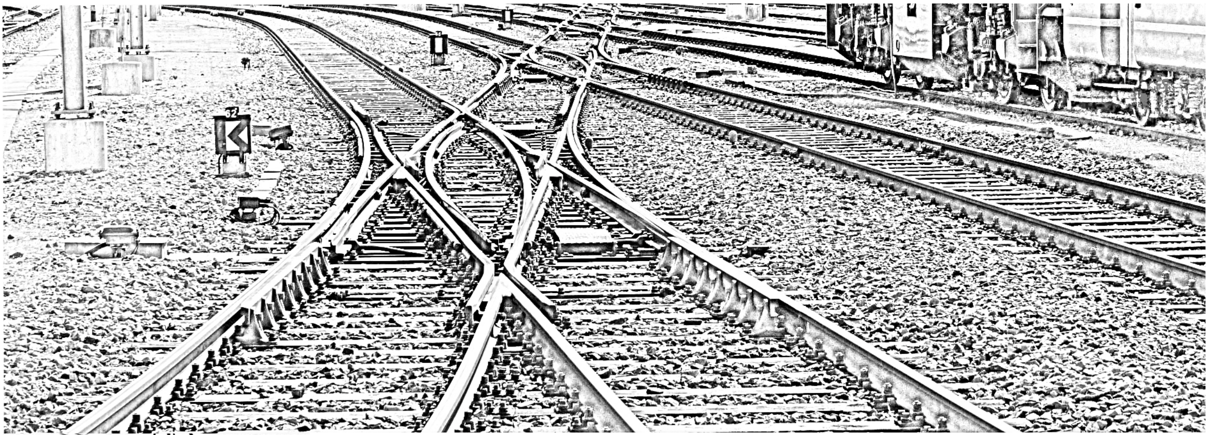
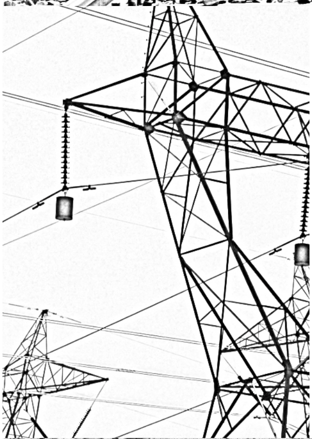
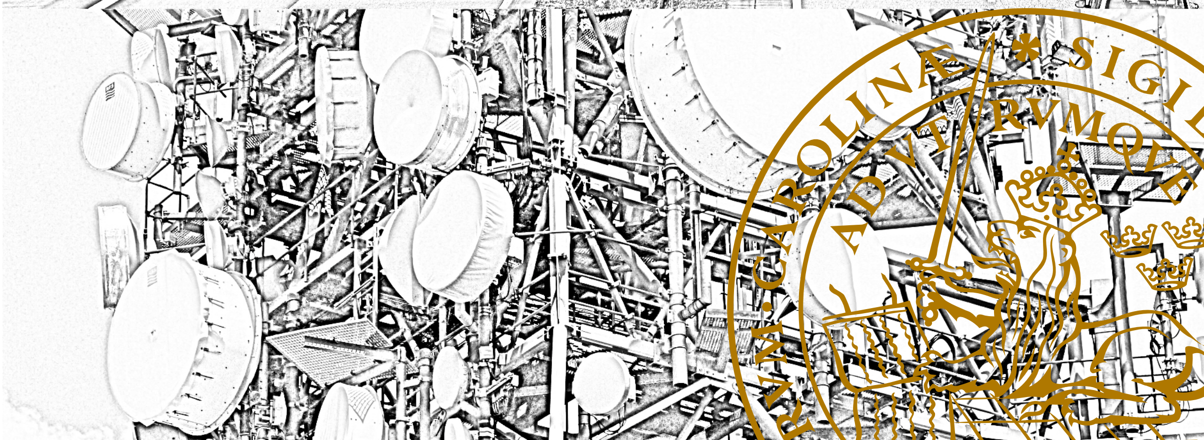




Exploring governance of interdependency-related risks

Implications for cross-sector resilience of Swedish critical infrastructures

TOVE RYDÉN SONESSON | FACULTY OF ENGINEERING | LUND UNIVERSITY



Printed by Media-Tryck, Lund 2021 NORDIC SWAN ECOLABEL 3041 0903

Lund University
Faculty of Engineering
Division of Risk Management and Societal Safety

ISBN 978-91-7895-941-9

Exploring the governance of interdependency-related risks

Implications for the cross-sector resilience of Swedish critical infrastructures

Tove Rydén Sonesson

LUND UNIVERSITY

Division for Risk Management and Societal Safety
Lund university
Box 118
SE-221 00 Lund
Sweden

ISBN 978-91-7895-941-9 (print)
ISBN 978-91-7895-942-6 (pdf)

Printed in Sweden by Media-Tryck, Lund University
Lund 2021

NORDIC SWAN ECOLABEL
Printed matter
3041 0903

Media-Tryck is a Nordic Swan Ecolabel
certified provider of printed material.
Read more about our environmental
work at www.mediatryck.lu.se

MADE IN SWEDEN

Summary

Over time, it has become evident that society relies heavily on critical infrastructures to deliver essential societal services, such as electricity, telecommunications and transportation. Simultaneously, it has become clear that these critical infrastructures are also highly interdependent. Interdependencies allow consequences that follow from an adverse event to cascade across critical infrastructures and societal sectors and intensify the crisis that often follows upon critical infrastructure breakdowns. Therefore, critical infrastructures need to be resilient to risks that affect them directly and to risks originating from their interdependent nature, here referred to as interdependency-related risks.

Promoting resilience to interdependency-related shocks requires the involvement of many both public and private actors across several societal sectors. Therefore, this research introduces the notion of cross-sector resilience and explores how existing risk governance activities account for interdependency-related risks. It furthermore adopts an understanding of risk governance as a process that encompasses both the process of assessing, or understanding, and managing, or making decisions about, risk.

The results of a systematic scoping review of the scientific literature suggest that few studies take an applied national perspective or consider how the two governance processes of assessing and managing risk can be linked. Therefore, this research adopted an applied perspective and found that Swedish critical infrastructures are predominantly governed in silos. In addition, it found that there seems to be a gap between how interdependency-related risks are assessed and managed on the cross-sector level. Therefore, the research took two additional steps towards identifying a way to overcome these challenges. First, it identified several mechanisms that seem essential for the governance of interdependency-related risks in national critical infrastructures. Second, it introduced a generic modelling and simulation approach and showed how such approaches could bridge the gap between assessment and management of interdependent real-life infrastructures.

To conclude, the thesis suggests that future research should depart from these mechanisms and modelling and simulation results to align better the assessment and the management perspective and design strategies and approaches that can incentivise critical infrastructure actors to improve their cross-sector resilience.

Sammanfattning

Över tid har det blivit uppenbart att samhällsviktiga verksamheter och kritiska infrastrukturer är centrala för att upprätthålla både viktiga samhällsfunktioner, så som elproduktion, dricksvattenförsörjning och internet, och samhällets övergripande funktionalitet. Det har samtidigt blivit tydligt att dessa samhällsviktiga verksamheter och kritiska infrastrukturer även är starkt beroende av varandra. Dessa beroenden kan leda till att konsekvenserna vid en störning i en samhällsviktig verksamhet eller kritisk infrastruktur kan sprida sig till andra och intensifiera den kris som typiskt följer av infrastrukturstörningar. Därför måste samhällsviktiga verksamheter och kritiska infrastrukturer inte bara vara motståndskraftiga mot händelser som påverkar dem direkt utan även mot de händelser som härrör från deras beroende till andra.

Att främja samhällsviktiga verksamheters och kritiska infrastrukturers motståndskraft, eller resiliens, mot störningar som uppkommer på grund av eller förvärras av beroenden kräver att både privata och offentliga aktörer från flera samhällssektorer samarbetar kring både analys och hantering av risker. Därför introducerar avhandlingen begreppet sektorsöverskridande resiliens och undersöker hur existerande riskstyrning (*risk governance* på engelska) tar hänsyn till beroenden. I denna forskning definieras riskstyrning som en process som omfattar både processen att analysera, eller skapa förståelse för, och att hantera, eller fatta beslut om, risker.

En systematisk genomgång av den vetenskapliga litteraturen på detta område tyder på att det finns få studier som tillämpar både ett applicerat och ett nationellt perspektiv samt att den litteratur som gör det sällan gör en tydlig koppling mellan de två riskstyrningsprocesserna som lyfts i ovan. Genom att ta ett applicerat perspektiv, kommer forskningen som presenteras i denna avhandling vidare fram till att analys och hantering av risker i svenska samhällsviktiga verksamheter och kritiska infrastrukturer ofta begränsas till enskilda samhällssektorer, dvs. många gånger saknas det sektorsöverskridande perspektivet. Att inte väga in detta perspektiv kan begränsa möjligheterna att hantera beroenderelaterade risker samt påverka den sektorsöverskridande resiliensen negativt. Som ett första steg att bemöta dessa utmaningar identifieras därför ett antal mekanismer som kan påverka riskstyrningen av beroenderelaterade risker och en generisk modellering och simuleringsansats som, bland annat, illustrerar nackdelarna med att inte beakta beroenderisker presenteras.

Slutligen föreslås att framtida forskning på området med fördel kan utgå från dessa mekanismer och den typ av resultat som modellerings- och simuleringsansatsen kan ge för att stärka kopplingen mellan analys och hantering av beroenderisker och skapa incitament och förutsättningar för att stärka de samhällsviktiga verksamheternas och kritiska infrastrukturernas sektorsöverskridande resiliens.

Acknowledgements

I am very thankful for the support I have gotten over the years so far spent as a PhD student. First, I would like to thank ISF and the Swedish Police Authority for funding my licentiate project and the Swedish Civil Contingencies Agency for supporting the continuation of the CenCIP project, allowing me to continue my research for the remainder of my PhD time. I also thank all the professionals who gave some of their time to partake in my studies.

To my supervisors, Alex and Jonas, thank you for giving me this opportunity and your support. You have put in many hours to help me, given me valuable comments and genuinely cared about my academic progress as well as my overall wellbeing. For that, I am very thankful!

To all my colleagues at the division for risk management and societal safety, thank you for providing a friendly work environment and striving to make the division a good workplace for all its employees. A special thanks to Björn for our joint coffee runs in both Malmö and Lund and for constantly reminding me to take a break for the daily 10 a clock fika. To my roomies, Maja and Josefin, a huge thanks for all the laughs, welcome distractions and discussions on semi-research related (and often wholly non-research related) topics. You have all, in your separate ways, made my journey this far so much more enjoyable.

To my family, I am indescribably thankful for you being my untiring and "totally objective" cheerleaders and for your unconditional love regardless of my academic achievements.

To Fabian, my rock, my love and all those cheesy things, everything from crappy work stuff to unexpected obstacles on our many travels gets much more manageable with you by my side. Without you, I would definitely not have come even this far.

Onward and upwards!

Malmö, 1 September, 2021

Table of Contents

Introduction

Following past disruptive events such as the 2001 terrorist attack in New York and the 2003 Italian Blackout, securing critical infrastructures such as energy, transportation, and telecommunication has become a policy priority worldwide (DHS, 2013; Directive 2008/114/EC; Swedish Civil Contingencies Agency, 2014; ANZCTC, 2015; HM Government, 2015). As critical infrastructure issues have gained more policy and scientific attention, so has the fact that the organisations, structures and functions that make up these critical infrastructures are highly interdependent (Directive 2008/114/EC; SWD(2013) 318 final; Florin & Linkov, 2016; IRGC, 2018; OECD, 2003; 2019; Ouyang, 2014; Rinaldi, Peerenboom & Kelly, 2001; Satumtira & Dueñas-Osorio, 2010). Interdependencies have the potential to amplify the negative consequences of a critical infrastructure breakdown as they create pathways for consequences to cascade across infrastructures and infrastructure sectors, simultaneously affecting a large portion of society (Buldyrev, Parshani, Paul, Stanley & Havlin, 2010; Johansson, Hassel, Cedergren, Svegrup & Arvidsson, 2015; McDaniels, Chang, Peterson, Mikawoz & Reed, 2007; Svegrup, Johansson & Hassel, 2016; van Eeten, Nieuwenhuijs, Luiijf, Klaver & Cruz, 2011; Zimmerman & Restrepo, 2009). Hence, critical infrastructures are confronted with risks that arise from or are amplified by interdependencies – in this thesis referred to as interdependency-related risks.

Interdependency-related risks are characterised by uncertainty, complexity and ambiguity (Aven & Renn, 2019; IRGC, 2018; Schweizer, 2019; van Asselt, Vos & Wildhaber, 2015). For such risks, traditional quantitative risk assessment and management strategies are often insufficient (van Asselt & Renn, 2011; Aven & Renn, 2019; IRGC, 2018; Schweizer, 2019), which has opened the door for resilience as a complementary perspective (Heinimann & Hatfield, 2017; IRGC, 2005; Labaka, Hernantes & Sarriegi, 2016; Linkov et al., 2014; Marana, Labaka & Sarriegi, 2018; OECD, 2010; Park, Seager, Rao, Convertino & Linkov, 2013; Rehak, Senovsky, Hromada & Lovecek, 2019). This perspective does not replace more traditional and protection-oriented ones. Instead, it acknowledges that it is hard, and often not feasible, to protect critical infrastructures from every possible hazard and emphasises adaptive and predictive abilities.

While researchers across several scientific disciplines have adopted the resilience concept over the years (Folke et al., 2010; Woods, 2015), its application for addressing real-life critical infrastructures has just left its starting blocks (Pursiainen, 2018) and is still avidly debated (see Rød & Johansson, 2020). Debates aside, resilience is often linked to the ability to anticipate, absorb, recover from, and adapt to disruptive events (see Hickford, Blainey, Ortega Hortelano & Pant, 2018; Park et al., 2013; Rehak et al., 2019; Woods, 2015). This research adopts this resilience perspective and introduces the concept of cross-sector resilience to emphasise its focus on resilience in the cross-sector and multi-actor settings studied. It defines cross-sector resilience as the ability of several critical infrastructures to efficiently maintain their functions by anticipating, absorbing, adapting to, and recovering from the impacts of interdependency-related shocks.

Interdependencies and interdependency-related shocks have attracted increased attention in both the scientific and policy literature. However, governments still appear to be grappling with adopting an interdependency perspective into their critical infrastructure efforts (COM(2020) 829 final; European Commission, 2020; OECD, 2019; SWD(2013) 318 final). While a significant amount of research aiming to assess the interdependencies between critical infrastructures has been presented in the scientific literature, it has to a large extent been directed towards understanding the mechanism behind disruptions amplified by interdependencies rather than on how this understanding could strengthen the cross-sector resilience in practice (Ouyang, 2014; Kröger, 2008; Little, 2002; Rinaldi et al., 2001; Rydén Sonesson & Johansson, 2019; Satumtira & Dueñas-Osorio, 2010). Hence, it remains less clear how and to what extent critical infrastructure actors work to increase their cross-sector resilience and how current scientific knowledge could inform this work.

This thesis positions itself in this body of research but has explicitly focused on how critical infrastructure resilience can be strengthened in the multiple interdependent critical infrastructure context. The unit of analysis has been national critical infrastructures in three vital infrastructure sectors: energy, transportation and telecommunication. The focus had been limited to aspects that are of cross-sector relevance.

Since critical infrastructures constitute open socio-technical systems, it is vital to be mindful of the socio-technical regimes that shape their design and behaviour. Therefore, risk governance was adopted as an analytical framework to study, understand and find some implications for actors, processes and mechanisms that affect how risks are understood and risk decisions are made in the cross-sector context. In line with this, the research behind this thesis aimed to:

> explore how existing risk governance processes account for interdependency-related risks and the implications this has for the cross-sector resilience of Swedish critical infrastructures.

Research process and questions

The research presented in this thesis has neither been entirely straightforward nor produced in a vacuum. Therefore, this section presents the context and process behind this research and the formation of its underlying research questions.

During my time as a PhD student at the Division of Risk Management and Societal Safety, my work has been financed by a project that stems from the European Union's Internal Security Fund (ISF) through the project "Interdependent National Critical Infrastructures" (A431,782/2016), administrated in Sweden by the Swedish Police Authority. The ISF project was initiated under the Centre for Critical Infrastructure Protection (CenCIP). CenCIP was founded in 2015 at Lund University with the financial support of the Swedish Civil Contingencies Agency and is a multidisciplinary research centre that encompasses researchers from four different departments within Lund University. The research conducted within the centre has departed from a common understanding of the critical infrastructure context as the interplay between two integrated systems: the functional and the organisational system, as depicted in Figure 1. The former represents different interconnected societal functions, and the latter the interacting organisations that own, operate or somehow affect these functions. Within this framework, research has, amongst other things, aimed to both understand and build a capability to understand and model interdependencies in the functional system and suggest conceptual models and recommendations for how to support the management of risk, vulnerability and crises. This research has inspired, informed and made up the foundation for the research process described below.

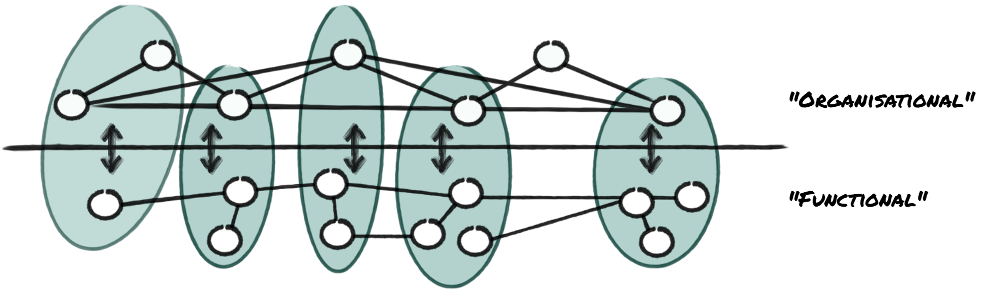


Figure 1. CenCIP framwork
The CenCIP understanding simplified though a model of the critical infrastructure protection context as a system divided into two integrated subsystems: (1) a functional system that represents the interconnected societal functions and (2) an organisational system that represents the multi-actor context in which these functions are owned and operated. Adopted from the CenCIP website: https://www.cencip.lu.se/.

The introductory section at the beginning of this chapter presented the rationale and overarching research aim of the presented research. To create a structure to address the research aim, I adopted an understanding of risk governance as two integrated processes: (1) assessment and (2) management (in line with, e.g. IRGC, 2017). The former relates to the process of understanding risk. It includes all activities related to, among other things, gathering and synthesising information about risks and building capability and knowledge on how to analyse them and the resilience of the exposed system. This includes, but is not limited to, hazard identification, gathering information on exposure and vulnerability of assets to identified hazards, estimating consequences, frequencies and uncertainties related to the realisation of identified hazards, mapping stakeholder opinions and public concerns, the identification of potential countermeasures, and building and using models to analyse, for example, vulnerabilities in and resilience of the studied systems. The latter relates to the process of deciding what to do about risk and involves all activities connected to, for example, the systematic generation, evaluation, selection, implementation, monitoring and review of risk management strategies based on the knowledge generated from assessment activities. While it should be noted that the activities within the two processes are often not carried out entirely separately or sequentially, this distinction between assessment and management provided a helpful framework for addressing the research aim and formulating a set of research questions.

To study the linkage between the two assessment and management processes, Paper I used a scoping review approach designed around the research question below in the context of (real-world) national interdependent critical infrastructures.

> RQ1: In the scientific literature, to what extent do approaches for assessing the resilience of real-life interdependent critical infrastructure and cross-sector management guide one another, and what characterises these approaches?

