

# Critical Infrastructure Resilience

- Comparing Swedish critical infrastructures based on interruption data

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**Lund 2018**

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**Number of pages:** 221

**Illustrations:** Elsa Axelsdóttir & Rasmus Jonason Bjärenstam

### Keywords

critical infrastructure, resilience assessment, resilience metrics, resilience analysis, Sweden, spatial planning

### Abstract

Today's modern societies are becoming increasingly dependent on the vital societal functions that technical critical infrastructures provide, for example availability of electricity, tap water and internet connectivity. Hence, it is of essence that these infrastructures are resilient to interruptions.

The purpose of this thesis is to investigate and contrast resilience levels of different types of technical critical infrastructures in Sweden. A generic resilience assessment approach is developed that utilises interruption data, as given by data on duration and consequence of failures that are gathered by infrastructure owners. This interruption data is used as a measure to indicate the level of 'functionality' of each infrastructure over a given duration. When the functionality is analysed over time, a so called 'resilience curve' can be derived. These resilience curves for different infrastructures are then used as basis to contrast and compare resilience levels achieved by the different infrastructures.

The resilience assessment approach has successfully been applied to interruption data, enabling objective quantifications in a unified manner, for eight different Swedish critical infrastructures. The results reveal that the Swedish electricity transmission system is most resilient. Least resilient, with a great margin, is railway transport system. Second least resilient infrastructure is the electricity distribution system. The rest of the infrastructures, water supply system, road transport system and telecommunication systems with regard to mobile communication, broadband services and fixed telephony, lies between these three, but all relatively on similar levels.

Examples are given for the possible fields of usage with respect to the suggested approach and the presented results. It is concluded that the results produced by the approach could be useful in risk management processes and related work within spatial planning or societal safety. The possibility to measure resilience as a function of time in a unified manner across different types of infrastructures, enables comparisons between the infrastructures. Such information could be used as a basis for decision makers to e.g. evaluate policy and mitigation decisions.

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Avdelningen för Riskhantering och samhällssäkerhet, Lunds tekniska högskola, Lunds universitet, Lund 2018.

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# PREFACE

This master thesis marks our final moment in concluding our education at LTH - Lund University. Elsa Axelsdóttir is concluding the M.Sc. program in Risk Management and Safety Engineering at the Division of Risk Management and Societal Safety; and Rasmus Jonason Bjärenstam is concluding both the B.Sc. program in Fire Protection Engineering at the Division of Fire Safety Engineering and the M.Sc. program in Risk Management and Safety Engineering at the Division of Risk Management and Societal Safety.

Our sincerest appreciations to our supervisor Jonas Johansson, Associate Professor at the Division of Risk Management and Societal Safety, for all his valuable assistance, and commentary throughout the thesis work.

This work would not have been possible without gaining access to interruption data for the different types of critical infrastructures within Sweden. The number of responses exceeded our expectations and we are thankful to the employee(s) at the respective actor for allocating time in their busy schedule to answer our e-mails in our inquiries for interruption data.

We are especially grateful to those actors and contact persons that provided us with interruption data of which the resilience analysis of this thesis is based upon. Furthermore, for answering any additional questions that came up. These actors and respective contact person(s) are the following:

- Svenska kraftnät, Hampus Bergquist
- Energiföretagen, Matz Tapper
- Trafikverket, Elena Karanova and Fredrik Möller (Road data)
- Trafikverket, Anders Nilsson (Railway data)
- Stockholm Vatten och Avfall, Erik Karlsson
- Post- och telestyrelsen, Hans Åkermark and Björn Scharin



# SUMMARY

This thesis aims to investigate and compare resilience levels of different types of technical critical infrastructures in Sweden by utilising interruption data and to discuss how these types of results can be put to real use. To enable such comparisons, a generic resilience assessment approach is developed. The developed approach is tested and verified by applying it on interruption data from several different infrastructures. The scope is limited to Swedish technical critical infrastructures, of which we have analysed data from the electricity transmission system, several electricity distribution systems, the national road transportation system, the national railway transportation system, the largest water supply system in Sweden and telecommunication systems; where the telecommunication systems has been split up into three sub-infrastructures with respect to mobile communication, fixed telephony and broadband services. The study has been carried out as a quantitative empirical data analysis. The data gathering process was a significant part of the conducted work, which was made through emails, phone calls and online meetings.

To analyse resilience based on interruptions two fundamental metrics are necessary, the duration of the disruption and the system functionality loss during the disruption. Interruptions are most often logged with a calendar duration, specified by start and end date times of the interruption, normally with an accuracy of whole minutes, is used to derive the duration metric. Further, interruptions are normally logged with some kind of consequence parameter, e.g. number of customers not served. The consequence parameter divided by a total system ‘baseline’ is used to derive the functionality loss metric, i.e. depicting how big part of the system that was affected by the interruption. Interruptions that had been logged by infrastructure owners but lacked the fundamental information to derive these two metrics had to be omitted. The developed resilience assessment approach takes a national systems perspective, where all interruptions for a given type of infrastructure are deemed to put a strain on a national system. This is done by aggregating all individual interruptions from several systems belonging to one type of infrastructure, e.g. interruption data from several different electricity distribution systems were aggregated into a national electricity distribution infrastructure. Then the national system functionality can be plotted over time as ‘resilience curves’. These curves/plots are then used as the main source for subsequent analyses.

The resilience assessment approach has successfully been applied on real-life infrastructure interruption data, sometimes covering several years, to measure and compare their respective level of resilience. The results reveal that electricity transmission system is most resilient. Least resilient, with a great margin, is railway transport system. Second least comes electricity distribution systems. The rest of the infrastructures, water supply system, road transport system

and the telecommunication systems in terms of mobile communication, broadband services and fixed telephony, are slightly less resilient than electricity transmission system, but all on similar levels.

