sweden, travels across Øresund two times a year.
20 Woman, 26, Danish, traveling with her infant, commutes daily from Sweden to Denmark.
21 Woman, 23, Swiss/French, first time crossing the bridge.
22 Woman, 43, Swedish, living in Denmark, travels two times a week from Denmark to Sweden.
23 Man, 69, Danish, returning to Denmark from a dentist appointment in Malmö, travels across Øresund four times a year.
24 Woman, 17, Swedish, on a pleasure trip, travels across Øresund three times a year.
25 Man, 39, Portuguese, living in Sweden, commutes every day for work in Copenhagen
26 Man, 42, Swedish, travels across Øresund once a month on business trips.
27 Man, 33, Kurdish, living in Sweden, travels across Øresund four times a month to visit family in Denmark.
28 Women, 33 and 20, both Danish, traveling on a one-day pleasure trip to Sweden, travel rarely across Øresund.
29 Man, 35, Finnish, going from Copenhagen Airport to Sweden on a business trip, travels across Øresund once a month
30 Man, 25, Swedish, traveling with his family to Copenhagen Airport from Sweden, first trip across Øresund this year.
31 Man, 45, Swedish, travels with a group of ten people to Copenhagen on a company leisure trip.
32 Woman, 57, Swedish, commutes daily from Sweden to Copenhagen.
33 Married couple, both Swedish, both retired, 68 and 67, travel across Øresund five times a year on pleasure trips.
34 Man, 35, Swedish, commutes daily from Sweden to Denmark.
35 Woman, 35, Danish, living in Sweden, commutes daily from Sweden to Denmark.
36 Man, 47, Norwegian, living in Malmö, commutes daily from Sweden to Denmark.
37 Family of four, Swedish, going from Sweden to Copenhagen Airport, the father travels across Øresund once a month on business trips.
38 Woman, 32, German, on a one-day visit to Sweden during a vacation in Denmark, travels across Øresund 10-15 times a year. Note: Did not permit recording – handwritten notes from interview used instead.
39 Man, 36, Swedish, commutes daily to Denmark from Sweden.
40 Man, 49, Swedish, commutes daily to Denmark from Sweden.
41 Woman, 32, Swedish, commutes daily to Denmark from Sweden.
42 Woman, 43, German, returning to Copenhagen Airport from a one-day business trip to Sweden.
43 Man, 45, Danish, living in Sweden, commutes daily to work in Denmark.
44 Woman, 71, Danish, returning from a dentist appointment in Sweden, travels across Øresund two times a year.
45 Man, 50, New Zeeland/Swedish, living in Sweden, on a business trip to Denmark, crosses Øresund twice a month.