The scoping review results are described in Paper I and, in short, revealed that the assessment and management perspectives are seldomly considered in tandem. The reasons for this can be many and cannot be fully substantiated from the scoping study evidence alone. Therefore, to enable linkage of the two studied perspectives in the applied setting, more knowledge on the practical context was deemed of essence. Therefore, the following research questions were formulated and explored in Paper II.

> RQ2a: What enabling and hampering mechanism for managing interdependency-related risks can be found in Swedish national critical infrastructures?

> RQ2b: What are the implications of RQ2a for assessment approaches?

In line with the research questions, a document and interview study was designed that focused on the management perspective. From the study several mechanisms were identified that seemed to affect how interdependency-related risks are accounted for. Paper II describes these mechanisms and discusses their implications for future assessment approaches.

The scoping study described in Paper I identified that applied studies of several interdependent national critical infrastructures are still relatively scarce. However, one promising and extensively used approach for creating a basis for assessments of critical infrastructures is modelling and simulation (M&S) (see Ouyang, 2014). M&S approaches were also identified as the most commonly used assessment methodology in Paper I. Building on this, a third research question was formulated and addressed in Paper III:

> RQ3: How can modelling and simulation be used to inform management decisions that promote resilient interdependent national critical infrastructures?

To address RQ3, a third study departed from the assessment perspective and involved developing and applying a modelling and simulation approach. The approach is detailed in Paper III but can, in short, be described as a generic multi-layer network theory-based approach. The choice of a network theory-based approach was made in part because it was identified as the most commonly used approach in Paper I and, in part, as it enables a rather minimalistic first step that does not necessitate large amounts of unattainable data. The developed approach was used to analyse and illustrate the effects of interdependencies between a power and an internet infrastructure. Implications of the results, their usefulness and the limitations of modelling and simulation for supporting management decisions were further discussed.

An overview of the above-described research process is presented in Figure 2. Figure 2 illustrates the connection between the research questions and the appended papers and the chronology of the three appended papers. The figure also describes how the different studies have informed each other and the two risk governance processes they mainly explore.

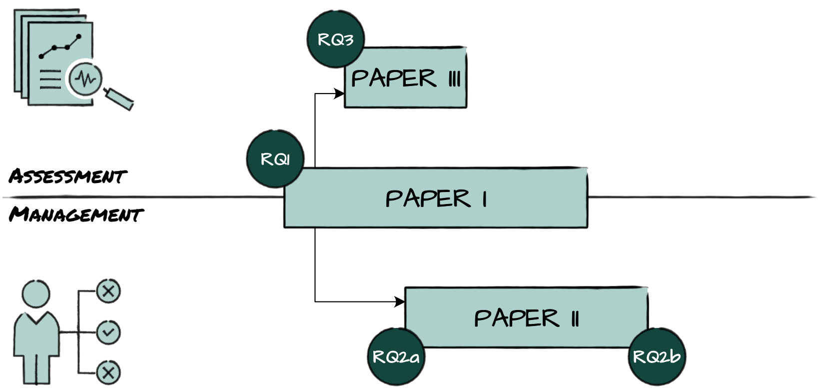


Figure 2. Research process illustrated
Illustration of the correlation between the research questions, the appended papers, and the two risk governance processes, assessment and management, explored in this thesis.

List of publications

Appended papers

I. **Rydén Sonesson, T.**, Johansson, J., and Cedergren, A. (manuscript). Exploring assessment and management of critical infrastructure interdependencies: A scoping review. To be submitted to an international peer-reviewed journal.

II. **Rydén Sonesson, T.**, Johansson, J., and Cedergren, A. (2021). Exploring Enabling and Hampering Mechanisms for Cross-sector Resilience of Swedish Critical Infrastructures. *Safety Science, 142*, 105383.

III. **Rydén Sonesson, T.**, and Johansson, J. (2019). Modelling National Interdependent Critical Infrastructures: Application and Discussion for the Swedish Power and Internet Backbone. In M. Beer and E. Zio (Eds.), Proceedings of the 29th European Safety and Reliability Conference, ESREL19, Hannover, Germany, September 22–26, 2019, pp. 3358-3365.

Related publications

Rydén Sonesson, T., Kallträsk, E., Johansson, J., Cedergren, A., (2020). Risk Governance State-of-Affair Across Swedish Interdependent Infrastructures. ESREL 2020 & PSAM 15th, Venice, Italy, 21-16 June.

Rydén Sonesson, T., Johansson, J. (2019). Towards cross-sector risk management in Swedish critical infrastructures, SRA Nordic 2019, Copenhagen, Denmark, 7–8 November.

Rydén Sonesson, T., Johansson, J., Cedergren, A., (2018). Modelling and Simulation of Critical Infrastructures for Improved Risk Governance: An exploratory literature review, SRA Nordic 2018, Stavanger, Norway, 8-9 November.

Conceptual framework

This chapter presents the conceptual framework that underpins the thesis. The four most central conceptual points of departure are presented and connected. First, the notion of critical infrastructures is presented, emphasising their interdependent nature. Second, the notion of interdependency-related risks is introduced and defined as risks that stem from or are amplified by interdependencies between critical infrastructure actors, structures or functions. Third, the notion of cross-sector resilience is put forward and defined as the ability of interdependent critical infrastructures to efficiently maintain their functions by anticipating, absorbing, adapting to and recovering from the impacts of interdependency-related shocks. Finally, risk governance is introduced as an analytical framework to understand how the interplay between actors, processes, and mechanisms affects how interdependency-related risks are understood and decisions are made regarding uncertain, complex and ambiguous interdependency-related risks.

Interdependent critical infrastructures

This research views critical infrastructures as large-scale human-made systems designed to provide society with vital goods or services (e.g. energy, data or transportation), and that would cause severe societal consequences if incapacitated. Hence, it adopts a relatively broad interpretation of what constitutes critical infrastructures. Critical infrastructures or, as they are sometimes also referred to as, lifeline systems or infrastructures (e.g. Zorn and Shamseldin, 2015; Holand, 2015), and their protection rose to the top of the international political agenda following the 2001 terrorist attack in the US (Brown, Carlyle, Salmerón & Wood, 2006). As the attention to the protection of critical infrastructures has increased, so has the recognition of the role and potential effects of interdependencies between them in the event of a disruption (Buldyrev et al., 2010; Dueñas-Osorio & Vemuru, 2009; European Commission, 2020; Johansson and Hassel, 2010; McDaniels et al., 2007; O'Rourke, 2007; Rinaldi et al., 2001; Vespignani, 2010; Zimmerman & Restrepo, 2009). The remainder of this section explores the interdependency concept a bit further.

Interdependencies or dependencies

This thesis emphasizes interdependencies between national critical infrastructures. A notion that is tightly related to that of independencies is dependencies. Both notions can conceptually be described as a connection or relationship between two infrastructures. These connections or relationships can have different origins. For example, they can result from geographic closeness, customer-supplier relationships, reliance on information-sharing, or a combination of several such factors that give rise to a dependency or interdependency. Hence, dependencies and interdependencies share some basic similarities and can simplistically be seen as unidirectional respectively bidirectional connections as depicted in Figure 3.

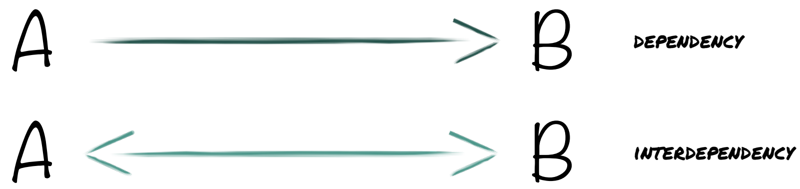


Figure 3. Dependency and interdependency
Illustration of the difference between dependencies and interdependencies between infrastructure A and B.

What would then be the reason for emphasising the interdependency rather than the dependency concept in this research? In reality, connections between critical infrastructures tend to be much less straightforward than depicted in Figure 3 and can be the result of multiple connections across several infrastructures, as illustrated in Figure 4. Therefore, it is essential to take a holistic approach, acknowledging that critical infrastructures constitute open systems that are influenced by each other and their environment (Rinaldi et al., 2001). To accommodate this, the interdependency concept has over the years come to be understood not only as a bidirectional connection in parity with the dependency one but also as a more general concept that relates broadly to the existence of dependencies – often used in terms of interdependent critical infrastructures. This conceptualisation is relatively established in the scientific literature and has come to indicate the overarching problem at the core of this thesis.

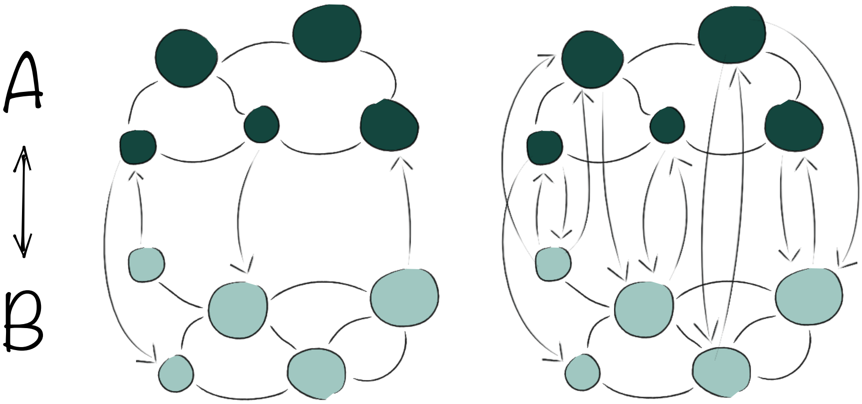


Figure 4. Complex interdependency between critical infrastructures
Illustration of how interdependencies between two critical infrastructures can be the result of many complex connections between them.

Direct or indirect interdependencies

Interdependencies can be either direct or indirect (Johansson and Hassel, 2010). As Figure 5 illustrates, a direct interdependency between critical infrastructure A and B occur when a change in infrastructure A gives rise to changes in infrastructure B due to B's dependence on, for example, a service or physical structure provided by A. In contrast, an indirect interdependency occurs if the change in A affects infrastructure B through a third infrastructure C. Note that indirect interdependencies can be of a higher order than in the presented example, i.e. span across several infrastructures (Johansson et al., 2015). Such higher-order, or *n*th-order, interdependencies create the potential for a chain of events where a disruption in one infrastructure sequentially affects several directly and indirectly dependent infrastructures causing significant consequences to society (Pescaroli and Alexander, 2015; Rinaldi et al., 2001).

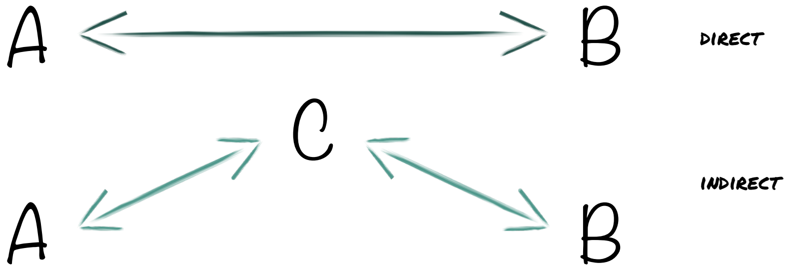


Figure 5. Direct and indirect interdependencies
Illustration of the difference between direct and indirect dependencies between infrastructure A and B.

Interdependency-related risks

The concept of risk has been adopted and used across an extensive array of fields (Aven & Zio, 2014). Consequently, a wide variety of interpretations of risk have been proposed over the years (Aven et al., 2018), and the true nature of the concept has been heavily debated across scientific disciplines (Aven & Zio, 2014; Hansson, 2010). The debate can simplistically be described as a spectrum between two extremes (Hansson, 2010). On the one side stand those who subscribe to the interpretation that risk is a social construct that is always a matter of perspective and thus, intrinsically subjective (see Slovic, 1987; Boholm, Corvellec & Karlsson, 2012); and on the other, those that understand risk as something quantifiable, fact-driven and 'value-free' or 'objective' (see Kaplan & Garrick, 1981; Haimes, 2009a). In between the two, we find those that emphasise the dual nature of risk and attributes the concept with both subjective and objective attributes (Hansson, 2010; Aven & Renn, 2009). This thesis subscribes to the latter perspective and views risk as a broad concept based on both values and facts that contains both subjective and objective aspects.

In the broader and dual interpretation adopted in this thesis, risk is often defined by two dimensions: (1) the potential consequences to something of human value and (2) the uncertainty related to the extent or severity of said consequences (Aven & Renn, 2010; Aven et al., 2018; IRGC, 2017; Hansson, 2010). The upside of this interpretation is that it can, to some degree, encompass and emphasise both the subjective and the objective aspects of risk (Schweizer, 2019). For example, in traditional quantitative risk analyses, consequences are often quantified in terms of the number of casualties and the uncertainty is statistically quantified in terms of probabilities (Aven, 2020). In this example, measuring the consequences in human lives might seem logical but is very much a value-driven choice based on the assumption that human lives should be protected. However, in choosing what to measure, we also choose what we will not consider. While preserving human lives might be a value that is easy to agree upon, in other contexts, for example, prioritising between services supplied by critical infrastructures might offer more ambiguity. In other words, even quantitative risk analysis within an objectivistic tradition is imbued with underlying values (Fischhoff, 1995) that "are reflected in how risks are characterised, measured, and interpreted" (Renn, 1998, p. 54).

The research presented in this thesis focuses on the cross-sector dimension of critical infrastructures. Due to interdependencies, a risk in one infrastructure can be a dependent variable for the risk in another (Rinaldi et al., 2001). For example, the risk of a fraction of customers in a telecommunications network being disconnected could theoretically be described as a time-variant function of the risk of a power outage in the energy sector due to a strong dependence of telecom networks upon power supply. This thesis focuses on these types of risks and denotes them as interdependency-related risks.

Interdependency-related risks are defined as risks that stem from or are amplified by interdependencies between critical infrastructure actors, structures or functions. Interdependency-related risks are characterised by uncertainty, complexity and ambiguity, and can thus be considered systemic risks (van Asselt & Renn, 2011; van Asselt et al., 2015; Aven & Renn, 2019; IRGC, 2018; OECD, 2003; Renn, Klinke & van Asselt, 2011; Schweizer, 2019).

Systemic risks constitute a complementary notion to so-called simple or conventional risks. Simple risks are recurring, follow a known cause-effect pattern, and the consequences are non-ambiguous. Hence, they can be approached probabilistically and using traditional risk decision-making strategies (Renn et al., 2011). On the other hand, as the name implies, systemic risks are connected to a breakdown that is not limited to some part of, but rather to an entire system (Kaufman & Scott, 2003). In general, what constitutes a system is context-dependent (Schweizer, 2019). In this thesis, a system refers to critical infrastructures that provide a particular societal function, such as telecommunications, electricity or transport, that make up the Swedish critical infrastructures system of systems.

These systems are owned and operated by many diverse actors with different values and incentives that can have different ideas on how to best deal with interdependency-related risks. Such diversity adds to the ambiguity of interdependency-related risks and introduces several challenges of dealing with them across sectors. Thus, systemic risks require both a systems and a multi-actor perspective which limits the usefulness of traditional quantitative risk assessment and management strategies and opens up for alternative points of departure, such as resilience and risk governance (van Asselt & Renn, 2011; Aven & Renn, 2019; IRGC, 2018; Schweizer, 2019).

Cross-sector resilience

Due to their interdependent and socio-technical nature, national critical infrastructures make up a complex system of systems. In complex systems, many components or agents simultaneously interact in a non-linear or emergent fashion, limiting the possibility of anticipating their combined behaviour (Ottino, 2004; Oughton, Usher, Tyler & Hall, 2018). Hence, while anticipatory approaches can help us understand these systems to a certain extent, they cannot cover the entire scenario space (Cilliers, 2001; Johansson, Hassel & Zio, 2013). To prepare for that which they cannot predict, it is vital that critical infrastructures also embrace more adaptive resilience-oriented approaches (Boin & McConnell, 2007, Linkov et al., 2014).

The resilience concept has been around for several decades. Over this time, it has been adopted across many scientific disciplines (Folke, 2010; Walker and Cooper, 2011;

Woods, 2015), but its application for addressing real-life critical infrastructures has just recently left its starting blocks (COM(2020) 829 final; OECD, 2019; Pursiainen, 2018). While resilience in this setting is a relatively novel concept, it is essential to acknowledge that resilience-related activities have been carried out for much longer but attributed to other conceptual approaches. For example, several proposed definitions of resilience are similar or synonymous to or encompass descriptions of concepts such as robustness, fault-tolerance, flexibility, continuity, survivability, adaptation, reliability, security, dependability, performability, redundancy, trustworthiness and agility (van Asselt and Renn, 2011; Francis & Bekera, 2014; Hassel & Cedergren, 2019; Hickford et al., 2018; Hosseini, Barker & Ramirez-Marquez, 2016; OECD, 2019; Righi, Saurin & Wachs, 2015; Rød & Johansson, 2020; Pumpuni-Lenss, Blackburn & Garastenauer, 2017; Sterbenz et al., 2010; Tøndel, Foros, Kilskar, Hokstad & Jaatun, 2018). Hence, resilience should not be viewed independently from previous and parallel conceptual approaches (Righi et al., 2015).

Due to its relative novelty in the critical infrastructure context, the potential of resilience is still avidly discussed amongst critical infrastructure researchers, and several research gaps still exist (Rød & Johansson, 2020). Over the years, many – more or less similar – definitions and interpretations of resilience have been proposed (Aven et al., 2018; Haimes, 2009b; Hosseini et al., 2016; Hickford et al., 2018; Normandin & Therrien, 2016). However, the concept is often linked to the ability of critical infrastructures to anticipate, absorb, recover from, and adapt to disruptive events (see Bruneau et al., 2003; Hickford et al., 2018; Park et al., 2013; Rehak et al., 2019; Woods, 2015; Rød & Johansson, 2020). Hence, it focuses both on the preparatory and the reactive work before and after a disruption.

In line with the above, it can be useful to look at the distinction sometimes made in the scientific literature between specified and general resilience. The former relates to the resilience of a particular aspect or part of the system to a known type of disruption with regards to a specific control variable, such as the ability of a power transmission network to maintain a certain overall functionality in the event of storms with normally expected wind speeds and geographical extent. The specified resilience can be increased by, for example, managing foreseeable risks through the implementation of best practices (van der Merwe, Biggs & Preiser, 2018). On the other hand, the latter refers to the ability of a system to handle uncertainty and surprise, for example, related to unforeseen cascading disruptions. Increasing the general resilience of a system is less straightforward and often more costly than improving specified resilience. Promoting general resilience involves increasing the general capacity for adaption and transformation and typically requires long time frames. Examples of increasing the general technical resilience of the previously mentioned power system include investing in a more decentralised power system with diverse power sources or in additional safety margins and buffers (van der Merwe et al., 2018). The latter could include adopting a

N1 design criterion commonly used when designing technical infrastructure. The N1 design criterion stipulates that the network should be designed to remain functional in the event of a breakdown of any one component (Johansson, 2010). Both specified and general resilience need to be considered to achieve resilient critical infrastructure (Folke et al., 2010; van der Merwe et al., 2018; Walker, Abel, Anderies & Ryan, 2009; Walker & Salt, 2012).