In the thesis ideas are also presented on how the approach can be used to gain further insights about the studied infrastructures, mainly in relation to societal safety, spatial planning and risk management processes. These discussions conclude that knowledge about resilience levels, and how they vary between infrastructures and over time, can be useful, for example to reveal how risk factors and vulnerabilities differs between the infrastructures and how successfully resilience enhancing strategies for one infrastructure might be applicable and used in other infrastructures. As the approach is a retrospective, in the sense that it is based on empirical failure data, the results can be used to reveal the impact of different type of decisions. Is the attained resilience level over the years for a particular infrastructure in line with changes in e.g. legislative regulations or physical changes of the infrastructure? Examples are also given of how such information could potentially aid decision makers in the work with spatial planning, societal safety and risk management.

A significant amount of current research elaborates with the concept of resilience curves and how different characteristics and properties of the resilience can be measured and analysed. To our knowledge however, the presented approach of analysing and contrasting different type of infrastructure resilience levels, through the use of interruption data, has not been addressed in the scientific literature. As such, this thesis has been summarised and accepted as a scientific article, to be published and presented at the *European Safety and Reliability Conference* (ESREL) in the summer of 2018.

# LIST OF ABBREVIATIONS

ADT	Averaged daily traffic
CI	Critical Infrastructure
CRAD	Cause-reported additional-delays
End DT	End Date-Time, refers to specific end (of an interruption) calendar date and 24h-clock time
ENS	Energy Not Supplied
MSB	The Swedish Contingencies Agency (In Swedish: Myndligheten för samhällskydd och beredskap).
RAA	The Resilience Assessment Approach. In the text it refers only to our developed resilience assessment approach.
RADM	Registered additional delay minutes
RMP	Risk Management Process
RVA	Risk and Vulnerability Analysis
RQ	Research Question
Start DT	Start Date-Time, refers to specific start (of an interruption) calendar date and 24h-clock time
SvK	Svenska kraftnät
tCI	Technical Critical Infrastructure
TTS	Total traffic stop
VSF	Vital societal functions



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# 1 INTRODUCTION

## 1.1 BACKGROUND

Today's modern societies are increasingly dependent on critical infrastructures as a continuous supplier of the services we nowadays often take for granted, services that our everyday life in many ways rely on completely. If people more and more often tends to look down on their cell phone than what is going on around them, it is important that the 4G internet is fast enough. All those pages that needs to be swiped through better be loaded fast enough, and before the train arrives. On time! It is also important for the society to lift the eyes for those that might forget, so that at least someone can expect what is needed if, and when, the unexpected happens, so that we all can continue enjoying our train rides and that new app of ours. While living in a society that has taken on the quest and responsibility to protect us, it is of great importance for that society to limit the consequences and enable a swift recovery as possible when that something unexpected happens next.

*'Resilience'*: the ability to bounce back, comes from Latin and is a term that has been used for more than 100 years within medicine disciplines (Macgillivray, 1897). Even though the term is mentioned in a Swedish medical paper as early as 1943 (SAOB, 1957), it takes until 2015 before the word *'resilience'* is found in SAOL<sup>1</sup> (2015). To simplify and clarify, resilience is defined in this thesis as *'the ability to cope with and recover from stress'*. In terms of risk management, emergency preparedness and societal safety, the most common way of interpreting system resilience is that it is a measurable attribute. Given that a system affected by stress, increased resilience is achieved by:

- i) Better absorbing the stress, by reducing the initial impact from a given threat or hazard

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<sup>1</sup> Svenska Akademiens Ordlista (Eng. The Swedish Academy Glossary); a word list which for many acts as the standard of the Swedish language, defining real and correct Swedish words.

- ii) Better recovering from the stress, by decreasing the time until the system is restored again

Most often it is considered that resilience is achieved as a combination of the two (Hosseini, Barker, & Ramirez-Marquez, 2016).

The concept of resilience has had a boost of usage within the different fields of risk management, not least in regard to infrastructures, and specifically critical infrastructures, as well as societal safety. In nature the critical infrastructures in our society are complex and increasingly interdependent (Laugé, Hernantes, & Sarriegi, 2015; Rinaldi, Peerenboom, & Kelly, 2001). The volcanic eruption of Eyjafjallajökull in Iceland, 2010, the devastating impact of Hurricane Katrina, 2005, in New Orleans, USA and the 11/9 terrorist attack in USA in 2001 are only few examples of large scale events involving critical infrastructures that have resulted in large scale societal consequences. Events that, consequently, also exposed their vulnerabilities. However, these kinds of external events are not the only threats that infrastructures are exposed to, as they can originate within as well, as both low and high impact events shape the overall resilience. In the early stage of this thesis, after attaining some empirical interruption data gathered by Swedish authorities, businesses and organisations, it stood clear that the many theories of resilience assessments we had studied were inadequate in relation to the data achieved and our research questions, as they are either

- based on single large-scale kind of events or scenarios, where detailed information about how the system's characteristics is assumed to be known, hence also measured, and/or
- addressing resilience in only one specific type of infrastructure

No approach was found on the subject that assesses both multiple types of infrastructures whilst also addressing a string of different types of small- to large-scale events (Nan & Sansavini, 2017; Panteli, Mancarella, Trakas, Kyriakides, & Hatziargyriou, 2017; Ouyang & Dueñas-Osorio, 2014; MacKenzie & Barker, 2013; Ouyang & Dueñas-Osorio, 2012; Ouyang, Dueñas-Osorio, & Min, 2012; G. P. Cimellaro, Reinhorn, & Bruneau, 2010).