While resilience is an essential ability of individual critical infrastructures, it is argued to be especially important at the complex and dynamic cross-sector level studied in the thesis. To make a clear distinction between the two, this thesis refers to the latter as cross-sector resilience. Cross-sector resilience in the critical infrastructure setting is here defined as the ability of interdependent critical infrastructures to efficiently maintain their functions by anticipating, absorbing, adapting to and rapidly recovering from the impacts of interdependency-related shocks. This definition falls within what is often referred to as critical infrastructure resilience (see Australian Government, 2010; 2015a; 2015b; NIAC, 2009). Critical infrastructure resilience is a broad concept encompassing both the single infrastructure or organisation perspective and the interdependency or cross-sector perspective. Therefore, the rationale of introducing the concept of cross-sector resilience is to emphasise the cross-sector and multi-actor perspective adopted in this thesis.

Risk governance

Modern societies are heavily dependent on and shaped by the evolution of critical infrastructures, but critical infrastructures are also greatly affected by changes in society and existing socio-technical regimes. For example, innovations, such as information and communication technologies, have changed how critical infrastructures are designed and operated. Behavioural and political changes such as increased demand for sustainable energy sources are furthermore enforcing changes and updates in both the physical structure and ways of managing energy infrastructures. Hence, critical infrastructures constitute open socio-technical systems (Cilliers, 2001; Oughton et al., 2018) and cannot be viewed in isolation from the economic, technical, institutional, social and natural context in which they exist (Oughton et al., 2018; Pumpuni-Lenss et al., 2017). This thesis adopts risk governance as an analytical framework to understand how the interplay between actors, processes and mechanisms affect how interdependency-related risks are understood and decisions are made when a range of actors are involved and when risks are uncertain, complex and ambiguous.

Risk governance is closely tied to the general governance concept. In general terms, governance can be seen as an ‘umbrella term’ that illustrates the practices and structures of how present-day policy decisions are made (Kooiman, 2003; Boholm et al., 2012;

Schweizer, 2019). The governance concept is often linked to that of government (Rhodes, 1996). While the two share certain features, four main differences are often outlined in the scientific literature. First, governance is characterised by flexible rather than formal governmental control. Second, it acknowledges the significance of collaboration between and vested interest of many relatively autonomous actors in different societal domains, e.g. the government, the private sector and the civil society. Third, governance is carried out through networks rather than hierarchical decision-making structures. Finally, it involves a mixture of formal and informal decision-making processes and structure that includes the participation and not only the consultation of stakeholders (Ruhanen, Scott, Ritchie & Tkaczynski, 2010; Schweizer, 2019; Stoker, 1998).

Governance as a broader concept has been used across various fields and contexts over a long period – most prominently within the fields of public administration, political sciences and corporate management. The concept is far from unambiguous, which is shown by, amongst others, Rhodes (1997; 2012), Treib, Bähr and Falkner (2007), and Hufty (2010), who illustrates that, in the general sense of the concept, several types of governance exist that do not necessarily have very much in common. Hence, many different definitions have been proposed in the scientific literature (see Boholm et al., 2012; Hiteva & Watson, 2016; Rhodes, 1997; van Asselt and Renn, 2011).

This thesis focuses on risk governance and interprets it as a framework to understand how societies make decisions on issues that have uncertain and potentially harmful consequences (Aven & Renn, 2010; Renn & Klinke, 2015). Hence, it is seen as a broad concept encompassing all actors, norms, processes and conventions that directly and indirectly influence these decisions. According to Renn & Schweizer (2009), this decision making often includes actors that can be divided into one out of four categories: (1) governments, (2) economic players, (3) civil society, and (4) experts and scientists. One of the main concerns of risk governance is to explore how these actors interact and whether the actions of and interaction between these actors reduce or amplify risk.

This thesis views resilience as one end goal of risk governance of interdependent critical infrastructures. Resilience in socio-technical systems, such as critical infrastructures, can be seen as a desirable end goal or an ideal state towards which the systems should continuously strive (Rehak et al., 2019). In line with this, many resilience definitions include the notion of acceptability and, thus, has highly normative undertones (de Bruijn, Buurman, Mens, Dahm & Klijn, 2017; Helfgott, 2018; Therrien & Normandin, 2020). Therefore, it is helpful that risk governance can serve both descriptive and normative purposes. In other words, it can be used both to analyse and describe the way risk-related decisions are being made and how it could be improved to reduce risk (Cedergren & Tehler, 2014; van Asselt & Renn, 2011).

The normative undertones of the resilience definition also highlight that a multitude of stakeholder interests and values must be included in the process of identifying and prioritising resilience enhancing measures (van Asselt et al., 2015; Boholm et al., 2012; Klinke & Renn, 2002). These stakeholders interact horizontally within and vertically across administrative levels, often referred to as horizontal and vertical risk governance. The former describes interactions between actors on the same administrative or functional level, while the latter describes interactions of actors across levels (van Asselt & Renn, 2011; Aven & Renn, 2010). As its unit of analysis is limited to national infrastructures, this thesis mainly focuses on horizontal governance.

Methodology

This chapter outlines and comments on the overarching research approach and methods adopted and data collection performed in the thesis. First, it presents a discussion on the overarching exploratory research approach that permeates this thesis. Then, descriptions of the specific methods used and data collection performed in the individual studies presented in the appended papers are given.

On the exploratory research approach

Over the last two decades, critical infrastructure research has cemented itself as an interdisciplinary field that has generated vast amounts of research publications (see Ouyang, 2014; Rød & Johansson, 2020). However, little of this literature has focused on governance structures for critical infrastructures' resilience specifically linked to interdependency-related risks on the national level (Rydén Sonesson, Johansson & Cedergren, 2020). Scientific exploration is suitable when researchers come across a process, phenomenon or group that has been subjected to limited scientific scrutiny but where they believe interesting discoveries can be made (Stebbins, 2001). On this rationale, it was deemed suitable to take an exploratory approach to research this topic.

Exploration can be both implicitly and explicitly found in many scientific disciplines. In contrast to confirmatory approaches that mainly depart from established theory, focus on testing hypothesis and primarily rely on deductive reasoning, exploration mainly focuses on observations and formulate theory and hypotheses from data using inductive arguments (Davies, 2011; Givens, 2012; Stebbins, 2001). Its tolerance of induction is one of the main merits and the source of some of the major drawbacks of and critique against the explorative approach. The main critique is the perceived difficulty to ensure validity and reliability that comes with it. These are essential issues to deal with regardless of the research approach and can be especially challenging using qualitative research methods. Here, constant awareness of one's own biases, transparency, flexibility and open-mindedness are crucial. However, the most effective way to increase validity and reliability is through concatenating many studies on the same topic (Stebbins, 2001).

In the scientific literature, what constitutes an exploratory research approach are also subject to two interpretations. The first interpretation put exploration in the methods realm and use it synonymously with 'pilot study', 'feasibility study' or 'exploratory trial'. In other words, the explorative research approach is seen as an exercise to explore the fruitfulness of a research project and, ultimately, to guide confirmative studies, and not as a standalone research study (Clow & James, 2014; Hallingberg et al., 2018; Singh, 2015; Tripodi & Bender, 2019). The second interpretation instead ties the explorative research approach to the notions of methodology and research process. In the second approach, exploration is viewed as a research tradition in its own right that can produce generalisable conclusions about the phenomenon, process, or group under study (Davies, 2011; Given, 2012; Stebbins, 2001). While this thesis acknowledges the value of pilot or feasibility studies, it also recognises the standalone value of exploratory research and the power of concatenating such research studies. This research has taken an overall explorative approach and mainly departs from the latter of the interpretations above. However, it is acknowledged that the research presented has been informed by theory and sometimes inspired by confirmatory traditions.

Methods

This section presents an overview of the methods adopted and the type of data collected. For more detailed descriptions, readers are referred to the method sections of the appended papers.

Scoping review

All studies that make up the basis of this thesis have included some, more or less structured, reviews of relevant literature and Paper I presents the direct outcome of a scoping review. A scoping review is an explorative method that provides a structured approach to cover an extensive material in a shorter amount of time than, for example, a systematic review. The process of a scoping review, generally, includes mapping key concepts of a research area in terms of its extent, range and nature by systematically searching, selecting and synthesising primary research findings (Anderson, Allen, Peckham & Goodwin, 2008; Arksey and O'Malley, 2005; Colquhoun et al., 2014; Daudt, van Mossel & Scott, 2013; Davis, Drey & Gould, 2009; Levac, Colquhoun & O'Brien, 2010; O'Brien et al., 2016; Peters et al., 2015; Pham et al., 2014; Tricco et al., 2016).

A scoping review can either be taken on as a means of determining the value of undertaking a full systematic review (Arksey & O'Malley, 2005) or as a stand-alone research activity (Mays, Roberts & Popay, 2001). Paper I falls into the latter category.

The analysis underpinning a scoping review generally includes charting of papers according to some predefined charting scheme. While an a priori scheme was constructed for the scoping study presented in Paper I, we used an explorative approach to charting and analysing the material. Therefore, emphasis was put on characteristics that emerged from the studied material, and the charting scheme was iteratively updated accordingly. More emphasis than is commonly the case for scoping reviews was also put on qualitative aspects of the material (which was enabled by the relatively small number of papers relevant to the scope of the paper).

Interviews

Interviews were used as one of the data collection methods in Paper II. Interviews can span from a completely structured questionnaire-based to an entirely unstructured and conversation-like format. For Paper II, a semi-structured interview format was used to accommodate the exploratory approach while ensuring some thematic consistency across interviews. Subsequently, all interviews were guided by the same broad set of questions that was adjusted based on the answers provided by the respondents (Lantz, 1993; Leech, 2002; Whiting, 2008). Analysis of the interview transcripts followed an inductive approach to code, categorise, sort and summarise the interview data (Burnard, Gill, Stewart, Treasure & Chadwick, 2008; Graneheim & Lundman, 2003).

A less structured approach increases the possibility for exploration, but it also increases the risks of biases. Response bias, or social-desirability bias, can affect how respondents answer questions (see Furnham, 1986; Nederhof, 1985). Researchers' biases can affect the design, data collection, analysis and publishing phases of a study (see Fusch & Ness, 2015; Pannucci & Wilkins, 2010). The former could be especially problematic for the respondents' answers related to, for example, vulnerabilities. Acknowledging vulnerabilities in the own organisation or infrastructure might be perceived as acknowledging flaws or admitting failure.

To fight biases, many researchers have advocated taking a reflexive approach, which requires awareness of how biases emerge, structured methods for data collection, and systematically reducing the risk of biases in the analysis of the raw data (Whiting, 2008). Therefore, the semi-structured approach was chosen over a completely unstructured one, and the transcripts were analysed iteratively.

The in-depth format of interviews also limits the number of interviews that can feasibly be carried out, transcribed and analysed. For Paper II, the number of respondents was small. The small number of respondents created challenges concerning representativeness. Therefore, interviews were used in conjunction with a document study.

Document analysis

Paper II uses document analysis together with interviews to study how national critical infrastructure actors govern interdependency-related risks. In general, documents can range from formal to informal and include both visual and textual artefacts that in some way describe the context in which they have been produced (Coffey, 2013). For Paper II, the studied documents were mainly formal and publicly available agency documents.

The general purpose of document analyses is to "elicit meaning, gain understanding, and develop empirical knowledge" from different types of written material (Bowen, 2009,p. 27). Document analyses are commonly carried out through an iterative process that involves skimming, reading (in-depth) and interpreting the content. For the latter, content and thematic analysis (see the following subsection) is often used to code and find meaning and overarching themes in the studied material. During mapping and charting activities, many different aspects of the studied material could be considered. For example, it is generally of great interest to reflect upon the context in which the documents were constructed, their original purpose and intended readers, and if some information is absent, incomplete or limited.

As for most other methods, document analysis entails both merits and drawbacks. Compared to many other qualitative methods, such as interviews or observations, the main merits of the document analysis are its stability, exactness, lack of obtrusiveness and reactivity, cost-effectiveness, availability, and efficiency. The main limitations are inadequate detail, low retrievability, and biased selectivity (Bowen, 2009).

Content and Thematic analysis

Content and thematic analysis were used in the analysis of documents and interview transcripts in Paper II. Content analysis with an a priori coding scheme was used to analyse the documents and derive code frequencies, while a more flexible thematic analysis was used for the interviews. In line with the presented recommendations, the analysis step in the scoping review method in Paper I drew inspiration from both content and thematic analysis (Levac et al., 2010). While some distinctions between the two analysis approaches can be identified in the scientific literature, they share many similarities and are often used synonymously (Vaismoradi, Turunen & Bondas, 2013). Therefore, they are addressed in conjunction in this section.

The main differences between the two analysis approaches lie in the type of conclusions they can produce and how (Neuendorf, 2019). Where the thematic analysis is generally strictly qualitative, the content analysis tends to provide possibilities for quantification. Content analysis often relies on coding frequencies as a proxy for importance and to identify themes. In contrast, the thematic analysis makes judgements on importance based on the degree to which a theme makes significant contributions to answering the research questions (Vaismoradi et al., 2013). Therefore, content analysis often starts with an a priori coding scheme (to enable quantification), while codes and themes in the thematic analysis are derived from the data (Neuendorf, 2019).

As for many other qualitative methods (see, for example, the reflection on response and researcher bias in the interview section), content and thematic analysis have been subjected to critique based on the perceived difficulty to guarantee validity and reliability (Long & Johnson, 2000). One common way to ensure the reliability of charting activities in general and content analysis, in particular, is through interrater reliability tests (Vaismoradi et al., 2013). Interrater reliability tests were used in both Paper I and Paper II to check and increase the overall reliability of both the coding schemes and the inclusion criteria. Interrater reliability tests are typically not performed for thematic analysis (Neuendorf, 2019; Vaismoradi et al., 2013). Therefore, Paper II also used member checks and peer briefing exercises (Hsieh et al., 2005; Janesick, 2015; Long & Johnson, 2000). In addition, coding stability was ensured through repeated coding of the transcripts, documents and papers in the two studies, contributing to increased reliability.

Modelling and simulation

Paper III describes a modelling and simulation (M&S) approach used to assess the effects of disruptions in two interdependent critical infrastructures and discuss how these types of analyses could potentially inform the governance of interdependency-related risks. From a methodological perspective, modelling and simulation can be viewed as a set of methods, techniques and procedures rather than one method as it encompasses a diverse set of approaches that are applied in a wide range of fields. Some scholars even go as far as describing modelling and simulation as a science (Padilla, Diallo & Tolk, 2011) or methodology (Birta & Arbez, 2019) in its own right. In this thesis, modelling and simulation, and more specifically one branch of critical infrastructure modelling, has been adopted to explore how information on the potential effects of interdependency-related risks could be used to inform risk governance in critical infrastructures. In this context, modelling and simulation have been adopted as a specific methodological approach rather than an overarching methodology. However, it is acknowledged that modelling and simulation can be used in a much broader sense.

Modelling and simulation can be used for many different purposes, such as education, forecasting, design or evaluation (Birta & Arbez, 2019). In the context of critical infrastructure interdependencies, the purpose of modelling and simulation is often to better understand the effects of interdependencies across critical infrastructures. In 2014, Ouyang (2014) presented a, since then, much-cited review paper on the topic. Ouyang categorised the studied modelling and simulation literature into six different types of approaches: (1) empirical, (2) agent-based, (3) system dynamics, (4) economic theory-based, (5) network-based, and (6) other approaches. Amongst these approaches, the fourth and the fifth was identified in Paper I as the most commonly utilised methods to assess the effects of interdependencies in applied studies on a national level. Amongst the economic theory-based modelling approaches identified, all utilised so-called inoperability input-output models (IIMs). These approaches use data on purchases and sales between sectors or industries as a proxy for interdependencies and can study how the financial consequences in one sector or industry cascade to others. As a result, they can mainly be used for macroeconomic-level or industry-level interdependency analysis. The network-based approaches describe critical infrastructures as nodes and edges that represent the physical critical infrastructure components and relational connections between them. This way, it is possible to study the effects of, for example, component failures (Ouyang, 2014). In Paper III, we wanted to study interdependencies at both the system and the component level and include functional aspects of the critical infrastructure systems. Therefore, we chose to depart from a network-based modelling and simulation approach.

Previous studies have shown that while more detailed functional models give better estimates of the systems' actual performance than purely topological network-based ones, they also come with the downsides of high computational cost and input data requirements (LaRocca, Johansson, Hassel & Guikema, 2015; Thacker, Pant & Hall, 2017). Interdependent critical infrastructures make up a rather large system of systems, and data access for research purposes is often restricted.. Therefore, the approach adopted in Paper III extended on previous work by Johansson (2010), Johansson & Hassel (2010), Johansson et al. (2013), and Svegrup, Johansson and Hassel (2019) and departed from a network-based functional model. It, thus, tried to take an intermediate route by adding some of the complexity of real-life infrastructure by adding a functional model to the network-based approach. The rationale behind this choice was that our main goal was to create a sufficiently accurate model that would allow us to populate it with real-life data for the large-scale infrastructures studied that, in the long run, could be used to inform the risk governance of interdependency-related risks. In other words, the goal was to keep the model as simple as possible to minimise data requirements while still capturing the salient properties of critical infrastructure interdependencies. Though such simplified representations of the real infrastructures can be very valuable to understand the effect of interdependencies better, it is crucial to be mindful that the presented modelling approach is, like all models, a simplified representation of the real systems studied.

The Swedish context

This chapter aims to give an introduction to the context in which this thesis has been produced. Though critical infrastructures are studied and discussed worldwide, this research concentrates on the Swedish context, and the unit of analysis applied is national critical infrastructures. To limit the scope of the research, it has also primarily focused on three fundamental infrastructure sectors: energy, transportation and telecommunication. Therefore, this section describe the context and actors that are most relevant from the national perspective and the infrastructures under study.

Swedish critical infrastructure resilience

In Sweden, critical infrastructure resilience is part of the overall crisis management process (Swedish Civil Contingencies Agency, 2018). As for crisis management, collaborations between actors and the principles of responsibility, parity and proximity make up the foundation for the Swedish critical infrastructure resilience work (Große & Olausson, 2019; Swedish Civil Contingencies Agency, 2013; Wimelius & Engberg, 2015). This means that the actor that is responsible for an activity or societal function under normal conditions should keep that responsibility in times of crisis, that actors should strive to carry out their functions in a similar way during a crisis as during normal conditions, and that a crisis should be managed where it occurs and by those who are directly concerned and responsible. These principles, subsequently, put operators of critical infrastructures in the centre of the management of critical infrastructure-related crises.

The Swedish critical infrastructure work began in its current form in the late 2000s (Pursiainen, 2018). However, already in the vulnerability and safety investigation from 2001, technical infrastructures was described as particularly significant due to their societal importance and a high degree of mutual dependencies (SOU 2001:41). In 2010, the government commissioned the Swedish Civil Contingencies Agency to formulate a national strategy for critical infrastructure protection. The strategy was presented in 2011 and presented several milestones for the work up until 2020 (Swedish Civil Contingencies Agency, 2011). One milestone was to present an Action Plan for how the strategy should be concretised, which was done in 2013[1]. The Action Plan stated that it aimed to "create a resilient society with an improved ability in [vital societal functions and critical infrastructures] to withstand and recover from serious disruptions" (Swedish Civil Contingencies Agency, 2014, p. 9). In achieving this aim, the Action Plan outlined three strategic principles: to use a systems perspective, to measures before, during and after a disruption, and to cover all threat and risk types (all-hazard approach). It also proposed that the aim could be achieved if critical infrastructure actors implement a systematic safety process framework. The framework includes risk management, business continuity management, and managing events (Swedish Civil Contingencies Agency, 2014). The action plan also defined that a critical infrastructure refers to an infrastructure that meets at least one of the following conditions: (1) a loss or severe disruption in the services provided by the infrastructure can, by itself, or in combination with the loss or sever disruption in other infrastructure, quickly give rise to a severe societal crisis, or (2) the infrastructure is vital or very essential to manage and minimise the consequences of an occurring crisis (Swedish Civil Contingencies Agency, 2013). In 2020, the Swedish Civil Contingencies Agency outlined a new critical infrastructure definition. The new definition states that critical infrastructures refer to organisations, services or infrastructures that sustain or ensure societal functions necessary to satisfy society's basic needs, values or safety (Swedish Civil Contingencies Agency, 2020a). The motivation for the change was to find a definition that was easier to understand and use.

Though an all-hazard approach underlines the Swedish approach, added focus in the critical infrastructure work has increased Swedish society's preparedness for military and malicious cybersecurity threats. For example, as outlined in the Swedish parliament's 2015 defence policy and the commissioning of a national cybersecurity centre initiated in 2020. The latter is a joint venture between the Swedish Armed Forces, the Swedish Security Services, the National Defence Radio Establishment and the Swedish Civil Contingencies Agency in collaboration with the Post and Telecom Authority, the Swedish Police and the Swedish Defence Materiel Administration.

European critical infrastructure resilience

As a member of the European Union (EU), Sweden is influenced by the work performed in and obligations to the European Commission. The European critical infrastructure efforts originated in the mid-2000s. Back then, the purpose of the work was mainly to enhance the prevention of, preparedness for, and response to terrorist

[1] The 2013 version was published in Swedish (Swedish Civil Contingencies Agency, 2013). An English version was published in 2014 (Swedish Civil Contingencies Agency, 2014).

attacks involving critical infrastructures. In late 2005, the Justice and Home Affairs Council urged the Commission to propose a European Programme for critical infrastructure protection (EPCIP). The response of the Commission came a year later in its communication on a European Programme for Critical Infrastructure Protection (COM(2006) 786 final). The communication provided a legal framework for implementing the EPCIP with the general objective to improve the protection of critical infrastructures in the European Union. The document emphasised an all-hazards approach and urged the member states to draw up national protection programmes that should include a classification of national critical infrastructures (NCIs), identification of geographical and sectoral interdependencies, and contingency planning.

Though they welcomed the identification and designation of European critical infrastructures (ECI), which was part of the EPCIP initiative, the Council of the European Union concluded in 2007 that the protection of critical infrastructures should predominately be an issue for the individual member states. In 2008, the Council presented Directive 2008/114/EC on the identification and designation of European critical infrastructures and assessing the need to improve their protection (the ECI Directive) – which constitutes a ground pillar of the EPCIP. The ECI Directive focused on critical infrastructures that traversed member state borders and were limited to energy (electricity, oil, and gas) and transportation (road, rail, air and inland waterways transport, and ocean and short-sea shipping and ports) sectors. It also proposed a four-step process to identify ECIs and put requirements on the ECIs to appoint a security liaison officer and to produce operator security plans. While introducing these requirements, the Directive clearly stated that the ultimate responsibility for protecting critical infrastructures is still a task for the member states.

In recent years, efforts have been directed towards investigating the state of the EPCIP and how it could be improved. During 2012, the ECI Directive and the general EPCIP work went through a revision period – as regulated by the original Directive. The review was summarised in a European Commission staff working document (SWD(2012) 190 final) on the review of the EPCIP. The working document concludes that the ECI Directive has been implemented in the legislation of the member states and states that the EPCIP has helped the EU work by putting the issue on the agenda, which has sparked policy and increased awareness and collaboration regarding ECIs. However, it also concludes that its sector-specific focus and lack of systems-thinking pose a challenge to the member states and that no indications have been given that it has improved security in the energy and transport sectors.

In the following year, a follow-up European Commission staff working paper (SWD(2013) 318 final) was published on a new approach to the European Programme for Critical Infrastructure Protection. In this document, the need to emphasise the interdependent behaviour of critical infrastructures was highlighted. It was acknowledged that these interdependencies can span several infrastructures in multiple member states and that this emphasises the need to consider interdependencies in the EPCIP – something that had been missing from the joint European work up until this point. The resilience concept was given more prominence than in previous documents, and several suggestions for the work until 2020 were given. For example, broadening the scope of the work to take a cross-sectoral approach to better account for interdependencies; applying a multi-scale perspective fostering local, national and international CIP initiatives; and adopting a broader focus by applying a beyond-EU perspective and seek more collaboration and knowledge outside the Union.

In 2019, a second review of the ECI Directive was presented in a Commission staff working document (SWD(2019) 308 final). The evaluation indicated that while the ECI Directive has been partially effective in achieving its stated objectives, the existing structure is insufficient given increasing interdependencies within and between critical infrastructure sectors and the evolving risks they face. The critique sparked a proposal for additional measures on critical infrastructure protection (COM(2020) 37 final). On the 16th of December 2020, around six months after the publication of the Working program, a proposal for a new Directive on the resilience of critical entities (COM(2020) 829 final) was presented. If enforced, the new Directive would replace the 2008 ECI Directive. As the title suggests, the proposal emphasised the resilience of critical entities rather than critical infrastructure protection. Critical entities are described as public or private operators of critical infrastructures that provide necessary services for vital societal functions and economic activities. In contrast to the 2008 ECI Directive, the proposed new Directive also emphasised the importance of coordination with the proposal for a revised Directive on the Security of Network and Information Systems[2].

Swedish critical infrastructure actors

In Sweden, the ownership and operations of critical infrastructures are divided between many heterogeneous actors or entities, such as authorities and private and public operators at local, regional and national scales (Swedish Civil Contingencies Agency, 2014). All public or private organisations are responsible for evaluating whether or not they constitute a critical infrastructure (Swedish Civil Contingencies Agency, 2020b). This section provides a brief overview of the roles of the central government, central government agencies, local and regional government and private actors in the Swedish critical infrastructure context.

[2] Eee Directive 2016/1148 and COM(2020) 823 final for more information on the update of the NIS Directive.

Central government

In Sweden, the government answers to the parliament. Therefore, it is obliged to carry out decisions taken by the chamber (Government Offices of Sweden, 2015a). As the central government in Sweden is relatively small compared to the size and number of its agencies (Duit & Galaz, 2008; Hall, 2015), this work is carried out through delegation to the government offices and its ministries and the agencies and state-owned enterprises (Government Offices of Sweden, 2015a; Hall, 2015). To coordinate and steer this delegation process, the government provides agencies with annual appropriations directives and ordinances. In these documents, the government details a framework for agency operations, such as goals to fulfil, budgetary constraints, and how the budget should be distributed between its different activities. In other words, even though its influence over the agencies' day-to-day operations is limited, the government can set the course and goals for their operations (Hall, 2015; Governance Offices of Sweden, 2015b). The agencies' work is followed up every year through an annual report. The report contains, amongst other things, information about expenditures, returns and results. This information is evaluated and makes up part of the foundation for the following year's national budget and appropriation directives (Government Offices of Sweden, 2015b).

Swedish governments are typified by collective decision-making. In other words, they are engaged in a high degree of coordination and negotiation, and the influence of individual ministers are often relatively weak (Hall, 2015) – especially in their relationship with agencies whose operational decisions they are legally prohibited from influencing (Government Offices of Sweden, 2015b). The government also has the power to create, rearrange and dismantle formal administrative units, such as ministries, departments and agencies, and to assign them specific responsibilities that mirrors what is perceived as the most important political issues (Jacobsson & Sundström, 2015). Hence, though the government does not have an operative role in protecting critical infrastructures, it is ultimately the entity that steers the overall direction and priorities of critical infrastructure protection in Sweden.

Government agencies

Swedish government agencies can constitute both infrastructure owners and regulatory and supervisory bodies. Therefore, they are often central actors for increasing the cross-sector resilience of critical infrastructures. In 2020, Sweden had 341 government agencies that employed around 229 000 people (Swedish Agency for Public Administration, 2020). Swedish agencies' operations are carried out with a great degree of independence from the central government (Duit & Galaz, 2008; Hall, 2015). Though the independence of Swedish agencies from the government is high, agency work is supposed to be carried out in line with the goals of the publicly elected representatives through the government.

The Swedish Civil Contingencies Agency

As a member of the European Union, Sweden is immersed in the European Programme for Critical Infrastructure Protection (EPCIP). Within the scope of the EPCIP, the Swedish Civil Contingencies Agency has been appointed the role of national contact point for the tasks performed within the European Union 'Council directive 2008/114/EC' (2008) on the identification and designation of European Critical Infrastructures. The Agency also supports Swedish critical infrastructure actors in their work to identify and systematically maintain critical infrastructures. According to the Agency, the latter is done by developing methods, provide training, consultations and lectures (Swedish Civil Contingencies Agency, 2014; 2020b; 2020c).

Local and regional government

While this thesis limits its scope to national critical infrastructures, it is relevant to have some insight into what happens at the local and regional levels of government. Sweden has 290 municipalities and 21 regional councils (Government Offices of Sweden, 2015a). Municipalities and regions have strong self-government and are responsible for providing several public services in their geographical areas (Swedish Association of Local Authorities and Regions, n.d.). For example, the municipalities are responsible for carrying out several welfare services, such as pre-university education, elderly care, and child care. The county councils have historically been responsible for healthcare and public transportation and have, in recent years, also been given responsibility for regional development (Hall, 2015). As part of this self-government, municipalities and regions also have a special responsibility to identify critical infrastructures and critical dependencies within their geographical areas (Swedish Civil Contingencies Agency, 2020b).

Private actors

As in many other countries, several critical infrastructure sectors that state actors previously dominated have been subjected to deregulations and some, such as the telecommunications subsector, was not state-owned from the start. Consequently, private actors represent a considerable part of the national critical infrastructure system in most sectors (Swedish Civil Contingencies Agency, 2020b). According to the 2011 national strategy for protecting critical infrastructures, private actors are included in the national strategy (Swedish Civil Contingencies Agency, 2011). However, their inclusion in and responsibilities within the crisis management system tend to be less clearly governed in existing legal frameworks, and the goals and values that underpin their operations sometimes differ from the public actors'.

Overview of the three focus sectors

In this thesis, the focus has been put on three critical infrastructure sectors: Transport, Energy and Telecommunication. This section gives a brief overview of the three sectors.

Transportation

The transportation sector includes four central agencies: the Swedish Transport Agency, the Swedish Transport Administration, the Swedish Maritime Administration, and the Swedish Aviation Administration. The Swedish Transport Agency is involved in issues that concern all modes of transportation. Its primary responsibility is to formulate and monitor the sector's compliance with rules and regulations across the Swedish transportation sector (Swedish Transport Agency, 2017).

The Swedish land transport network comprises 98 500 km state roads, 42 800 km municipal roads, 41 shuttle-ferries and 14 200 km railway that connects the countries 525 railway stations (Swedish Transport Administration, 2017; 2020; 2021). Though the railway market is entirely deregulated since 2012 (Alexandersson, Hultén, Nilsson & Pyddoke, 2012), a relatively small number of organisations dominate, several of which are still partly owned by the state. For both the rail and road transportation sectors, most of the physical infrastructure is owned and operated by public actors, while private or semi-private companies carry out traffic. The public actors include the Swedish Transport Administration and the municipalities, while the private include a handful of large cargo and passenger operators (Swedish Agency for Public Management, 2005; Swedish Transport Agency, 2017). Apart from being a public infrastructure owner, the Swedish Transport Administration is also responsible for the long-term strategic planning of the overall transportation system (i.e. across transport modes) and have recently been given a coordinating role in the sector's crisis preparedness and response system (SFS 2017:842).

The Swedish maritime transportation system connects Sweden to the rest of the world through its 50 domestic ports. The ports constitute crucial transport hubs as 90% of all raw materials and goods enter and exit the country by sea (Swedish Maritime Administration, 2013). Swedish ports are often owned or partly owned by the municipalities in which they are located, but there are numerous examples where they are operated by private actors (Aula et al., 2020). Responsibility for managing and developing the maritime infrastructure and for monitoring the sector's fulfilment of the political transport goals lies with the Swedish Maritime Administration.

The Swedish air transportation network consists of ten national and 33 regional airports. The national airports are run by the state-owned company Swedavia. Municipalities and regions typically own regional airports, but some private actors exist. The regional airports are typically smaller than the state ones and organise themselves in an interest group called the Swedish Regional Airport Association (SRFF). The Association is represented by the Swedish Regional Airports (RSF) (Swedish Aviation Administration, 2021; Swedish Regional Airports, 2021). The Swedish Aviation Administration is a state-owned company. The Administration is responsible for providing efficient and safe air navigation services in Sweden. Apart from the Swedish Aviation Administration, one private company – Aviation Capacity Resources (ACR) – also provides air navigation services (Swedish Aviation Administration, 2021).

Energy

The energy sector in Sweden can be divided into four main sub-sectors: electricity, gas, district heating, and oil, petroleum and biofuel. The electricity, district heating and natural gas markets are regulated, monitored and licensed by the Swedish Energy Markets Inspectorate. The Swedish Energy Markets Inspectorate can, thus, regulate the resilience of large parts of the energy market by putting requirements, such as compulsory risk and vulnerability analyses or incident reports, on its actors and decide which actors are allowed to operate in the sector. Apart from the Swedish Energy Market Inspectorate, The Swedish Energy Agency is a second important public actor at the national level with a sector-wide responsibility for overarching analysis, strategy and crisis coordination of the energy system as a whole.

Since almost a decade back, Sweden is a net exporter of electricity. Four-fifths of Sweden's domestic electricity production comes from hydroelectric and nuclear power plants. Apart from these two, wind power and cogeneration[3] is the third and fourth most common energy source (Aula, 2020; Swedish Energy Agency, 2020). In the electricity sub-sector, the agency SVK is responsible for the operation, maintenance and development of the national transmission system and for coordinating, planning, and supporting crisis management activities. Apart from SVK, significant actors from the national point of view include the three regional sub-transmission system operators (E.ON., Vattenfall and Ellevio) and the approximately 170 distribution system operators. Apart from the physical infrastructure owners and operators, other relevant actors include the electricity producers, who are a heterogeneous group that include both electricity-producing households and big energy companies, and the around 100

[3] Cogeneration is sometimes also known under the name of combined heat and power plants.

electricity suppliers that buy and sell[4] electricity from producers to the end-customers (Swedish Energy Markets Inspectorate, 2021a).

The 600 km long Swedish national gas transmission system is relatively small and located in the Southwest. The gas system's primary customers include households[5], industries and district heating companies (Swedish Energy Markets Inspectorate, 2021b). Sweden has seven gas network operators and seven gas providers at the regional or municipal levels, but the national transmission network is operated by SwedeGas who is also responsible for monitoring the short term balance between the input and the output to and from the gas system (Swedish Consumer Energy Markets Bureau, 2020a; Swedish Energy Markets Inspectorate, 2021a). While Sweden has domestic biogas production, mainly produced in local co-digestion plants or at wastewater plants, most of the gas distributed in the gas network is imported natural gas – primarily from Denmark (Swedish Energy Markets Inspectorate, 2021b; Gåverud, Lundgren & Glimhall, 2009). Apart from network owners and operators, and gas producers and suppliers, Sweden also has some commercial gas stock owners. The stocks can even out seasonal variations in gas demand and compensate for supply disruptions. In addition to the commercial actors, SwedeGas also owns a small gas stock (Swedish Energy Markets Inspectorate, 2021a).

More than half of the heating needs in Sweden are fulfilled by the district heating system. District heating is distributed to the households by the approximately 200 district heating companies generally operated at a municipal scale (Aula et al., 2020; Swedish Consumer Energy Markets Bureau, 2020b). The district heating market was deregulated in the mid-1990s, which resulted in a substantial shift from municipal toward private ownership. Buyers included large energy companies such as Vattenfall, E.ON and Fortum. Biomass from the forestry industry and waste constitutes the primary fuel input. Most of the biomass is provided by private forestry companies, while waste is provided by municipal waste companies and imported from other countries (Dzebo & Nykvist, 2017; Werner, 2017).

The oil, petroleum and biofuel sub-sector includes many national and international producers and distributors, and Sweden has a significant fuel import dependency. Most of the actors are private actors, and the Swedish Energy Agency monitors the actors' compliance with regulations (Swedish Energy Agency, 2016).

[4] Exchanges in electricity take place on an open market and the retail companies have total price freedom. All electricity retail company are, however, obliged to report prices and conditions to the Energy Markets Inspectorate (EI, 2021).

[5] The gas system supplies 37 000 Swedish households with energy for both cooking and heating.

Telecommunications

The agency that oversees the telecommunications sector is the Post and Telecom Authority (PTS). The sector comprises many actors[6], ranging from dark fibre owners to pure service providers. While the total number of actors are large, five operators (Telia, Tele2, Telenor, High 3G Access and Net1) provide mobile service to a majority of the Swedish customers and in different constellations own the mobile networks (Hedlund, Lodin & Montelius, 2018). Similarly, Telia Company[7], Telenor AB Sverige[8], Tele2 Sverige and Hi3G Access, IP-Only, Teracom, Netnod, Stokab, and Gothnet AB are the largest and most prominent owners and operators of national infrastructure for electronic communication. These actors provide a mix of wired and wireless transmission, redistribution points or communication endpoints, access networks and access points. In addition to these actors, Svenska kraftnät and the Swedish Transport Administration own and operate national communications networks that run alongside their respective infrastructures (Aula et al., 2020). The Metropolitan Area Networks (MANs) have been important actors in the Swedish broadband rollout and own around 60 per cent of the physical infrastructure. The MANs operate at the municipal level and are typically owned, with some exceptions, by the municipalities or the municipal energy companies. Together, they are significant providers of dark fibre services that connect operators and end-users (SSNF, 2020).

According to ordinance SFS 2015:1052, PTS has a particular task for emergency preparedness and response measures in the sector and regulates the sector according to a mandate established in the Electronic Communications Act (SFS 2003:389). PTS also chairs the National Telecommunications Cooperation Group. The group was formed in 2005 to increase the sector’s preparedness planning and crisis response and includes both public and private actors (Hedlund et al., 2018). The group's main activities include exercises and training events and information-sharing in both preparing for and responding to disruptions. As part of the latter, the PTS provides a common web platform with a GIS interface to share disruption information within the group (Aula et al., 2020).

[6] 640 registered operators in 2018.

[7] Partly owned by the Swedish state.

[8] Controlled by the Norwegian state.

Overview of findings

This chapter gives an overview of the findings from the appended papers. In line with the aim of this thesis, the appended papers have aspired to explore different aspects of the resilience of national critical infrastructures to interdependency-related risks and how these risks are being governed. Two governance perspectives are studied: (1) assessment and (2) management. Paper I explores the aim from the intersection between the two perspectives, while Paper II and III depart from the management, respectively, the assessment perspective. See Figure 2 in the introductory section for an illustration.

Paper I

Exploring Assessment and Management of Critical Infrastructure Interdependencies: A Scoping Review

Paper I presents a scoping review that was conducted to study the extent to which approaches for assessing and managing interdependency-related risks are linked in the applied scientific literature on national interdependent critical infrastructures. Two search strings that cater to each of the two studied perspectives were formulated, and the scientific journal database Scopus was used to perform the search. The search was limited to peer-reviewed papers published in scientific journals. In total, 629 unique papers were identified. These papers were put through a scanning process and scrutinised against four inclusion criteria, following which 31 papers remained and were put through the final analysis. A charting scheme was used to map out quantitative and qualitative characteristics of the identified approaches.

One notable finding from Paper I were that a surprisingly small number of papers was found that fulfil all the predefined inclusion criteria, i.e. were applied, studied a national context and dealt with interdependencies. While it is possible to argue that the inclusion criteria were rather strict, the lack of studies that fulfil them do highlight a gap with regards to and a need for more applied studies of interdependent critical infrastructures.