After a large-scale event, such as an earthquake or a flood, in a modern society, there is probably much information to be gathered that justifies many of these resilience theories. However, the more common every day kind of incidents seems to be left out or forgotten. So even if there is much written about resilience assessments on critical infrastructures, there is not much to be found on how to perform large-scale assessments, with large-scale interruption data sets, including low to high impact events. There seem to be a gap in research in how to use the different frameworks and methods for assessing resilience, when the available interruption data does not fit any of the assessment tools and/or methods presented in scientific literature (to our knowledge).

## 1.2 AIM AND PURPOSE

The aim of this thesis is to explore how resilient different technical critical infrastructures are, by analysing real data of disruptive events and failures gathered from different Swedish companies, organisations and authorities. The ambition is to develop a generic approach for measuring resilience based on interruption data, an approach that in a unified manner will define the level of resilience for different types of technical critical infrastructures. The aim is further to analyse the resilience of different Swedish critical infrastructures. This is here done by gathering and analysing interruption data for those critical infrastructures by a generic approach. Assuming that the resilience levels can be defined and measured with the developed approach, the various reasons and sources for the resilience differences can be brought to light. This opens for discussions about those differences and about how such an approach can be utilised. Our ambition is to give some ideas and answers to questions related to what practical opportunities can be derived from an implementation of the approach, and how such knowledge could be utilised within the fields of risk management, societal safety and spatial planning. The intention behind this is to clarify why the concept of resilience is important and how it might be used to increase societal safety and improve the functioning of technical critical infrastructures.

## 1.3 RESEARCH QUESTIONS

The results from this thesis work aims to address three research questions. The main research question (RQ), RQ1 makes the foundation of the thesis and is followed by RQ2 and RQ3.

- RQ1. How can the resilience of different critical infrastructure be measured through empirical interruption data and compared in a unified manner?
- RQ2. How resilient are the different types of critical infrastructures?
- RQ3. How can such results be used as input to the risk management and spatial planning process?

Initially our intention was to also address a fourth research question:

- D. What are plausible explanations for differences and similarities of the resilience levels for different critical infrastructures (e.g. technical aspects, safety cultural aspects, legislative or regulatory aspects)?

However, due to time limitation and underestimations of the work of collection the necessary data and analysis of the data, this question turned out to widen the scope too much. Instead we chose to briefly bring up the topic in the discussion and address possible future research in relation to this question, hoping for someone else to undertake such work in the future (see Chapter 8).

## 1.4 DELIMITATIONS AND LIMITATIONS

Defining resilience from several different comprehensive sets of interruption data have proven difficult and time-consuming, to narrow down to an appropriate scope for the thesis and set some boundaries for what to be expected of the thesis, limitations and delimitations are here clarified.

### 1.4.1 DELIMITATIONS

As resilience is a widely used and it is a multidisciplinary concept, it is important to clarify that in this thesis the concept will be strictly addressed from a ‘Systems Engineering’ perspective. Further, before attempting to obtain interruption data for critical infrastructure we choose to delimit ourselves to technical critical infrastructures, such as: aviation-, railway-, road- and maritime transport, telecommunication and internet, the electric power grid (e.g. electrical transmission and distribution) and water supply. To further narrow the scope down we limit ourselves to technical critical infrastructures within the geographical area of Sweden and aiming for a national infrastructure perspective. The work of this thesis is highly dependent on the possibility to get access to interruption data as our intent is to use empirical interruption data to estimate resilience level of several different infrastructures. It was uncertain from the start for how many infrastructures we would be able to obtain data for. For this reason, we decided to cast a broader net in our search of empirical interruption data to see which actors that collected and could share the type of data of interest to us. For the critical infrastructures that we managed to gain access to interruption data, we only asked for data for the past ten years.

### 1.4.2 LIMITATIONS

The thesis is very much limited to the type and amount of interruption data that can be collected, so depending on how far back the data has been gathered and what parameters that are included in the data, the limitations will vary both in terms of time span and data quality. To develop a generic resilience assessment approach that utilises interruption data to draw conclusions regarding the resilience level of different types of critical infrastructure, possibly in combination with probabilistic theories and perhaps stochastic models, it is obvious that the data quantity and quality will be a limiting factor. Following point gives indication of limiting factors:

- If interruption data is systematically gathered by an actor for some instance and if it is publicly available, the latter as there is a possibility that the data is seen to be of sensitive nature.
- We are limited to the parameters the respective actor collects (e.g. which is normally a reflection of if the data is gathered for internal or regulatory purposes).

- We are further limited to the time span for which the infrastructure actor has been recording interruptions.
- Sample size of the interruption data in terms of the coverage of the critical infrastructure under study (e.g. percentage of the total number of actors within the infrastructure).
- How well the data represents reality, i.e. what are the limitation of the respective actor's data gathering process.
- Geographical scope of the sample data, as there is not always possibility to get access to data that represent the national level.
- How well methods and theory presented in scientific literature that can be applied to the type of real-life data that is gathered.



# 2 THEORETICAL BACKGROUND

A literature review was conducted to get a more in depth understanding of the central concepts and available resilience methods to serve as an inspiration to formulate the Resilience Assessment Approach (RAA) to measure resilience level for different types of critical infrastructures (CIs). The review was targeted mainly towards literature involving quantitative methods to assess resilience of technical CIs by utilising the databases LUBsearch and LOVISA. The following keywords were used: Resilience in different combinations with words like Metric, Assessment, Model, Modelling, Framework, System, Critical Infrastructure, Technical Infrastructure System, Quantitative.