Focusing on the studies that fulfilled the criteria, the scoping study found that modelling and simulation approaches are the most commonly used applied approaches to study interdependencies (45%). These approaches tend to focus on assessing the effects of interdependencies in the event of a disruption and almost exclusively utilise network theory and economic theory-based approaches. Paper I proposes that this could be attributed to, among other things, data accessibility issues and network size and complexity. Hence, a research opportunity was identified to map out the feasibility of different assessment approaches in the applied setting while accounting for data accessibility and stakeholder needs and limitations.

Providing decision-makers with a decision-making basis was identified as a motive for the presented approaches in over two-thirds of the studied papers. However, only a quarter of the papers mention any specific decision-maker and even fewer provide a detailed discussion on the context in which these approaches could be used and how they aid the decision-making process. This called attention to a research opportunity related to charting out the usefulness of different assessment results in various parts of explicit decision-making processes, which could put more emphasis on the management perspective and tie the two perspectives together. However, it also raised questions of who the intended decision-maker and decision-making process is and on what basis assessment methods are chosen in the studied approaches.

To summarise, Paper I draws attention to a gap in the applied literature. It also finds the link between assessment and management perspectives to be rather indistinct. Based on the presented findings, the paper also identifies two significant challenges for future research on closing the gap between the assessment and management perspective:

1. More studies are needed to map out and understand the governance structures and processes that influence the ability of critical infrastructures to collectively and efficiently maintain their functions by anticipating, absorbing, adapting to and recovering from the impacts of interdependency-related shocks.
2. Practical feasibility and stakeholder adoption of models and simulation approaches need to be explored and considered in developing new assessment and management approaches. Such activities should consider, for example, access to data.
3. Studies are needed to study the potential pathways, drawbacks, and merits of integrating the two types of studies described above.

Paper II

Governance and Interdependencies of Critical Infrastructures: Exploring Mechanisms for Cross-sector Resilience

Paper II presents a combined document and interview study that aimed to explore enabling and hampering mechanisms for addressing interdependency-related risks of Swedish critical infrastructures. For the document study, documents were mainly retrieved from public sources using Google Advanced search. A side effect of this approach was that it was mainly possible to retrieve documents from public actors. In other words, limited insight could be found in the documents about private actors. In total, 125 unique documents were found, out of which 32 were deemed relevant for inclusion in the final analysis. For the interview study, respondents were identified through a purposive sampling approach. In total, 11 respondents were available and interviewed during five one-on-one interviews and one group interview. All interviews were recorded and transcribed verbatim before analysis to ensure transparency and enable future revision.

The study yielded nine central findings:

1. Swedish critical infrastructures primarily operate in silos. For example, collaborations tend to emerge spontaneously within rather than across sectors.
2. Personal networks and trust are two central factors that explain the rise of collaboration across critical infrastructure organisations.
3. Formal and informal information-sharing exist both within and across sectors. Individuals are more prone to share information with others when trust relationships or mutual information needs exist.
4. The actors acknowledge the existence of interdependencies, but no readily available methods for identifying and assessing interdependency-related risks could be found.
5. The motivation to address and manage interdependency-related risks appear to increases amongst the actors when ownership of a specific risk or interdependency-related issue is clear and when the consequences are tightly linked to the core business of the organisations in question. This seems to be more prevalent when it comes to interdependencies related to the physical infrastructures.
6. Past events that highlight certain interdependencies or interdependency-related risks seem to highly influence the focus of collaborations and other governance activities concerning interdependency-related risks. Hence, it

appears as if this work is predominantly of a reactive rather than a proactive nature.

7. Compliance with legal requirements is an essential factor influencing the actors' priorities concerning what activities to join.
8. Prospective financial gains and losses highly influence the actors' decision to partake and invest in, for example, collaboration on interdependency-related risks.
9. Customer demands are regarded as very important in how the actors prioritise their work.

While these findings offer insights into some of the challenges for increasing the cross-sector resilience of Swedish critical infrastructures, they do not provide enough information to suggest how to improve the cross-sector resilience in practice. Therefore, Paper II also uses the findings to outline three potential ways forward for future research to explore. First, Swedish critical infrastructure actors seem to have limited incentives to partake in interdependency-related risk governance. This seems to prevent the formation of cross-sector governance networks and thus, cements existing silos. Hence, more knowledge is required about the mechanisms for forming and maintaining such cross-sector networks in the Swedish context. We see great practical and scientific potential in future studies of mechanisms that can, for example, inform investments to incentivise cross-sector projects. Second, the findings of Paper II suggest that past events can shed light on gaps in existing resilience work. Hence, there is an opportunity for future research to explore procedures for efficiently seizing the windows of opportunity that come with past events on the cross-sector level. For example, studying how near-misses and modelling and simulation approaches can be incorporated to sustain the work in the absence of large-scale disruptions. Finally, both the practical and scientific literature seems to suffer from a lack of readily available applied assessment approaches that can address interdependencies across sectors – another opportunity for future research

Paper III

Modelling National Interdependent Critical Infrastructures: Application and Discussion for the Swedish Power and Internet Backbone

Paper III puts forward a modelling and simulation approach that aimed to create a foundation upon which to explore further the usefulness of models and simulations in a risk governance context. The proposed model was constructed in four parts: (1) a structural model in which the systems are represented by nodes and edges, e.g. links between components and their spatial distributions, (2) a functional model that describes non-topological properties related to flows within each system, such as edge capacity, and demand or supply in sink and source nodes, (3) a dependency model that describes how components in the two systems are dependent on each other (based on proximity), and (4) a consequence model that describes the effects of disruption on society by connecting users to the components or nodes in the model. In constructing the model, we departed from existing approaches (for example, Johansson, 2010; Johansson & Hassel, 2010; Johansson et al., 2013; Svegrup et al., 2019) and used a network theory-based approach in which we incorporated a functional model with capacity flow constraints. This approach allowed us to capture the salient properties of technical infrastructures while keeping down the computational cost. It also made it possible to populate the model using real-life data. The model was used to perform a set of disruption simulations that aimed to study the effects of different strains on two national critical infrastructure networks – a power transmission system and a dependent telecommunications system.

The simulation illustrated three significant challenges related to assessing and managing interdependency-related risks. First, when performing a simulation to study the deterioration of the telecommunications system when all components are randomly removed, we saw, as illustrated in Figure 6, that the telecommunications network deteriorate far more rapidly when also considering interdependency-related events than in the non-dependent case. Consequently, the dependency from the telecommunications system on the power transmission system increased its vulnerability substantially. Second, when solely disturbing the power transmission system components, we saw that the magnitude of the consequences (in terms of the fraction of disturbed services and number of affected customers) in the telecommunications system was generally higher than in the power transmission system where the disruption originated as illustrated in Figure 7. This is illustrated by the grey scenario dots, which are disproportionally found in the upper half of the plot. Third, when attempting to find critical scenarios by ranking lower-level strain scenarios (i.e. scenarios where only one to five components are disrupted) based on the consequences to each of the two systems, we saw that the highest-ranking scenarios often did not overlap across the two infrastructure systems. In other words, identifying and prioritising critical scenarios in the across sectors perspective was not entirely straightforward, as illustrated by the general lack of overlapping priorities in Figure 8.

These results highlighted the prevalence of complex vulnerability issues related to interdependencies seen in previous studies (e.g. Buldyrev et al., 2010; Johansson & Hassel, 2010; Johansson et al., 2013; Thacker et al., 2017). Thus, while the model is simplified but representative of real-world systems, Paper III provides a basis for understanding some of the issues related to assessing and managing interdependency-related risks. It also illustrates the importance of including interdependency-related and societal consequences in assessing and managing interdependency-related risks.

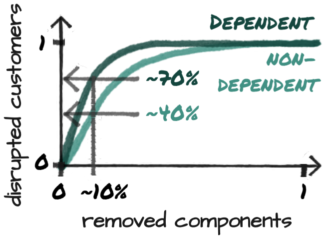


Figure 6. Interdependency vulnerability.
Interdependent behaviour of the modelled telecommunications (telco) system to random strains in both the power transmission system and the power system. From top to bottom: 1) mean values of in-dependent behaviour simulations, 2) mean values of dependent behaviour simulations, and 3) residual of ICS system independent and dependent behaviour.

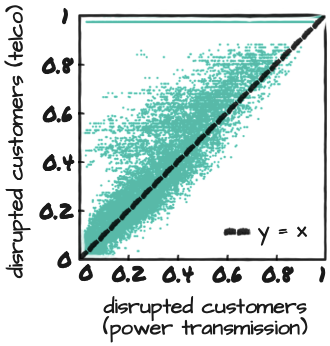


Figure 7. Asymmetrical consequences
The magnitude of consequences for the power transmission system (x-axis) plotted against the magnitude of the consequences for the telecommunications (telco) system (y-axis) for a large number of scenarios where only the power system is strained. The asymmetrical spread of the data points indicates that the magnitude of the consequences tends to be higher in the telecommunications networks than in the power transmission network.

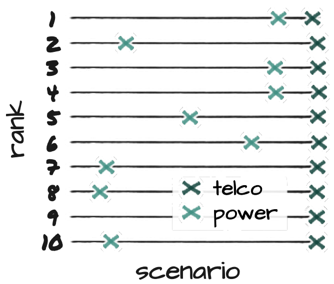


Figure 8. Scenario rank comparison
Ranking of scenarios in the N-2 scenario simulation based on highest consequences for each of the two studied infrastructures. The figure illustrates that the top scenarios do generally not overlap.

Discussion

In this chapter, I discuss the practical and scientific implications of the findings presented in the previous chapter in general and related to future research in particular. I also provide a more general reflection on the research from which the findings emerged.

Practical and scientific implications of the findings

In this section, I discuss the findings from the three studies that underpin the presented research and focus on their practical and scientific implications. The discussion is divided into five sections that cover the five themes which I find would be particularly interesting and relevant to pursue in the next steps of my research studies. The themes include sectoral silos, legal frameworks and incentives, analytical resolution, balancing past events and anticipation, and aligning assessment and management.

Sectoral silos

In Paper II, we found that one major prevailing challenge for the governance of interdependency-related risks at the national level in Sweden is the prevalence of sectoral silos. This existence of sectoral silos was seen, among other things, in that self-initiated governance networks seem to arise primarily within sectors. As illustrated in Paper III and other similar studies (see Paper I for examples of references to further literature), assessing and managing risks related to critical infrastructure failures in sectoral silos are tied to significant downsides, such as the risk of underestimating the severity of a particular risk or a difficulty prioritising which components to protect in the multi-actor setting. Thus, both future research and policy work needs to identify ways to break these sectoral silos. As a first step towards this, Paper II describes several mechanisms that could influence engagement in cross-sector activities. For example, trust, personal networks, past events, compliance with laws and regulations and clear mutual needs and gains stood out as factors that incentivise actors to break sectoral silos. While identifying these factors can be valuable, it would be advantageous to study how their interplay affects the actors' incentives to partake in, for example, cross-sector collaboration.

Legal frameworks and incentives

Swedish critical infrastructure actors generally seem to operate within their respective sectors with limited cross-sector coordination. Therefore, the Swedish Civil Contingencies Agency (MSB) is an important actor in promoting cross-sector resilience as the agency has been given a coordinating and supporting role regarding the general cross-sector crisis preparedness and capabilities in Sweden (SFS 2008:1002). However, Paper II identifies compliance with laws and regulations as an essential mechanism for the existing risk governance structures. Since MSB's role is coordinating and supporting rather than regulatory in terms of cross-sector engagement of public and private actors, this finding highlights the importance of the regulatory sector agencies, such as the Swedish Post and Telecom Authority and Energy Markets Inspectorate, to emphasise interdependency-related issues. However, these agencies generally operate in the same sectoral silos as the operators themselves, and critical infrastructure regulations in Sweden have primarily been carried out on a sector basis. Hence, the current legal incentives could increase the prevalence of silos and, thus, constitute a challenge for promoting a cross-sector resilience perspective. This challenge represents an opportunity for more profound studies on the influence of current legal frameworks on the cross-sector resilience of critical infrastructures.

Another exciting aspect connected to legal frameworks and incentives for cross-sector resilience is the newly proposed replacement of the European Critical Infrastructure (ECI) Directive. While Sweden has performed work related to preparing critical infrastructures for disasters before the introduction of the original 2008 ECI Directive, it appears that EU initiatives have sped up and changed the focus of the work.

In the original directive, the primary focus was on identifying physical and transboundary ECIs in the energy and transportation sectors, and the general stance was that critical infrastructure protection was predominately an issue for the Member States (Council Directive 2008/14/EC). In the new 2020 directive proposal, on the other hand, the European Commission is given a more central and active role, and the focus is broadened to include more sectors, such as health and water. It also shifts focus from the physical infrastructures to the critical entities or organisations that own and operate said infrastructures and emphasises both interdependencies and resilience (COM(2020) 829 final). Therefore, it would be fascinating to study the potential, and future impacts of the new ECI directive translated to the Swedish critical infrastructure context if the new directive is implemented. This could include a detailed comparative analysis of the two versions of the ECI Directive put in the context of the relatively decentralised Swedish critical infrastructure setting or a longitudinal study of its implementation and the potentially changing role of the European Commission in this work.

Analytical resolution

As this thesis and its appurtenant studies focus mainly on national critical infrastructures, its studies have been limited to horizontal risk governance at the national level. As a result, the local and regional perspectives have been given limited attention. However, Sweden is characterised by a decentralised crisis management system in which the responsibility and proximity principles[9] are central. Thus, local and regional actors also play an essential role in the overall crisis management and building capacity to deal with and reduce the negative societal consequences of critical infrastructure breakdowns. From my limited experience in the local and regional settings, I have understood that they are subjected to the same type of silos and division of critical infrastructure ownership between public and private actors as the national. At the local and regional levels, the municipalities and county councils also have a special responsibility to identify critical infrastructures and dependencies within their geographical areas and conduct risk and vulnerability analyses for the municipalities and the regions. However, similarly to the Swedish Civil Contingencies Agency, they have a limited possibility to influence, for example, how private actors manage their critical infrastructures and mostly have to rely on voluntary participation. Here, I see a potential future research in exploring the governance of interdependency-related risks and its implications for the cross-sector resilience on the local and regional levels. For example, this could include exploring the extent the private critical infrastructure owners are included, comparative studies on how local and regional work differs from the national, how work at the different levels affects each other, and how assessment methods, such as modelling and simulation approaches, could be scaled to or be informed by data from different administrative levels. It also opens up for studies and discussions on whether the criticality of an infrastructure service can differ across administrative levels and what challenges this could entail.

Balancing past events and anticipation

Paper II argues that Swedish critical infrastructures need to become better at balancing learning from past events and anticipation. While the Swedish Civil Contingencies Agency's (2014) Action Plan for the Protection of Vital Societal Functions and Critical Infrastructures emphasises both a system and an all-hazards approach to create a resilient society, the findings from Paper II indicate that in reality, past events largely

[9] See the chapter on the Swedish context for a description of the crisis management principles.

influence the management of interdependency-related risks. Hence, Paper II suggests that this work has been of a reactive rather than a proactive nature and corroborates existing research that has shown that avoiding failures of the past is a strong motivator for decision-makers (Amundsen, Berglund & Westskogh, 2010; de Bruijn & van Eeten, 2007; Levy, 1994; Næss, Bang, Eriksen & Vevatne, 2005). While adapting to past events is an essential aspect of resilience, a risk governance approach that focuses too much on past events creates several challenges, two of which will be discussed further.

First, an excessive focus on past events can give rise to either over or underemphasising a specific risk depending on the actors' perception of outcome of the event. If an event is construed as a 'disaster that almost happened', i.e. as an illustration of vulnerabilities, the event can incentivise the involved actors to increase their resilience to similar events. On the other hand, if it is interpreted as a 'disaster that was avoided', i.e. as an illustration of a high degree of resilience, it can decrease the incentives to take measures regardless of the actual resilience levels (Dillon, Tinsley & Burns, 2014). So, what implications does this have for the governance of interdependency-related risks in critical infrastructures? It illustrates the importance of framing both past and potential future events, which has implications for both assessment and management. In the assessment process, one needs to be aware of how the context and framing of a post-event evaluation or an anticipatory assessment could affect how its results are interpreted in the management process. In the management process, on the other hand, decision-makers need to be mindful that past experiences and successes might influence how risky an event is perceived and, thus, influence the decision at hand. Here, there might be room for more research on applying structured approaches, for example, modelling and simulation approaches, that can be utilised to counteract the influence of framing a past or future event on logical assumptions and decision-making.

Second, past events tend to result in a tendency to over-prepare for specific events that already occurred. Apart from the fact that it is often implausible that the same chain of events happens twice, this mainly strengthens specified resilience. Focusing too much on specified resilience, without complementary strategies to increase the general resilience, can make critical infrastructures vulnerable to unexpected and not previously experienced events. Here, I see an opportunity for more studies on how to strike a balance between using the window of opportunity created by an event and allocating too many resources to prepare for a specific type of experienced event. For example, by targeting studies towards how past events could be systematically integrated with more anticipatory assessment approaches to create a basis for more balanced decision-making. Such studies could, for example, take inspiration from Abrahamsson, Hassel and Tehler (2010), who made use of a systems dynamic model and counterfactual scenarios to overcome similar challenges in a public crisis management setting.

Confidentiality and information-sharing

A discrepancy between the scientific and practical domains identified in the research findings includes the issue of confidentiality. Amongst the 31 papers identified in Paper I, almost a quarter highlight confidentiality as a common challenge for information-sharing related to, for example, vulnerabilities in critical infrastructures. In these papers, this issue is addressed rather superficially and often as an explanation to the lack of access to information and to motivate why simplified models or proxy data are used. In contrast, the respondents in Paper II seemed to reason that while confidentiality and information security can be hard to navigate and limits what information can be made available to the public, it does not constitute an obstacle for information-sharing between central actors. Instead, issues mentioned concerning such information-sharing were connected to technical and organisational solutions, knowing what information to ask for and how to keep such information both updated and secure. Hence, few formal platforms or structured procedures for collecting and sharing data across actors seem to exist in the practical domain. Therefore, it might be reasonable to believe that there might be difficulties in acquiring real-world data to evaluate cross-sector methods in scientific settings, which are mirrored in the results of Paper I. The lack of data for testing out scientific approaches requires joint efforts between scientists and practitioners to find a way forward that allows for developing assessment approaches that balance the need for information security and understanding interdependency-related risks and their implication for cross-sector resilience.

Another interesting aspect here is that other studies in the Swedish context, but in a regional and municipal context, have found that confidentiality constitutes an issue for information-sharing also in the practical domain (Arvidsson et al., 2021). This could indicate that the role of confidentiality differs at different administrative levels and shows a need for more research on both this contrast and the role of confidentiality in general.

Aligning management and assessment approaches

Paper II finds that while critical infrastructure actors acknowledge interdependencies in the Swedish context, assessments have mainly been carried out within sectors and no readily available approaches for assessing and managing interdependency-related risks seem to exist in practice – a governance deficiency that has also been found in other practically oriented studies (European Commission, 2020; IRGC, 2017). Furthermore, Paper I shows that applied methodological approaches are few and diverse for the national level studied here. While method diversity might be necessary to tackle the heterogeneity of the critical infrastructures and the threats they face, some harmonisation is most likely needed to perform cross-sector analyses. In addition, Paper I finds that the studied papers generally lack a discussion on how the presented assessment approaches align with actual decision-making processes. Together, these findings indicate a need for more applied studies on assessment methods and constructing a framework that detail how these methods could be combined and applied systematically for different purposes to assess and manage interdependency-related risks in the applied domain. Such a framework could, for example, answer questions such as which approaches are appropriate for what types of decisions, who should use them or be involved and what competencies do they need to have, and how should the information that the approaches generate be disseminated? It could also include an account of the limitations of each approach. As decision-making, in reality, involves balancing many different social, political, financial and technical values, multi-criteria methodologies could be an interesting avenue to explore within such a framework. Using such an approach could enable weighting together the results from several approaches representing different values and end-goals relevant to a particular decision.

Here, it should be noted that, in the broader scientific literature, a myriad of different approaches are offered (see, for example, Griot, 2010, Ouyang, 2014). These studies are often not limited to applied studies at the national level, but future studies could depart from the presented approaches and test them in an applied setting.

Three reflections on the research process

Pursuing a PhD is not solely a matter of conducting research but also learning the craft of being a researcher. As this licentiate thesis constitutes the halfway mark of this journey, I cannot claim to have gotten to the end of this process. However, I have learned during my time as a PhD student that the road of research is never as straight as we describe in the papers we publish. Instead, more often than not, the road to scientific findings is – as the Beatles sings – a long and winding one. In this section, I provide some reflection on three of the bends in the road that I have struggled with during my time as a PhD student. First, I reflect on the choice of conceptual points of departure. Second, I reflect on the usefulness and challenges of using and bridging the two perspectives of assessment and management. Finally, I reflect on some practical difficulties of conducting the presented research.

On the chosen conceptual points of departure

In this thesis, I have chosen to focus on risk, resilience and risk governance as the main building blocks for my conceptual framework. This choice was not straightforward, and I humbly acknowledge that there are probably many other conceptual points of departure that could have been useful. Therefore, in this section, I reflect upon the usefulness and pitfalls that I have experienced related to these conceptual choices.

After some deliberation on which conceptual road I should tread, I chose to focus on both risk and resilience as, in my mind, the two are highly interconnected. Where resilience describes a capability, risk describes threats to that which we value. Hence, resilience includes all anticipatory, reactive and adaptive capabilities that can be utilised to prevent, deal with and adapt to effectuated risks. The main issue that I had with this understanding of risk and resilience was that it could encompass so much. Where was I to draw the line? For the sake of limiting the scope of my studies, I, therefore, introduced the notions of interdependency-related risks and cross-sector resilience to denote what I intend to explore. I think this delimitation worked reasonably well and helped me to get Paper II on track. However, I am still a bit wary that both resilience and risk governance have such holistic ambitions and what focusing primarily on cross-sector resilience means for the resilience of individual critical infrastructure actors. Therefore, I see potential in exploring this further, for example, in the light of a broader holistic framework that encompasses both the single infrastructure and the cross-sector perspective. I would also like to explore the notion of specific versus general resilience more since I have not had the time to fully explore the differentiation between the two in the practical context. I think this distinction could provide a good framework for broadening the work of strengthening general resilience as it focuses more on the abstract unknowns.

Since resilience is such a broad strategy encompassing many different types of abilities, another challenge was to relate the activities of the critical infrastructure actors and modelling and simulation approaches to how precisely they impact, analyse or inform the cross-sector resilience. The above is a topic that I plan to continue to work with, especially in going forward with the modelling and simulation approach planned for the continuation of Paper III.

Early in the research process, risk governance was already part of the discussions on how to conceptually approach the context of dealing with risks to and strengthening the resilience of interdependent critical infrastructures. However, putting my finger on how to best approach the notion has been a challenge. At the start, having read the critique on risk governance and being somewhat weary of the notion's normative ambitions, I wanted to take a step back to understand more of its foundation in the broader governance concept. Diving into the broader governance literature without a political science or public administration background was overwhelming. However, by studying these discussions, I realised that the risk governance conceptualisation encompassed much of what I was looking for to study in the multi-actor setting entrenched with – to use the risk governance vocabulary – complex, uncertain and ambiguous risks that arise from the existence of interdependencies between critical infrastructures. Thus, departing from the proposition that critical infrastructures constitute open socio-technical systems, risk governance seemed to be a valuable conceptualisation to explore the role of interdependencies for the cross-sector resilience of Swedish critical infrastructures.

On a conceptual level, risk governance, thus, ticked a lot of the boxes but introduced added difficulties in operationalisation and delimitations in my studies. By definition, risk governance discourages reductionistic undertakings. To exemplify, in their highly cited paper on the topic, van Asselt and Renn (2011, p. 432) describe risk governance as follows:

> "risk governance pertains to the various ways in which many actors, individuals, and institutions, public and private, deal with risks surrounded by uncertainty, complexity, and/or ambiguity. It includes formal institutions and regimes and informal arrangements. It refers to the totality of actors, rules, conventions, processes, and mechanisms concerned with how relevant risk information is collected, analyzed, and communicated, and how regulatory decisions are taken".

The above and similar statements gave me the initial impression that risk governance should include everything and everyone, making a comprehensive operationalisation of the concept within the scope of an explorative scientific study tedious and close to impossible within the time frame of a PhD project. It also led me to grapple with questions such as how to draw the boundaries of a study, how and what data sources do we need, and what questions do we need to ask to get a fair representation of the current state of affair with regards to the governance of interdependency-related risks? To climb up from this rabbit hole, I had to accept that while I could not paint a complete picture, I could still make a valuable contribution to the broader understanding of how interdependency-related risks are governed in national Swedish critical infrastructures. I, therefore, came to pragmatically adopt an understanding of risk governance in the studied context as a process that can be described to encompass the sub-processes of assessing and managing risks. These processes are most likely fragmented and integrated into other activities and exist in a multi-actor context that arises as a result of many organisational, physical, legal, financial and geographical interdependencies that blurs the boundaries between the involved organisations.

Despite the above problematisation and delimitation of the risk governance concept, I see the benefit of both emphasising that risks are often not simple and the somewhat abstract nature of the concept. This abstractness makes it theoretically possible to scale the concept to fit different decision-making contexts – for example, different administrative decision-making levels ranging from the local to the global level – which could be valuable in studying the vertical or multi-level governance of interdependency-related risks – a topic I would be interested in exploring further. However, what makes this challenging is operationalising the framework to the different contexts, as discussed in the previous paragraphs.

On bridging the two processes of assessment and management

As discussed in the section above, one of the main drawbacks of the governance concept is that it is rather abstract and hard to operationalise. My approach to deal with this has been to distinguish between the processes of assessment and management, where the former relates to activities connected to the process of understanding risk and the latter to activities tied to deciding what to do about it. This framework allowed me to structure my work and identify challenges and opportunities for cross-sector resilience in Swedish critical infrastructures. In Paper I, I explored the connection between the two. In Paper II and III, I departed from the management and the assessment perspective, respectively. As such, this conceptualisation has been helpful to make sure that I broadly cover the different aspects of risk governance and identify research gaps. For example, Paper I identified a gap between the two processes, and Paper II's lack of identified structured assessment approaches indicates that this gap exists in the practical domain as well. I interpret this as an indication of the fruitfulness of the conceptualisation. It also means that I still have many possibilities to continue working with bridging this gap between the two processes. However, the question remains whether this understanding of risk governance will be as useful when moving from exploring challenges and prerequisites to suggesting solutions and normative approaches that might require a less abstract and all-encompassing conceptualisation.

On practical challenges

While choosing and operationalising my conceptual framework have given rise to some of the main challenges in my thesis work, I have also encountered several more practical challenges worth mentioning. For starters, before becoming a PhD student, I did not have any prior experience within the field of national critical infrastructures. Therefore, I had much to learn about both how these organisations and infrastructures function and had no prior personal network to reach out to when, for example, identifying respondents. However, my lack of experience also had its upsides as it allowed me to approach the subject with an outsider perspective.

Connected to the lack of contacts, I have experienced difficulties in accessing respondents for my interview study. On the national level in a relatively small country like Sweden, the number of potential respondents is comparatively few and challenging to access as they get many requests to partake in different projects. Limited access to respondents is a challenge that is hard to overcome. Overcoming this challenge will require creative solutions and continuing building my personal network.

On a similar note, it has become increasingly difficult to gather data and information on the organisations and infrastructures that I want to study. I think that this could be partly a result of the recent recommissioning of the civil defence in Sweden and the new Protective Security Act (SFS 2018:585) that put an added and more responsibility on both public and private actors to enforce measures aimed at protecting "activities that are of importance for Sweden's security" (SOU 2018:82, p. 27). Since 2015, a changing geopolitical situation has resulted in the resumption of the total and civil defence movement that was gradually decommissioned in the 1990s (SOU 2021:25). Total defence includes both the military and the civil defence and involves the entire society's resilience in war and the threat of war (Swedish Defence University, 2019). In contrast to improving the national capacity to prevent and manage peacetime-related unintentional and seemingly random crises that have been the focus since the 1990s, the total defence movement focuses on preserving Sweden's sovereignty towards intentional attacks. This shifting narrative from threats departing from chance towards active actions has been noticeable in working with critical infrastructures, especially gathering and synthesising data. For example, I have never partaken in a workshop with practitioners where one or more participants have not raised these issues.

Moving away from information and data access difficulties, trying to cover and bridge the two perspectives of management and assessment also have, and will probably continue to be, a challenge regarding limiting the scope of my thesis. It has required me to apply both qualitative research approaches to understand the state of current risk governance state-of-affair and to dive into the technical literature to study and apply, for example, quantitative modelling and simulation approaches. This constitutes a challenge regarding both creating an understanding of my topic and achieving a good balance between breadth and depth in my thesis.

Conclusions

This concluding chapter will briefly address the fulfilment of the research aim, followed by a concluding commentary and a summary of suggestions for future research.

Addressing the research aim and questions

This thesis has aimed to explore how existing risk governance processes, divided into assessment and management, account for interdependency-related risks and the implications for the cross-sector resilience of Swedish critical infrastructures. Here, assessment is understood to relate to activities connected to understanding risk and management to activities tied to deciding what to do about it. One of the core findings of the presented research is that, when it comes to interdependency-related risks in the applied national setting, the assessment and management processes seem to be weakly linked in both the scientific and the practical domain. Thus, combined, the presented research implies that one way to strengthen the cross-sector resilience of critical infrastructures could be to better align the assessment and management of interdependency-related risks.

The two processes of assessment and management have further been addressed from different angles in the three appended papers. Each of the papers answers one of the three research questions that underpin the research and provide several more detailed findings, further summarised below.

In the scientific literature, to what extent do approaches for assessing the resilience of real-life interdependent critical infrastructure and cross-sector management guide one another, and what characterises these approaches? The link between the two perspectives is rather indistinct in the scientific literature, and the number of applied studies at a national level is few. Modelling and simulation seem to be the dominating approach to increase the understanding of interdependency-related risks. Decision-making is often part of the motivation or rationale of the proposed approaches, but who the decision-makers are or what decisions can be made is rarely discussed in depth.

What enabling and hampering mechanism for managing interdependency-related risks can be found in Swedish national critical infrastructures? What are the

implications of this for assessment approaches? Swedish critical infrastructures primarily operate in silos which can hamper the management of interdependency-related risks. Interdependencies are acknowledged, but their abstractness and the fact that critical infrastructure operators deal with many conflicting goals sometimes seem to decrease the incentives to deal with interdependency-related risks. Personal networks and trust, physical interdependencies tied to the core business, past events, legal frameworks, financial aspects and customer demands seem to increase the incentives to deal with interdependency-related risks. Assessment approaches that play at these factors could potentially impact how the actors deal with risk.

How can modelling and simulation be used to inform management decisions that promote resilient interdependent national critical infrastructures? The first step towards increasing the incentives to invest in cross-sector resilience is to illustrate the potential effects of interdependencies. Modelling and simulation approaches can be used to show that, in the event of a disruption, interdependencies can increase vulnerabilities and allow consequences to be asymmetrically distributed across sectors. They can also illustrate some of the downsides of making decisions on a sectoral basis.

Future research

In working with this thesis, I have only started to explore matters related to the governance of interdependency-related risks in critical infrastructures and taken the first steps towards describing some challenges that Swedish critical infrastructures face. In addition, I have identified several interesting directions for future research, which are summarised below.

- Several mechanisms are identified that seem to affect the incentives of critical infrastructure actors to address interdependency-related risks, break sectoral silos and partake in cross-sector collaboration. However, the interplay and degree to which these mechanisms can influence the incentives remain to be explored in future research.
- Current legal frameworks are implemented mainly within sectors. Future studies could explore how a change in these frameworks could potentially influence the incentives to deal with interdependency-related risks. This could include studies of the potential effects and ways to best implement the suggested new ECI Directive, which emphasises incorporating interdependency and resilience aspects.
- The research presented here is limited to horizontal risk governance at the national level. Therefore, future research could take a multi-level governance perspective to study the interplay between local, regional and national levels

and its implications for building capacity to deal with critical infrastructure breakdowns.

- Experienced past events are found in this research as a factor that can influence critical infrastructure actors' incentives to invest in reducing interdependency-related risks. While acting upon and learning from the past is an integral part of being resilient, too much focus on past events can have a hampering effect. Therefore, future studies could be directed towards both how to balance between learning from the past and anticipating future unexpected interdependency related threats and how the framing of past events affects post-event evaluations and anticipatory analyses.
- Discrepancies are identified between different studies related to the perceived issues with and benefits of confidentiality. Therefore, future studies could explore this discrepancy further, for example, by studying differences across administrative levels. Such studies could also investigate the perceived usefulness and obstacles of a common information-sharing platform.
- To align assessment and management, future studies could be directed towards adopting existing approaches to fit different decision-making contexts and creating a framework that could guide the user in which approaches are suitable for what decision-making context.

References

Abrahamsson, M., Hassel, H., & Tehler, H. (2010). Towards a system-oriented framework for analysing and evaluating emergency response. *Journal of Contingencies and Crisis Management, 18*(1), 14–25. https://doi.org/10.1111/j.1468-5973.2009.00601.x.

Alexandersson, G., Hultén, S., Nilsson, J.-E., & Pyddoke, R. (2012). *The liberalization of railway passenger transport in Sweden – Outstanding regulatory challenges* (CTS Working Paper 2012:5). Stockholm: Centre for Transport Studies (CTS).

Amundsen, H., Berglund, F., & Westskogh, H. (2010). Overcoming barriers to climate change adaptation-a question of multilevel governance? *Environment and Planning C: Government and Policy, 28(*2), 276–289. https://doi.org/10.1068/c0941.

Anderson, S., Allen, P., Peckham, S., & Goodwin, N. (2008). Asking the right questions: Scoping studies in the commissioning of research on the organisation and delivery of health services. *Health Research Policy and Systems, 6*(7). https://doi.org/10.1186/1478-4505-6-7.

Arksey, H., & O'Malley, L. (2005). Scoping studies: towards a methodological framework. *International Journal of Social Research Methodology, 8*(1), 19–32. https://doi.org/10.1080/1364557032000119616.

Arvidsson, B., Guldåker, N, & Johansson, J. (2021). A methodological approach for mapping and analysing cascading effects of flooding events. Manuscript submitted for publication.

Australian Government. (2010). *Critical Infrastructure Resilience Strategy*. Canberra: Commonwealth of Australia.

Australian Government. (2015a). *Critical Infrastructure Resilience Strategy: Plan.* Canberra: Commonwealth of Australia.

Australian Government. (2015b). *Critical Infrastructure Resilience Strategy: Policy Statement*. Canberra: Commonwealth of Australia.

Australia-New Zealand Counter-Terrorism Committee (ANZCTC). (2015). National Guidelines for Protecting Critical Infrastructure from Terrorism. Retrieved May 7, 2021, from https://www.nationalsecurity.gov.au/Media-and-publications/Publications/Pages/default.aspx#_ngftpocift .

Aula, I., Amundsen, R., Buvarp, P., Harrami, O., Lindgren, J., Sahlén, V., & Wedebrand, C. (2020). *Critical Nordic Flows: Collaboration between Finland, Norway and Sweden on Security of Supply and Critical Infrastructure Protection*. Helsinki, Finland.

Aven, T. (2020). Three influential risk foundation papers from the 80s and 90s: Are they still state-of-the-art? *Reliability Engineering and System Safety, 193*, 106680. https://doi.org/10.1016/j.ress.2019.106680.

Aven, T., Ben-Haim, Y., Andersen, H. B., Cox, T., López Droguett, E., Greenberg, M., … Zio, E. (2018). *Society for Risk Analysis Glossary*. Retrieved from http://sra.org/sites/default/files/pdf/SRA_glossary_20150622.pdf.

Aven, T., & Renn, O. (2009). On risk defined as an event where the outcome is uncertain. *Journal of Risk Research*. https://doi.org/10.1080/13669870802488883.

Aven, T., & Renn, O. (2010). *Risk management and governance: Concepts, guidelines and applications* (Vol. 16). Berlin, Heidelberg: Springer-Verlag. https://www.doi.org/10.1007/978-3-642-13926-0.

Aven, T., & Renn, O. (2019). Some foundational issues related to risk governance and different types of risks. *Journal of Risk Research*, 1–14. https://doi.org/10.1080/13669877.2019.1569099.

Aven, T., & Zio, E. (2014). Foundational Issues in Risk Assessment and Risk Management. *Risk Analysis, 34*(7), 1164–1172. https://doi.org/https://doi.org/10.1111/risa.12132.

Birta, L. G., & Arbez, G. (2019). *Modelling and simulation: Exploring Dynamic System Behaviour: Simulation Foundations, Methods and Applications* (3rd ed.). Cham: Springer Nature Switzerland.

Brown, G., Carlyle, M., Salmerón, J., & Wood, K. (2006). *Defending critical infrastructure. Interfaces, 36*(6), 530–544. https://doi.org/10.1287/inte.1060.0252.

Boholm, Å., Corvellec, H., & Karlsson, M. (2012). The practice of risk governance: Lessons from the field. *Journal of Risk Research, 15*(1), 1–20. https://doi.org/10.1080/13669877.2011.587886.

Boin, A., & McConnell, A. (2007). Preparing for Critical Infrastructure Breakdowns: The Limits of Crisis Management and the Need for Resilience. *Journal of Contingencies and Crisis Management, 15*(1), 50–59. https://doi.org/10.1111/j.1468-5973.2007.00504.x.

Bowen, G. A. (2009). Document Analysis as a Qualitative Research Method. *Qualitative Research Journal, 9*(2), 27–40. https://doi.org/10.3316/QRJ0902027.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., … Von Winterfeldt, D. (2003). A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra, 19*(4), 733–752. https://doi.org/10.1193/1.1623497.

Buldyrev, S. V, Parshani, R., Paul, G., Stanley, H. E., & Havlin, S. (2010). Catastrophic cascade of failures in interdependent networks. *Nature, 464*(7291), 1025–1028. https://doi.org/10.1038/nature08932.

Burnard, P., Gill, P., Stewart, K., Treasure, E., & Chadwick, B. (2008). Analysing and presenting qualitative data. *British Dental Journal, 204*(8), 429–432. https://doi.org/10.1038/sj.bdj.2008.292.

Cedergren, A., & Tehler, H. (2014). Studying risk governance using a design perspective. *Safety Science, 68*, 89–98. https://doi.org/10.1016/j.ssci.2014.03.006.

Cilliers, P. (2001). Boundaries, Hierarchies and Networks in Complex Systems. International *Journal of Innovation Management, 5*(2), 135–147. https://doi.org/10.1142/S1363919601000312.

Clow, K. E., and James, K. E. (2014). The Marketing Research Process. In Essentials of Marketing Research: Putting Research into Practice (pp. 25–60). Thousand Oaks: SAGE Publications, Inc.