To give a context for the ideas and work in the thesis and to establish a theoretical background for arguments put forward, this chapter will start with an introductive part of underpinning concepts for the thesis (section 2.1). In the second part of the chapter the focus is narrowed towards resilience in the field of engineering (section 2.2), where we present the ideas put forward in relevant academic literature regarding assessing resilience of CIs, followed by a discussion about what has and has not been done so far (to our knowledge) in this field of study. The latter, to introduce what kind of theories and ideas that is lacking in the scientific literature and is of essence to be able to fulfil the aim of the thesis.

## 2.1 CONCEPTS

### 2.1.1 CRITICAL INFRASTRUCTURE

Modern society is highly dependent on vital societal functions (VSF) (e.g. electricity, water, food) which are provided by various critical infrastructure (CI) (e.g. electric transmission and

distribution grids, water distribution networks, and road transportation) (MSB, 2014). The infrastructures that are considered to be critical are those that if a disruptive or destructive event occurs results in severe impact on the nation's economy, security and/or social well-being, in essence severely impacting services and systems that are of significance to human activity (MSB, 2014; Brown, 2006; Rinaldi et al., 2001). Furthermore, infrastructures are complex systems that are highly interconnected and dependent upon each other. For an individual CI to operate at normal functionality it requires either products and/or services from other CIs (Laugé et al., 2015; Rinaldi et al., 2001).

The Swedish Contingency Agency (MSB) (2017a) refers to a critical infrastructure as “the activities, facilities, nodes, infrastructure and services that maintain the function that they are a part of” (p. 1), this is similar to how CI are defined for example in USA, Canada and European Union (Homeland Security, 2017; Public Safety Canada, 2017; EU, 2008). CI can be present at any level of society, that is national, regional and local (MSB, 2017a). Additionally, MSB (2017a) refers to vital societal functions as “...the activities that maintain a given functionality. Each such function is included in one or more societal sectors” (p. 1). What determines a CI according to MSB (2017a) is if the infrastructure meets one of the stated criteria (p. 1):

- “A loss of or a severe disruption to the activity that alone or together with other similar events, rapidly leads to a serious societal emergency or crisis”.
- “The activity is necessary and very essential so that the harmful effects of a societal crisis can be mitigated as much as possible”.

CIs can be identified within different sectors. MSB (2014) refers to them as societal sectors. Within each sector various VSF are present. In Sweden there are eleven societal sectors: *Energy supply, Financial services, Trade & Industry, Health, medical and care services, Municipal technical services, Information and communication, Food, Public administration (management functions and support functions), Protection, safety and security, and Transport*. It varies between nation to nation which and how many sectors that are classified as critical infrastructure sectors. For example there are sixteen sectors in USA (Homeland Security, 2017), in Canada ten sectors (Public Safety Canada, 2017), and in UK thirteen sectors have been identified as critical or national infrastructures (CPNI, n.d.).

Nations all over the world recognise the importance of protecting CIs with the aim to reduce the vulnerability of the CIs and strengthen their resilience (European Commission, 2017; Homeland Security, 2017; Public Safety Canada, 2017; MSB, 2014). The concept of CIs was relatively new in USA in 2006 according to Brown (2006). It was first defined in an official federal policy in 1996, Executive Order 13010 signed by President Bill Clinton which related to protection of critical infrastructures. The September 11 2001 terrorist attacks highlighted the issues of defence and security, and CI protection became a top federal priority (Brown, 2006).



The European Union also developed a critical infrastructure protection program, following September 11, 2001 and the bombings in London and Madrid, in which the 2008 EU-directive was important part. This directive focusses on European critical infrastructure and their protection and where CI was defined from an EU perspective (MSB, 2015, 2009; EU, 2008). In Sweden the concept was not formally defined, and a plan sketched out until 2013. This was done in a document from the MSB (2013) regarding an action plan for the protection of vital societal functions and critical infrastructure. The European program was one of the driving forces behind the Swedish action plan (MSB, 2015). Even though the CI term has been around for some time now, it is still relatively new within Sweden.

Brown (2006) emphasises that long before the critical infrastructure concept became a trend within the political scene, “threats to services and systems that are important to human activity have always been with us” (p. xiii). Disturbances due to infrastructure failure can result in consequences spanning from benign to catastrophic (Little, 2003). These failures can result from various hazards and threats that the CI faces. It can be nature related hazards, such as lightning, hurricanes and severe storms, earthquakes and floods. It can also be related to threats such as antagonistic and premeditated destruction of the CI. Failures can also arise due to degradation of the CI (simple wear-and-tear), insufficient maintenance, outdated technology, accidents and recurring human errors (Brown, 2006).

As mentioned previously, CIs are dependent and interconnected (in other words interdependent). The combined operational characteristics of infrastructures are strongly influenced by how strong the linkage between the infrastructures are (Johansson, Hassel, Cedergren, Svegrup, & Arvidsson, 2015). Tight connection means that the system has little or no flexibility to respond to failure or the changing condition. While loose connection, then the system is relatively flexible to respond to changing condition or failure (Rinaldi et al., 2001). Additionally, Nan and Sansavini (2017) states that “these interdependencies might also be a source of threat generating risks” (p. 35). This in turn makes mitigation strategies to minimize the damage to an infrastructure and to ensure its continuity of service complicated. Due to this linkage between infrastructures there is a possibility of a cascading failure could occur cross the boundary of the infrastructure (Little, 2003), meaning the failure of one infrastructure could result in a failure of another infrastructure. Thus, increasing the vulnerability of the infrastructures to negative impact which may not be easily foreseen (Nan & Sansavini, 2017; Johansson & Hassel, 2010; Wilhelmsson & Johansson, 2009). Rinaldi et al. (2001) broadly categorises three classes of infrastructure failure: *Cascading failure* – “a disruption in one infrastructure causes a failure [...] in a second infrastructure.” *Escalating failure* – a “disruption in one infrastructure exacerbates an independent disruption of a second infrastructure (p. 22) “(e.g., the time for recovery or restoration of an infrastructure increases because another infrastructure is not available)” (Little, 2003, p. 3), and *Common cause failure* – “two or more infrastructure networks

are disrupted at the same time [...] because of a common cause” (Rinaldi et al., 2001, p. 22) “(e.g., natural disaster, right-of-way corridor)” (Little, 2003, p. 3).

The critical infrastructure sectors presented by MSB (MSB refers to them as societal sectors) gives a starting point to determine which technical CIs we should attempt to get interruption data for from a national perspective for this thesis. CIs are the backbone of societies. Thus, it is important for a CI to be able to recover quickly from interruptions. Though interdependencies are not the focus of this thesis, it is important to mention to gain a better understanding of CIs vulnerabilities and that threats can also come from interruptions in other infrastructures. These dependencies can also prolong the recovery process and aggravate the consequences that arise in the society. This is where the concept of resilience is of value. The more resilient a system is, the quicker it recovers from disturbances.

## 2.1.2 RESILIENCE

To start with, as mentioned in the introduction, resilience comes from Latin and means *the ability to bounce back* (Hosseini et al., 2016; SAOL, 2015), and we simply define resilience as *‘the ability to cope with and recover from stress’*. Historically the term has been used in many fields and disciplines, an engineering article from as early as 1818 (Tredgold) is found mentioning resilience as the greatness describing how much strain a material can resist without permanent distortion, in this case regarding different kinds of timber. A medical paper is found mentioning the term already during the 19<sup>th</sup> century, where it describes resilience regarding certain tissue’s ability to bounce back in our private parts (Macgillivray, 1897). It is also a well-known and used concept in economics, where it can describe an economy’s ability to withstand and recover from a shock (Briguglio, Cordina, Farrugia, & Vella, 2009). Other disciplines where the term is frequently used is sociology, where resilience is can be defined as “... the ability of groups or communities to cope with external stresses and disturbances as a result of social, political and environmental change” (Adger, 2000, p. 1) and in ecology, where it is “... a characteristic of ecosystems to maintain themselves in the face of disturbance” (Adger, 2000, p. 1). The concept is used from many different perspectives, such as organisational structures’ operational continuances and adaptabilities, supply change management, safety engineering, disaster management, etc. (Bhamra, Dani, & Burnard, 2011). Regardless of the broad applications and usage there is a common ground that seems to be generic in all the different definitions, even if the terminology might differ slightly depending on the writer and the subject area. Fundamental properties that seem to be considered essential for a system to be resilient are given by abilities such as *preparedness*, *readiness*, *robustness*, *recoverability* and *adaptability* (Hosseini et al., 2016; Bhamra et al., 2011).

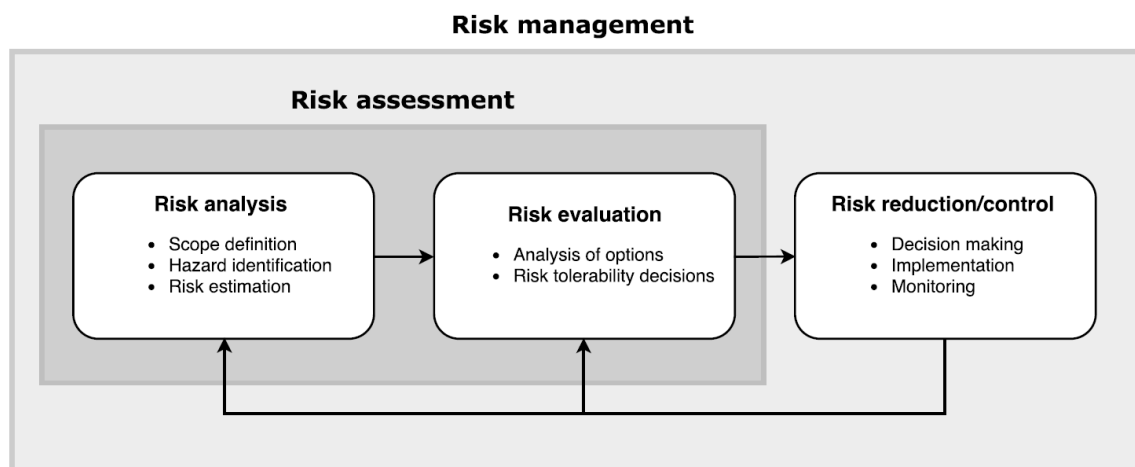
Understanding the concept of resilience, and how it differs between various disciplines, and its properties is fundamental in order to measure resilience of critical infrastructures. In section

2.2 we narrow the scope and focus on how researchers in academic literature related to engineering systems have been attempting to measure resilience and give examples of how researchers have approached quantification of resilience in critical infrastructures.

### 2.1.3 RISK MANAGEMENT

Risk management is often considered as a process that raises awareness of potential risks that a system can be exposed to (or threaten by) in terms of events that can result in negative consequences. This then provides a basis for managing the risks that fall outside of what is considered to be acceptable risk (e.g. through risk mitigation or risk prevention). A system can refer to entities such as organisations, whole society (or some of its parts at different levels, e.g. local or regional level), or one/several critical infrastructures. Consequently, risk management can be applied within multiple disciplines.