Coffey, A. (2013). Analysing Documents. In U. Flick (Ed.) The SAGE Handbook of Qualitative Data Analysis (pp. 367–379). London: Sage Publications.

Colquhoun, H. L., Levac, D., O'Brien, K. K., Straus, S., Tricco, A. C., Perrier, L., … Moher, D. (2014). Scoping reviews: time for clarity in definition, methods, and reporting. *Journal of Clinical Epidemiology, 67*(12), 1291–1294. https://doi.org/10.1016/j.jclinepi.2014.03.013.

COM (2006) 786 final. Communication from the Commission on a European Programme for Critical Infrastructure Protection. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52006DC0786.

COM(2020) 37 final. *Commission Work Programme 2020. A Union that strives for more*. Brussels: European Commission. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0037.

COM(2020) 823 final. *Proposal for a directive of the European Parliament and of the Council on measures for a high common level of cybersecurity across the Union, repealing Directive (EU) 2016/1148*. Brussels: European Commission. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0823&qid=1623913696889.

COM(2020) 829 final. *Proposal for a directive of the European Parliament and of the Council on the resilience of critical entities*. Brussels: European Commission. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0829&qid=1623913749887.

Daudt, H. M. L., van Mossel, C., & Scott, S. J. (2013). Enhancing the scoping study methodology: a large, inter-professional team's experience with Arksey and O'Malley's framework. *Bmc Medical Research Methodology, 13*(48).

Davis, K., Drey, N., & Gould, D. (2009). What are scoping studies? A review of the nursing literature. International Journal of Nursing Studies, 46, 1386–1400. https://doi.org/10.1016/j.ijnurstu.2009.02.010.

Davies, P. (2011). Exploratory Research. In V. Jupp (Ed.), The SAGE Dictionary of Social Research Methods (p. 111). London: SAGE Publications, Ltd.

de Bruijn, K., Buurman, J., Mens, M., Dahm, R., & Klijn, F. (2017). Resilience in practice: Five principles to enable societies to cope with extreme weather events. *Environmental Science and Policy, 70*, 21–30. https://doi.org/10.1016/j.envsci.2017.02.001.

De Bruijne, M. De, & Eeten, M. Van. (2007). Systems that Should Have Failed: Critical Infrastructure Protection in an Institutionally Fragmented Environment. Journal of Contingencies and Crisis Management, 15(1), 18–29.

Department for Homeland Security (DHS). (2013). NIPP 2013: Partnering for Critical Infrastructure Security and Resilience. Retrieved May 7, 2021 from https://www.dhs.gov/sites/default/files/publications/National-Infrastructure-Protection-Plan-2013-508.pdf.

Dillon, R. L., Tinsley, C. H., & Burns, W. J. (2014). Near-misses and future disaster preparedness. *Risk Analysis, 34*(10), 1907–1922. https://doi.org/10.1111/risa.12209.

Directive 2008/114/EC. *The identification of European critical infrastructures*. European Parliament, Council of the European Union. http://data.europa.eu/eli/dir/2008/114/oj.

Directive 2016/1148. *Measures for a high common level of security of network and information systems across the Union*. European Parliament, Council of the European Union. http://data.europa.eu/eli/dir/2016/1148/oj.

Dueñas-Osorio, L., & Vemuru, S. M. (2009). Cascading failures in complex infrastructure systems. *Structural Safety, 31*(2), 157–167. https://doi.org/10.1016/j.strusafe.2008.06.007.

Duit, A., & Galaz, V. (2008). Governance and complexity - Emerging issues for governance theory. *Governance, 21*(3), 311–335.

Dzebo, A., & Nykvist, B. (2017). A new regime and then what? Cracks and tensions in the socio-technical regime of the Swedish heat energy system. *Energy Research and Social Science, 29*(May), 113–122. https://doi.org/10.1016/j.erss.2017.05.018.

European Commission. (2020). *Proposal for measures to enhance the protection and resilience of critical infrastructure*. Ref. no: Ares(2020)3202859. Brussels: European Commission, DG HOME, unit D2 Counter-Terrorism. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=pi_com:Ares(2020)3202859

Fischhoff, B. (1995). Risk Perception and Communication Unplugged: Twenty Years of Process. *Risk Analysis, 15*(2), 137–145.

Florin, M.-V. & Linkov, I. (Eds.) (2016). IRGC resource guide on resilience. Lausanne: EPFL International Risk Governance Center (IRGC).

Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Chapin, T., & Rockström, J. (2010). Resilience thinking: Integrating resilience, adaptability and transformability. *Ecology and Society, 15*(4). https://doi.org/10.5751/ES-03610-150420.

Francis, R., & Bekera, B. (2014). A metric and frameworks for resilience analysis of engineered and infrastructure systems. *Reliability Engineering and System Safety, 121*, 90–103. https://doi.org/10.1016/j.ress.2013.07.004.

Furnham, A. (1986). Response bias, social desirability and dissimulation. *Personality and Individual Differences, 7*(3), 385–400. https://doi.org/10.1016/0191-8869(86)90014-0.

Fusch, P. I., & Ness, L. R. . (2015). Are We There Yet? Data Saturation in Qualitative Research. *The Qualitative Report, 20*(9), 1408–1416. https://doi.org/10.1097/HJH.0b013e32835fd32b.

Given, L. M. (Ed.). (2012). Exploratory Research. In The SAGE Encyclopaedia of Qualitative Research Methods (pp. 327–330). Thousand Oaks: SAGE Publications, Inc.

Government Offices of Sweden. (2015a). *The Swedish model of government administration*. Retrieved May 6, 2020 from: https://www.government.se/how-sweden-is-governed/the-swedish-model-of-government-administration/.

Government Offices of Sweden. (2015b). *Public agencies and how they are governed*. Retrieved May 5, 2020 from: https://www.government.se/how-sweden-is-governed/public-agencies-and-how-they-are-governed/.

Graneheim, U. H., & Lundman, B. (2004). Qualitative content analysis in nursing research: Concepts, procedures and measures to achieve trustworthiness. *Nurse Education Today, 24*(2), 105–112. https://doi.org/10.1016/j.nedt.2003.10.001.

Griot C. (2010). Modelling and simulation for critical infrastructure interdependency assessment: a meta-review for model characterisation. *International Journal of Critital Infrastructure, 6*(4), 363–679.

Große, C., & Olausson, P. M. (2019). Blind spots in interaction between actors in Swedish planning for critical infrastructure protection. *Safety Science, 118*(April), 424–434. https://doi.org/10.1016/j.ssci.2019.05.049.

Gåverud, H., Lundgren, J., & Glimhall, A. (2009). *Ökad andel biogas på en utvecklad gasmarknad: Analys över förutsättningarna för och förslag till en ökad andel biogas på den svenska marknaden* [Increased Share of biogas on A Developed Gas Market]. Eskilstuna: Swedish Energy Markets Inspectorate.

Haimes, Y. Y. (2009a). On the complex definition of risk: A systems-based approach. *Risk Analysis, 29*(12), 1647–1654. https://doi.org/10.1111/j.1539-6924.2009.01310.x.

Haimes, Y. Y. (2009b). On the definition of resilience in systems. *Risk Analysis, 29*(4), 498–501. https://doi.org/10.1111/j.1539-6924.2009.01216.x.

Hall, P. (2015). The Swedish Administrative Model. In J. Pierre (Ed.), Oxford Handbook of Swedish Politics. Oxford: Oxford University Press.

Hallingberg, B., Turley, R., Segrott, J., Wight, D., Craig, P., Moore, L., Murphy, S., Robling, M., Simpson, S. A., and Moore, G. (2018). Exploratory studies to decide whether and how to proceed with full-scale evaluations of public health interventions: A systematic review of guidance. *Pilot and Feasibility Studies, 4*(104).

Hansson, S. O. (2010). Risk: Objective or subjective, facts or values. *Journal of Risk Research, 13*(2), 231–238. https://doi.org/10.1080/13669870903126226.

Hassel, H., & Cedergren, A. (2019). Exploring the conceptual foundation of continuity management in the context of societal safety. *Risk Analysis, 39*(7), 1503–1519. https://doi.org/10.1111/risa.13263.

Hedlund, C., Lodin, C., & Montelius, A. (2018). *Arbete och normer för driftsäkra elektroniska kommunikationer*. Stockholm: Post- och Telestyrelsen (PTS).

Heinimann, H. R., & Hatfield, K. (2017). Infrastructure Resilience Assessment, Management and Governance – State and Perspectives. In I. Linkov & J. M. Palma-Oliveira (Eds.), *Resilience and Risk* (pp. 147–187). Dordrecht: Springer.https://doi.org/10.1007/978-94-024-1123-2.

Helfgott, A. (2018). Operationalising systemic resilience. *European Journal of Operational Research*, *268*, 852–864. https://doi.org/10.1016/j.ejor.2017.11.056.

Hickford, A. J., Blainey, S. P., Ortega Hortelano, A., & Pant, R. (2018). Resilience engineering: theory and practice in interdependent infrastructure systems. *Environment Systems and Decisions, 38*(3), 278–291. https://doi.org/10.1007/s10669-018-9707-4.

Hiteva, R., & Watson, J. (2019). Governance of interactions between infrastructure sectors: The making of smart grids in the UK. *Environmental Innovation and Societal Transitions, 32*, 140–152. https://doi.org/10.1016/j.eist.2019.02.006.

HM Government. (2015). *National Security Strategy and Strategic Defence and Security Review 2015*.

Holand, I. S. (2015). Lifeline Issue in Social Vulnerability Indexing: A Review of Indicators and Discussion of Indicator Application. *Natural Hazards Review, 16*(3). https://doi.org/10.1061/(ASCE)NH.1527-6996.0000148.

Hosseini, S., Barker, K., & Ramirez-Marquez, J. E. (2016). A review of definitions and measures of system resilience. *Reliability Engineering and System Safety, 145*, 47–61. https://doi.org/10.1016/j.ress.2015.08.006.

Hsieh, H. F., & Shannon, S. E. (2005). Three approaches to qualitative content analysis. *Qualitative Health Research, 15*(9), 1277–1288. https://doi.org/10.1177/1049732305276687.

Hufty, M. (2011). Governance: Exploring Four Approaches and Their Relevance to Research. In U. Wiesmann & H. Hurni (Eds.) *Research for Sustainable Development: Foundations, Experiences, and Perspectives* (pp. 165–183). Bern: Geographica Bernensia.

IRGC. (2005). *Risk Governance: Towards an integrative approach*. Geneva: International Risk Governance Council (IRGC). https://doi.org/10.1093/acrefore/9780190228613.013.246.

IRGC. (2017). *Introduction to the IRGC Risk Governance Framework, revised version.* Lausanne: EPFL International Risk Governance Centre.

IRGC. (2018). IRGC Guidelines for the Governance of Systemic Risks. Lausanne: International Risk Governance Center (IRGC).

Jacobsson, B., & Sundström, G. (2015). Governing the State. In J. Pierre (Ed.), *The Oxford Handbook of Swedish Politics*. Oxford: Oxford University Press.

Janesick, V. J. (2015). Peer Debriefing. In G. Ritzer (Ed.) *The Blackwell Encyclopedia of Sociology*, 2–3. Hoboken: John Wiley & Sons. https://doi.org/10.1002/9781405165518.wbeosp014.pub2.

Johansson, J. (2010). *Risk and Vulnerability Analysis of Large-Scale Technical Infrastructures: Addressing Socio-Technical Systems* (Doctoral dissertation, Faculty of Engineering, Lund University, Lund, Sweden) Retrieved from https://www.iea.lth.se/publications/Theses/LTH-IEA-1061.pdf.

Johansson, J., & Hassel, H. (2010). An approach for modelling interdependent infrastructures in the context of vulnerability analysis. *Reliability Engineering and System Safety, 95*(12), 1335–1344. https://doi.org/10.1016/j.ress.2010.06.010.

Johansson, J., Hassel, H., Cedergren, A., Svegrup, L., & Arvidsson, B. (2015). Method for describing and analysing cascading effects in past events: Initial conclusions and findings. In L. Podofillini, B. Sudret, B. Stojadinovic, E. Zio, and W. Kröger (Eds.)

Safety and Reliability of Complex Engineered Systems: Proceedings of the 25th European Safety and Reliability Conference, ESREL2015. Zürich: CRC Press.

Johansson, J., Hassel, H., & Zio, E. (2013). Reliability and vulnerability analyses of critical infrastructures: Comparing two approaches in the context of power systems. *Reliability Engineering and System Safety, 120*, 27–38. https://doi.org/10.1016/j.ress.2013.02.027.

Kaplan, S., & Garrick, B. J. (1981). On The Quantitative Definition of Risk. *Risk Analysis, 1*(1), 11–27. https://doi.org/10.1093/annhyg/24.2.245.

Kaufman, G. G., & Scott, K. E. (2003). What is systemic risk, and do bank regulators retard or contribute to it? *Independent Review, 7*(3), 371–391.

Klinke, A., & Renn, O. (2002). A new approach to risk evaluation and management: Risk-based, precaution-based, and discourse-based strategies. *Risk Analysis, 22*(6), 1071–1094. https://doi.org/10.1111/1539-6924.00274.

Kooiman, J. (2003). *Governing as governance.* Thousand Oaks: Sage Publications. https://www.doi.org/10.4135/9781446215012.

Kröger, W. (2008). Critical infrastructures at risk: A need for a new conceptual approach and extended analytical tools. Reliability *Engineering and System Safety, 93*(12), 1781–1787. https://doi.org/10.1016/j.ress.2008.03.005.

Labaka, L., Hernantes, J., & Sarriegi, J. M. (2016). A holistic framework for building critical infrastructure resilience. *Technological Forecasting and Social Change, 103*, 21–33. https://doi.org/10.1016/j.techfore.2015.11.005.

Lantz, A. (1993). *Intervjumetodik*. Lund: Studentlitteratur.

LaRocca, S., Johansson, J., Hassel, H., & Guikema, S. (2015). Topological Performance Measures as Surrogates for Physical Flow Models for Risk and Vulnerability Analysis for Electric Power Systems. *Risk Analysis, 35*(4), 608–623. https://doi.org/10.1111/risa.12281.

Leech, B. L. (2002). Asking questions: Techniques for semistructured interviews. *PS: Political Science and Politics, 35*(4), 665–668. https://doi.org/10.1017/S1049096502001129.

Levac, D., Colquhoun, H., & O'Brien, K. K. (2010). Scoping studies: advancing the methodology. *Implementation Science, 5*(68). https://doi.org/10.1186/1748-5908-5-69.

Levy, J. S. (1994). Learning and Foreign Policy: Sweeping a Conceptual Minefield. *International Organization, 48*(2), 279–312.

Linkov, I., Bridges, T., Creutzig, F., Decker, J., Fox-Lent, C., Kröger, W., … Thiel-Clemen. (2014). Changing the resilience paradigm. *Nature Climate Change, 4*, 407–409.

Little, R. G. (2002). Toward more robust infrastructure: Observations on improving the resilience and reliability of critical systems. In *Proceedings of the 36th Annual Hawaii International Conference on System Sciences, HICSS 2003* (pp. 58–66). IEEE. https://doi.org/10.1109/HICSS.2003.1173880.

Long, T., & Johnson, M. (2000). Reliability and Validity in Qualitative Research. *Clinical Effectiveness in Nursing, 4*, 30–37. https://doi.org/10.4135/9781412986182.n15.

Marana, P., Labaka, L., & Sarriegi, J. M. (2018). A framework for public-private-people partnerships in the city resilience-building process. *Safety Science, 110*, 39–50. https://doi.org/10.1016/j.ssci.2017.12.011.

Mays, N. , Roberts, E. ., & Popay, J. (2001). Synthesising research evidence. In N. . Fulop, P. . Allen, A. . Clark, & N. Black (Eds.), *Studying the organization and delivery of health services: research methods* (Vol. 194). London: Routledge.

McDaniels, T., Chang, S., Peterson, K., Mikawoz, J., & Reed, D. (2007). Empirical Framework for Characterizing Infrastructure Failure Interdependencies. *Journal of Infrastructure Systems, 13*(3), 175–184. https://doi.org/10.1061/(asce)1076-0342(2007).

Nederhof, A. J. (1985). Methods of coping with social desirability bias: A review. European *Journal of Social Psychology, 15(*3), 263–280. https://doi.org/https://doi.org/10.1002/ejsp.2420150303.

Neuendorf, K. A. (2019). Content analysis and thematic analysis. In P. Brough (Ed.), *Research methods for applied psychologists: Design, analysis and reporting* (pp. 211–223). New York: Routledge. https://doi.org/10.4324/9781315517971-21.

NIAC. (2009*). Critical Infrastructure Resilience: Final Report and Recommendations*.

Normandin, J. M., & Therrien, M. C. (2016). Resilience Factors Reconciled with Complexity: The Dynamics of Order and Disorder. *Journal of Contingencies and Crisis Management, 24*(2), 107–118. https://doi.org/10.1111/1468-5973.12107.

Næss, L. O., Bang, G., Eriksen, S., & Vevatne, J. (2005). Institutional adaptation to climate change: Flood responses at the municipal level in Norway. *Global Environmental Change, 15*(2), 125–138. https://doi.org/10.1016/j.gloenvcha.2004.10.003.

O'Brien, K. K., Colquhoun, H., Levac, D., Baxter, L., Tricco, A. C., Straus, S., … O'Malley, L. (2016). Advancing scoping study methodology: a web-based survey and consultation of perceptions on terminology, definition and methodological steps. *BMC Health Services Research, 16*(305). https://doi.org/10.1186/s12913-016-1579-z.

OECD. (2003). *Emerging Risks in the 21st.* Paris: OECD Publishing.

OECD. (2010). *Risk and Regulatory Policy: Improving the governance of risk*. Paris: OECD Publishing. https://doi.org/10.1787/9789264082939-en.

OECD. (2019). *Good Governance for Critical Infrastructure Resilience.* Paris: OECD Publishing.

O'Rourke, T. D. (2007). Critical Infrastructure, Interdependencies, and Resilience. *The Bridge – National Academy of Engineering, 37*(1), 365–386. https://doi.org/10.1061/9780784412824.ch10.

Ottino, J. M. (2004). Engineering complex systems. *Nature, 427*, 399. https://doi.org/10.1038/427399a.

Oughton, E. J., Usher, W., Tyler, P., & Hall, J. W. (2018). Infrastructure as a Complex Adaptive System. *Complexity, 2018*, 11–14. https://doi.org/10.1155/2018/3427826.

Ouyang, M. (2014). Review on modeling and simulation of interdependent critical infrastructure systems. *Reliability Engineering and System Safety, 121*, 43–60. https://doi.org/10.1016/j.ress.2013.06.040.

Padilla, J. J., Diallo, S. Y., & Tolk, A. (2011). *Do We Need M & S Science?, 4*, 161–166.

Pannucci, C. J., & Wilkins, E. G. (2010). Identifying and avoiding bias in research. *Plastic and Reconstructive Surgery, 126*(2), 619–625. https://doi.org/10.1097/PRS.0b013e3181de24bc.

Park, J., Seager, T. P., Rao, P. S. C., Convertino, M., & Linkov, I. (2013). Integrating risk and resilience approaches to catastrophe management in engineering systems. *Risk Analysis, 33*(3), 356–367. https://doi.org/10.1111/j.1539-6924.2012.01885.x.

Peters, M. D. J., Godfrey, C. M., Khalil, H., McInerney, P., Parker, D., & Soares, C. B. (2015). Guidance for conducting systematic scoping reviews. International Journal of Evidence-Based Healthcare, 13(3). http://doi.org/10.1097/XEB.0000000000000050.