According to the International Electrotechnical Commission [IEC] (1995) risk management consists of three parts, that is risk analysis, risk evaluation and risk reduction/control in systematic way (see Figure 1). Where risk assessment consists of the first two steps, i.e. risk analysis and risk evaluation, which involves identifying and analysing risk scenarios and then consider which risks are deemed acceptable and which are not with the aim to put forth potential risk mitigation options. For those risks that are deemed not acceptable an attempt is made to reduce or control the risks in order to achieve successful management (Nilsson, 2003).



**Figure 1 Risk management process, adapted from IEC (1995)**

The word risk is fundamental in the risk management process (RMP), as the risk management term indicates. Meaning, in order to manage the risks, one needs to define what risk is. However, the concept is not strictly and unambiguously defined, as its meaning can vary between disciplines and peoples' perspectives and is associated with impact on what humans values e.g. in relation to environment, economic (property), human life (European Commission, 2010;

Renn, 1998). Generally risk is defined by answering the three questions presented by Kaplan and Garrick (1981):

- i) What can go wrong?
- ii) What is the likelihood of it happening?
- iii) What are the consequences?

This way of defining risk is commonly used when conducting risk assessments of engineering systems. The outcome is a list with various scenarios, the probability of each scenario and consequences.

During the analysing phase of the RMP it is essential to consider the effects on what is believed being of value (in other words the consequences to what we as humans put value on) (MSB, 2017a). From the perspective of societal safety and protection of critical infrastructure and its vital societal functions MSB refers to these values as *core values* and within Sweden they are the following (MSB, 2014, p. 11):

- *Human life and health*
- *Vital societal functions*
- *Democracy, rules of law and human rights*
- *Environment and property*
- *National sovereignty*

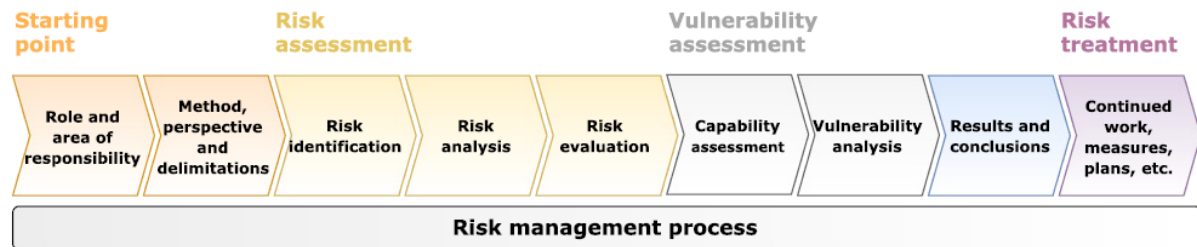
It can be expected in terms of this context that these values can vary from nation to nation, in terms how broadly they are defined.

Vulnerability is another term that is very relevant to the RMP (Johansson, Hassel, & Zio, 2013). It indicates the impact of an adverse event, meaning how serious and how much a system or society, or part thereof, is affected. Actors have certain capabilities to deal with the consequences of an event. That said, a degree of vulnerability can be indicated by the consequences when a society or an actor fails to anticipate, manage, withstand, and recover from an event (MSB, 2011).

In Sweden all municipalities, county boards and central agencies are bound by law to perform a risk and vulnerability analyses (RVAs). The reasoning behind it is to strengthening crisis preparedness of individual actors and the as a whole society at all levels (national, regional, local) (MSB, 2017a). “In accordance with MSB regulations on risk and vulnerability assessments, public sector actors are required to report identified VSF & CI and their critical dependencies” (MSB, 2017a, p. 1). These RVAs contribute to gaining knowledge of the national risk picture, as well as providing a basis for decision making, urban planning and information for

the public about societal risks. Overall, the aim of the RVA processes is to develop joint societal ability to manage risks and vulnerabilities, as well as prevent and mitigate them (MSB, 2017a).

A risk management process that incorporates both risk and vulnerability analysis in accordance to MSB (2011) is demonstrated in Figure 2.



**Figure 2 Risk management process which includes vulnerability assessment, adapted from MSB (2011). Translation from Swedish to English done by author of this thesis.**

Figure 1 and Figure 2 are just two of many ways to illustrate the risk management process. The benefits of having a well-defined RMP is that it enables for more effective management of risks (Swedish Standards Institute, 2009), which is considered essential for dealing with complex systems.

A successfully performed RAA as suggested by the scope of this thesis will quantify resilience for different tCIs. Such results could be found as useful tool in the RMP, e.g. in the risk analysis and vulnerability analysis stages of analysing certain risks. If the measured resilience results from different time-periods are compared, e.g. before and after a performed risk management process, it could possibly be used as an input for evaluation. Such results can then be used to compare between the tCIs, to display where different efforts are put to best use.

Furthermore, if such results are compared for a single large-scale event, like a storm, the results could possibly be used to analyse how vulnerable the different tCIs are for the given event.

## RESILIENCE AND RISK MANAGEMENT

In terms of risk engineering the concept of resilience has not been widely used until quite recently. As MacKenzie and Barker (2013) argues on system resilience and risk engineering, that historically has risk assessment procedures been focusing on the classical definition of risk as a product of a risk scenario's probability and consequence. This have meant that to mitigate the risk, work have mainly been put on preventive efforts that absorbs (lesser consequence) or avoids (lower probability) the risk. Lately emphasis has been made to enlighten the fact that disasters and disruptive events will continue to occur and shock societies in new and unanticipated ways, they will cause civil damage and lives no matter how well these societies are built and prepared, so that focus of risk management should be broadened and put on the risk event

as a whole; effort is needed in all phases: preparedness, response, and recovery (MacKenzie & Barker, 2013).