Pescaroli, G., & David, A. (2015). A definition of cascading disasters and cascading effects: Going beyond the " toppling dominos " metaphor. *Planet@Risk, 3*(1), 58–67.

Pham, M. T., Rajic, A., Greig, J. D., Sargeant, J. M., Papadopoulos, A., & McEwen, S. A. (2014). A scoping review of scoping reviews: advancing the approach and enhancing the consistency. *Research Synthesis Methods, 5*(4), 371–385. https://doi.org/10.1002/jrsm.1123.

Pumpuni-Lenss, G., Blackburn, T., & Garstenauer, A. (2017). Resilience in Complex Systems: An Agent-Based Approach. *Systems Engineering, 20*(2), 158–172. https://doi.org/10.1002/sys.21387.

Pursiainen, C. (2018). Critical infrastructure resilience: A Nordic model in the making? International Journal of Disaster Risk Reduction, 27(653390), 632–641. https://doi.org/10.1016/j.ijdrr.2017.08.006.

Rehak, D., Senovsky, P., Hromada, M., & Lovecek, T. (2019). Complex approach to assessing resilience of critical infrastructure elements. *International Journal of Critical Infrastructure Protection, 25*, 125–138. https://doi.org/10.1016/j.ijcip.2019.03.003.

Renn, O. (1998). Three decades of risk research: Accomplishments and new challenges. *Journal of Risk Research, 1*(1), 49–71. https://doi.org/10.1080/136698798377321.

Renn, O., & Klinke, A. (2015). Risk Governance and Resilience: New Approaches to Cope with Uncertainty and Ambiguity. In U. Fra.Paleo (Ed.), *Risk Governance: The Articulation of Hazard, Politics and Ecology* (pp. 19–41). Dordrecht: Springer. https://doi.org/10.1007/978-94-017-9328-5.

Renn, O., Klinke, A., & Van Asselt, M. (2011). Coping with complexity, uncertainty and ambiguity in risk governance: A synthesis. *Ambio, 40*(2), 231–246. https://doi.org/10.1007/s13280-010-0134-0.

Renn, O., & Schweizer, P. J. (2009). Inclusive risk governance: Concepts and application to environmental policy making. *Environmental Policy and Governance, 19*(3), 174–185. https://doi.org/10.1002/eet.507.

Rhodes, R. A. W. (1996). The New Governance: Governing without Government '. *Political Studies, 44*(4), 652–667.

Rhodes, R.A.W. (1997) *Understanding governance: policy networks, governance, reflexivity and accountability.* Philadelphia: Open University.

Rhodes, R. A. W. (2012). Waves Of Governance. In D. Levi-Faur (Ed.) *The Oxford Handbook of Governance*. Oxford: Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199560530.013.0003.

Righi, A. W., Saurin, T. A., & Wachs, P. (2015). A systematic literature review of resilience engineering: Research areas and a research agenda proposal. *Reliability Engineering and System Safety, 141*, 142–152. https://doi.org/10.1016/j.ress.2015.03.007.

Rinaldi, S. M., Peerenboom, J. P., & Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems Magazine, 21*(6), 11–25. https://doi.org/10.1109/37.969131.

Ruhanen, L., Scott, N., Ritchie, B., & Tkaczynski, A. (2010). Governance: a review and synthesis of the literature. *Tourism Review, 65*(4), 4–16. https://doi.org/10.1108/16605371011093836.

Rydén Sonesson, T., and Johansson, J. (2019). Modeling National Interdependent Critical Infrastructures: Application and Discussion for the Swedish Power and Internet Backbone. In M. Beer and E. Zio (Eds.) *Proceedings of the 29th European Safety and Reliability Conference*, ESREL 2019, Hannover, Germany, 22-16 September.

Rydén Sonesson, T., Johansson, J., and Cedergren, A. (2020). Exploring assessment and management of critical infrastructure interdependencies: A scoping review. Manuscript submitted for publication.

Rød B., Johansson, J. (2020). *Critical Infrastructures – How resilient are they?* Manuscript submitted for publication.

Satumtira, G., & Dueñas-Osorio, L. (2010). Synthesis of Modeling and Simulation Methods on Critical Infrastructure Interdependencies Research. In K. Gopalakrishnan & S. Peeta (Eds.), *Sustainable and Resilient Critical Infrastructure Systems*. Berlin, Heidelberg: Springer. https://doi.org/https://doi.org/10.1007/978-3-642-11405-2_1.

Schweizer, P. J. (2019). Systemic risks – concepts and challenges for risk governance. *Journal of Risk Research*, 1–16. https://doi.org/10.1080/13669877.2019.1687574.

SFS 2003:389. *Lag* (2003:389) *om elektronisk kommunikation*. Ministry of Infrastructure. https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/lag-2003389-om-elektronisk-kommunikation_sfs-2003-389.

SFS 2008:1002. *Förordning* (2008:1002) *med instruktion för Myndigheten för samhällsskydd och beredskap* [Ordinance with intructions to the Swedish Civil Contingencies Agency]. Ministry of Justice. Retrived from https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/forordning-20081002-med-instruktion-for_sfs-2008-1002.

SFS 2015:1052. *Förordning (2015:1052) om krisberedskap och bevakningsansvariga myndigheters åtgärder vid höjd beredskap*. Ministry of Justice. Retrieved from https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/forordning-20151052-om-krisberedskap-och_sfs-2015-1052.

SFS 2017:842. *Förordning om ändring i förordningen (2010:185) med instruktion för Trafikverket* [Ordinance About Changes to Ordinance (2010:185) With Instructions To the Swedish Transport Administration]. Stockholm: Ministry of Enterprise and Innovation.

SFS 2018:585. *Säkerhetsskyddslag* [Protective Security Act]. Stockholm: Ministry of Justice. https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/sakerhetsskyddslag-2018585_sfs-2018-585.

Singh, K. (2015). Research Process. In Quantitative Social Research Methods (pp. 62–87). New Delhi: SAGE Publications India Pvt Ltd.

Slovic, P. (1987). Perception of Risk. *Science, 236*(4799), 280–285.

SOU 2001:41. Säkerhet i en ny tid: Sårbarhets- och säkerhetsutredningen [Security in new times: Vulnerability and safety investigations]. Stockholm: Ministry of Defence.

SOU 2018:82. *Kompletteringar till den nya säkerhetsskyddslagen: Sammanfattning på svenska och engelska* [Supplements to the new Protective Security Act: Summary in Swedish and English]. Stockholm: Ministry of Justice. https://www.regeringen.se/rattsliga-dokument/statens-offentliga-utredningar/2018/11/sou-201882/.

SOU 2021:25. *Struktur för ökad motståndskraft: Slutbetänkande av Utredningen om civilt försvar* [Structure for Increased Resistance: Final Report of the Investigation on the Civil Defence]. Stockholm: Statens offetliga utredningar. Stockholm: Ministry of Justice. https://riksdagen.se/sv/dokument-lagar/dokument/statens-offentliga-utredningar/sou-2021-25-_H9B325.

SSNF. (2020). *Fakta om de svenska stadsnäten – en statistikrapport april 2020* [Facts about the Swedish Metropolitan Area Networks – A statistical report April 2020]. Stockholm: Swedish Local Fibre Alliance (SSNF).

Stebbins, R. A. (2001). *Exploratory research in the social sciences*. Thousand Oaks: Sage Publications.

Sterbenz, J. P. G., Hutchison, D., Çetinkaya, E. K., Jabbar, A., Rohrer, J. P., Schöller, M., & Smith, P. (2010). Resilience and survivability in communication networks: Strategies, principles, and survey of disciplines. *Computer Networks, 54*(8), 1245–1265. https://doi.org/10.1016/j.comnet.2010.03.005.

Stoker, G. (1998). Governance as theory: five propositions. *International social science journal, 50*(155), 17-28.

Svegrup, L., Johansson, J., & Hassel, H. (2016). Capturing societal interdependencies from a flow perspective Part II: Application. In L. Walls, R. Revie & T. Bedford (Eds.), *Risk, Reliability and Safety: Innovating Theory and Practice: Proceedings of the 26th European Safety and Reliability Conference, ESREL 2016*. Glasgow: CRC Press.

Svegrup, L., Johansson, J., & Hassel, H. (2019). Integration of Critical Infrastructure and Societal Consequence Models: Impact on Swedish Power System Mitigation Decisions. *Risk Analysis*. https://doi.org/10.1111/risa.13272.

SWD(2012) 190 final. *Review of the European programme for critical infrastructure protection (EPCIP)*. [Commission staff document]. Brussels: European Commission.

SWD(2013) 318 final. *A new approach to the European Programme for Critical Infrastructure Protection Making European Critical Infrastructures more secure*. [Commission staff document] Brussels: European Commission.

SWD(2019) 308 final. *Evaluation of council directive 2008/114 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection*. [Commission staff document]. Brussels: European Commission.

Swedish Agency for Public Management. (2005). *Six deregulations: Liberalisation of the markets for electricity, postal services, telecommunications, domestic air traffic, rail and taxi services in Sweden* (No. 2005:8). Stockholm. Retrieved from the Swedish Agency for Public Management's website: https://www.statskontoret.se/globalassets/publikationer/2000-2005-english/200508.pdf.

Swedish Agency for Public Management. (2020). *Fakta om statsförvaltningen* [Facts on the Swedish public administration]. Retrieved April 22, 2021, from https://www.statskontoret.se/var-verksamhet/forvaltningspolitikens-utveckling/arliga-uppfoljningar/.

Swedish Association of Local Authorities and Regions. (n.d.). *Municipalities and regions*. Retrieved May 6, 2020 from: https://skr.se/tjanster/englishpages/municipalitiesandregions.1088.html.

Swedish Aviation Administration. (2021). *Frågor & svar*. Retrieved April 21, 2021, from https://www.lfv.se/om-oss/fragorsvar.

Swedish Civil Contingencies Agencies (MSB). (2011). *Ett fungerande samhälle i en föränderlig värld* [A functioning society in a changing world: National strategy on critical infrastructure protection]. Karlstad.

Swedish Civil Contingencies Agency (MSB). (2013). *Handlingsplan för skydd av samhällsviktig verksamhet* [Action plan for the protection of critical infrastructure]. https://www.msb.se/contentassets/d8fca23b124c4686a629970fd2c1aa31/handlingsplan-for-skydd-av-samhallsviktig-verksamhet.pdf.

Swedish Civil Contingencies Agencies (MSB). (2014). *Action Plan for the Protection of Vital Societal Functions & Critical Infrastructure*. Retrieved from https://www.msb.seRibData/Filer/pdf/27412.pdf.

Swedish Civil Contingencies Agency (MSB). (2018). *Systematiskt arbete med skydd av samhällsviktig verksamhet: Stöd för arbete med riskhantering, kontinuitetshantering och att hantera inträffade händelser* [Systematic Critical Infrastructure Protection: A Support for Risk Management, Continuity Management and Managing Past Events]. Karlstad.

Swedish Civil Contingencies Agency (MSB). (2020a). *Uppdaterad definition samhällsviktig verksamhet* [Updated critical infrastructure definiton] [Memorandum]. Karlstad. https://www.msb.se/sv/amnesomraden/krisberedskap--civilt-forsvar/samhallets-funktionalitet/vad-ar-samhallsviktig-verksamhet/.

Swedish Civil Contingencies Agency (MSB). (2020b). *Vad är samhällsviktig verksamhet?* [What are critical infrastructures?]. Retrieved March 30, 2021, from

Swedish Civil Contingencies Agency (MSB). (2020c). *EU and critical infrastructure protection.* Retrieved March 31, 2021, from https://www.msb.se/en/about-msb/international-co-operation/cooperation-with-eu/eu-and-protection-of-essential-services/.

Swedish Consumer Energy Markets Bureau. (2020a). *Gasmarknaden i Sverige* [The Gas Market in Sweden]. Retrieved April 22, 2021, from https://www.energimarknadsbyran.se/gas/gasmarknaden-i-sverige/.

Swedish Consumer Energy Markets Bureau. (2020b). *Vad är fjärrvärme?* [What Is District Heating?]. Retrieved April 22, 2021, from https://www.energimarknadsbyran.se/fjarrvarme/vad-ar-fjarrvarme/.

Swedish Defence University. (2019). Förutsättningar för krisberedskap och totalförsvar i Sverige [Conditions for Swedish crisis prepardness and total defence]. (E. Andersson, Ed.). Stockholm, Sweden.

Swedish Energy Agency. (2016). *Handledning för beredskapslagring av olja* [Guide for Oil Emergency Stockpiling]. ISSN 1404-3343. Eskilstuna: Swedish Energy Agency.

Swedish Energy Agency. (2020). *Energiläget 2020* (ET 2020:1). ISSN 1404-3343. Eskilstuna: Swedish Energy Agency. Retrieved April 22, 2021 from http://www.energimyndigheten.se/nyhetsarkiv/2020/energilaget-2020---en-samlad-bild-pa-energiomradet-i-sverige/.

Swedish Energy Markets Inspectorate. (2021a). *Aktörerna på energimarknaderna* [The Actors on the Energy Markets]. Retrieved April 21, 2021, from https://ei.se/konsument/aktorerna-pa-energimarknaderna.

Swedish Energy Markets Inspectorate. (2021b). *The Swedish Natural Gas System Structure*. Retrieved April 22, 2021, from https://ei.se/ei-in-english/natural-gas/the-swedish-natural-gas-system-structure.

Swedish Maritime Administration. (2013). *New ways. New opportunities. Together. An introduction to the services and activities of the Swedish Maritime Administration*. Norrköping: Swedish Maritime Administration. Retrieved January 20, 2020 from the Swedish Maritime Administration's website: https://www.sjofartsverket.se/upload/Pdf-Gemensamma-Eng/VerksbroschyrEngelsk2013.pdf.

Swedish Regional Airports. (2021). *Om oss* [About us]. Retrieved from https://www.flygplatser.se/om-oss/.

Swedish Transport Agency. (2017). This is the Swedish Transport Agency, publication. no. TS2 201731, Borlänge: Swedish Transport Agency.

Swedish Transport Administration. (2017). *Drift av vägfärjetrafiken* [Shuttle-ferry Operations]. Retrieved April 21, 2021, from https://www.trafikverket.se/resa-och-trafik/vag/Sveriges-vagnat/Drift-av-farjetrafiken/.

Swedish Transport Administration. (2020). *Sveriges vägnät* [Sweden's Road Network]. Retrieved April 21, 2021, from https://www.trafikverket.se/resa-och-trafik/vag/Sveriges-vagnat/.

Swedish Transport Administration. (2021). *Järnkoll på spåren* [A close eye on the tracks]. Retrieved April 21, 2021, from https://www.trafikverket.se/resa-och-trafik/jarnvag/jarnkoll--fakta-om-den-svenska-jarnvagen/jarnkoll-pa-sparen/.

Thacker, S., Pant, R., & Hall, J. W. (2017). System-of-systems formulation and disruption analysis for multi-scale critical national infrastructures. *Reliability Engineering and System Safety, 167*, 30–41. https://doi.org/10.1016/j.ress.2017.04.023.

Therrien, M. C., & Normandin, J. M. (2020). From Policy Challenge to Implementation Strategy: Enabling Strategies for Network Governance of Urban Resilience. *Risk, Hazards and Crisis in Public Policy, 9*(2). https://doi.org/10.1002/rhc3.12192.

Treib, O., Bähr, H., & Falkner, G. (2007). Modes of governance: Towards a conceptual clarification. *Journal of European Public Policy, 14*(1), 1–20. https://doi.org/10.1080/135017606061071406.

Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K., Colquhoun, H., Kastner, M., … Straus, S. E. (2016). A scoping review on the conduct and reporting of scoping reviews. *BMC Medical Research Methodology, 16*(15). https://doi.org/10.1186/s12874-016-0116-4.

Tripodi, S., and Bender, K. (2019). In B. Thyers (Ed.) The Handbook of Social Work Research Methods (pp. 120–130). Thousand Oaks: SAGE Publications, Inc.

Tøndel, I. A., Foros, J., Kilskar, S. S., Hokstad, P., & Jaatun, M. G. (2018). Interdependencies and reliability in the combined ICT and power system: An overview of current research. *Applied Computing and Informatics, 14*(1), 17–27. https://doi.org/10.1016/j.aci.2017.01.001.

van Asselt, M. B. A., & Renn, O. (2011). Risk governance. *Journal of Risk Research, 14*(4), 431–449. https://doi.org/10.1007/978-94-007-1433-5_44.

van Asselt, M. B. A., Vos, E., & Wildhaber, I. (2015). Some reflections on EU governance of critical infrastructure risks. *European Journal of Risk Regulation, 6*(2), 185–190. https://doi.org/10.1017/S1867299X00004487.

van der Merwe, S. E., Biggs, R., & Preiser, R. (2018). A framework for conceptualizing and assessing the resilience of essential services produced by socio-technical systems. *Ecology and Society, 23*(2). https://doi.org/10.5751/ES-09623-230212.

van Eeten, M., Nieuwenhuijs, A., Luiijf, E., Klaver, M., & Cruz, E. (2011). The state and the threat of cascading failure across critical infrastructures: The implications of empirical evidence from media incident reports. *Public Administration, 89*(2), 381–400. https://doi.org/10.1111/j.1467-9299.2011.01926.x.

Vaismoradi, M., Turunen, H., & Bondas, T. (2013). Content analysis and thematic analysis: Implications for conducting a qualitative descriptive study. *Nursing and Health Sciences, 15*(3), 398–405. https://doi.org/10.1111/nhs.12048.

Vespignani, A. (2010). Complex networks: The fragility of interdependency. *Nature, 464*, 984–985. https://doi.org/10.1038/464984a.

Walker, B., Abel, N., Anderies, J. M., & Ryan, P. (2009). Resilience, adaptability, and transformability in the Goulburn-Broken Catchment, Australia. *Ecology and Society, 14*(1). https://doi.org/10.5751/ES-02824-140112.

Walker, B., & Salt, D. (2012). *Resilience Practice: Building Capacity to Absorb Disturbance and Maintain Function* (1st ed.). Washington, DC: Island Press. https://doi.org/https://doi.org/10.5822/978-1-61091-231-0.

Walker, J., & Cooper, M. (2011). Genealogies of resilience. *Security Dialogue, 42*(2), 143–160. https://doi.org/10.1177/0967010611399616.

Werner, S. (2017). District heating and cooling in Sweden. *Energy, 126*, 419–429. https://doi.org/10.1016/j.energy.2017.03.052.

Whiting, L. S. (2008). Semi-structured interviews : guidance for novice researchers. *Nursing Standard, 22*(23), 35–40. http://doi.org/10.7748/ns2008.02.22.23.35.c6420.

Wimelius, M. E., & Engberg, J. (2015). Crisis Management through Network Coordination: Experiences of Swedish Civil Defence Directors. *Journal of Contingencies and Crisis Management, 23*(3), 129–137. https://doi.org/10.1111/1468-5973.12s048.

Woods, D. D. (2015). Four concepts for resilience and the implications for the future of resilience engineering. *Reliability Engineering and System Safety, 141*, 5–9. https://doi.org/10.1016/j.ress.2015.03.018.

Zimmerman, R., & Restrepo, C. E. (2009). Analyzing cascading effects within infrastructure sectors for consequence reduction. In *2009 IEEE Conference on Technologies for Homeland Security, HST 2009* (pp. 165–170). Waltham, MA, United States: IEEE. https://doi.org/10.1109/THS.2009.5168029.

Zorn, C. R., & Shamseldin, A. Y. (2015). Post-disaster infrastructure restoration: A comparison of events for future planning. *International Journal of Disaster Risk Reduction, 13*, 158–166. https://doi.org/10.1016/j.ijdrr.2015.04.004.