#### 2.1.4 SPATIAL PLANNING

Spatial planning is an interdisciplinary activity of planning the spatial dimensions of society, basically referring to where to put what and for what reason. It deals with objectives that unites economic, social and environmental goals (ESDP, 1999). It is not simple to define, and the scope of spatial planning is interpreted differently amongst actors. It includes disciplines such as physical planning, community planning and urban planning. The United Nations Economic Commission for Europe (UNECE) summarizes the aim of spatial planning in ten items, which are the following (UNECE, 2008, p. vii)

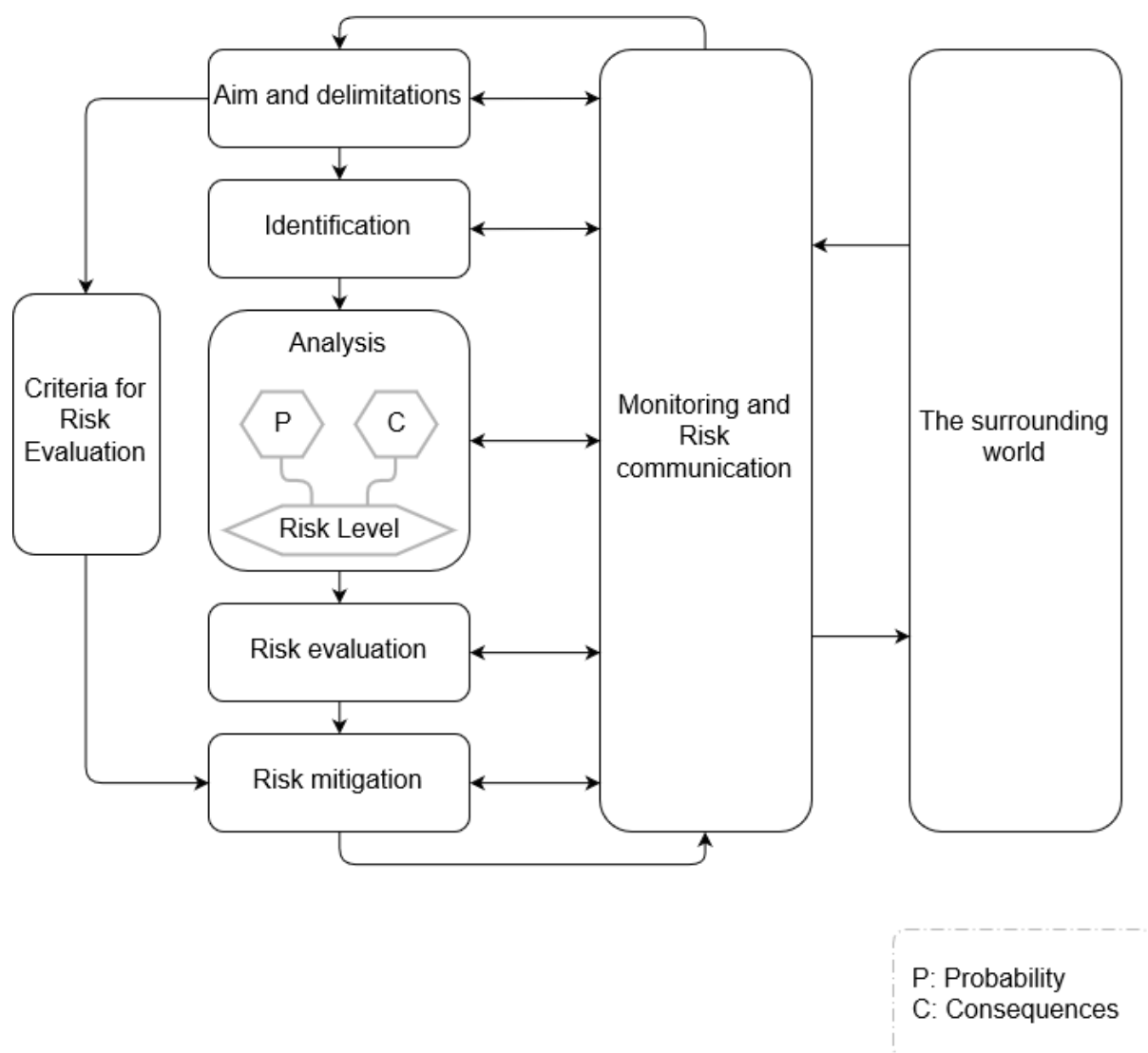
1. *Promote territorial cohesion through a more balanced social and economic development of regions, and improved competitiveness;*
2. *Encourage development generated by urban functions and improve the relationship between the town and countryside;*
3. *Promote more balanced accessibility;*
4. *Develop access to information and knowledge;*
5. *Reduce environmental damage;*
6. *Enhance and protect natural resources and natural heritage;*
7. *Enhance cultural heritage as a factor for development;*
8. *Develop energy resources while maintaining safety;*
9. *Encourage high-quality, sustainable tourism;*
10. *Limit the impact of natural disasters.*

To approach this concept with a Swedish perspective is complex, commissions and legislations of several authorities needs to be addressed to cover these items and there is no clear Swedish translation of the English term spatial planning, which makes it even more difficult to address (Nordregio, n.d.). We have found the different aspects of spatial planning and the shared responsibilities between actors to overlap each other and that they are sometimes difficult to differentiate. Boverket (2017) divides the Swedish scope of spatial planning in three levels, namely:

- National level
- Regional level
- Municipal level

Most of the Swedish spatial planning is carried on the two latter levels, where the municipalities have the most power and influence. They are responsible for everything from micro level decisions in the so-called ‘detailed development plans’, to an overall macro perspective in the municipality’s more general and so called ‘comprehensive plan’ (Boverket, 2017). Despite the municipalities’ self-governed power, the regional- and national level’s influence regarding spatial planning is still of importance from a risk perspective. Especially regarding tCIs, as they are crucial for the whole nation.

The RMP in relation to spatial planning in accordance to Räddningsverket (1998) does not differ much from the more classic schematics of the RMP (see Figure 3).



**Figure 3 Risk management process in the context of spatial planning, adapted from Räddningsverket (1998). Translation from Swedish to English done by authors of this thesis.**

## RESILIENCE AND SPATIAL PLANNING

As Fleischhauer (2008) states, hazards are more or less prone to be area-specific. While comparing the risks from a volcano (fixed location) with the risks with terrorism/storms (unpredictable location), it is obvious that some risks are spatially more easily assessed. However, calls for methods that can aid the process to identify, locate and quantify societal hazards are mentioned both by Fleischhauer (2008) and in the UNDP lead project of Pelling et al. (2004). It is of our belief, that if adapted and utilised in the right way, the RAA presented in this thesis could contribute in such processes.

## 2.2 RESILIENCE AND ENGINEERING

Various literature is available on suggestions how to measure resilience from different perspectives, where engineering perspective is of interest here. Methods depicted in academic literature to assess resilience of CIs can be divided into qualitative assessments and quantitative assessments (Hosseini et al., 2016). Qualitative assessments approaches uses ideas and reasoning to assess resilience, while quantitative methods uses calculations, statistical and mathematical approaches (G. P. Cimellaro, 2016). From an even wider perspective, these methods can be divided into three categories: expert based, modelling and simulation based, and empirical based methods. Methods that are considered expert based are typically based on assessment of system characteristics (e.g. redundancy and resourcefulness), where some sort of resilience index for the system is produced through aggregation of experts' opinions (Hassel & Johansson, 2016; Hosseini et al., 2016). The resilience elicitation approach depicted by Chang, McDaniels, Fox, Dhariwal, and Longstaff (2014) is one example of expert based method, where in context of interdependent critical infrastructures they estimate resilience levels based on expert opinions for a specific scenario which results in estimated service disruption levels. Severity of a disruption is rated from no loss to severe loss for various time lengths of disruptions. Modelling and simulation-based methods, in the contexts of assessing resilience of CI are quantitative approaches with the aim of observing the modelled behaviour of the system during disruptive event (Hosseini et al., 2016; Ouyang & Dueñas-Osorio, 2014). Some authors even include conceptualisation of more general resilience metrics which could be utilised for empirical resilience analysis and apply them in the context of modelling and simulation (Nan & Sansavini, 2017; Panteli et al., 2017). Methods based on modelling and simulation span e.g. from being network theoretical, optimization, Monte Carlo to fuzzy logic approaches (Hosseini et al., 2016).

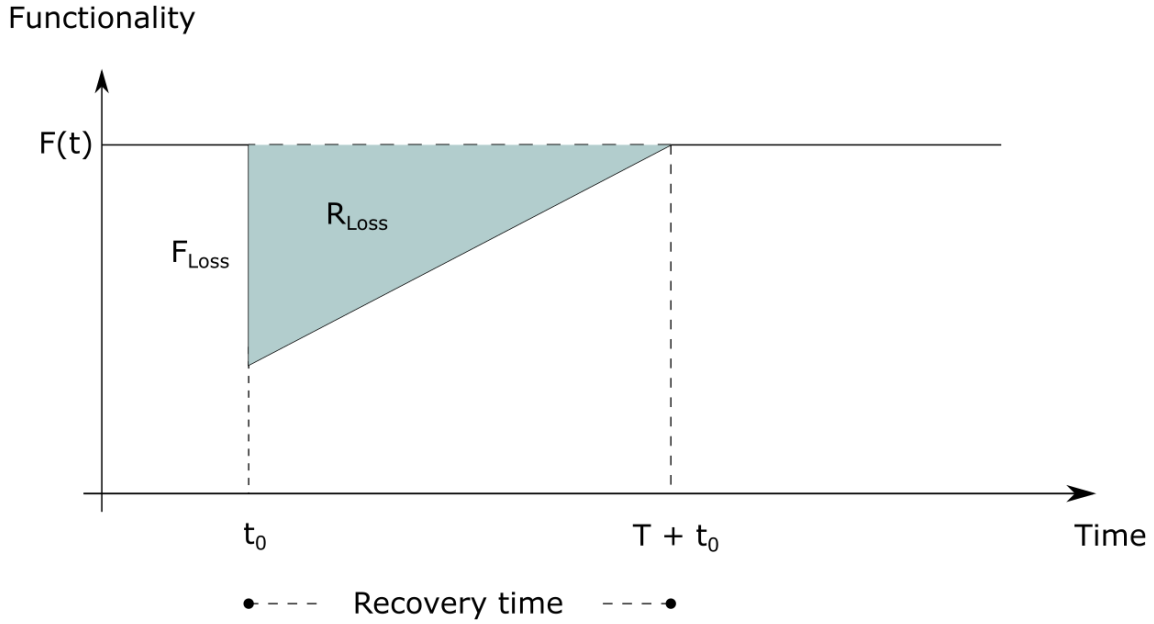
As mentioned so far, there are many ways to take on resilience assessments, all with different and unique strengths and weaknesses. However, for this thesis' purpose, the most interesting part of the literature and research are the methods with empirically produced results, meaning



that they use some form of data or other types of observations to empirically withdraw characteristics or parameters that are representative for measuring resilience. This topic is young and interesting work has been found that we have had the benefits of being inspired of. For instance, Wilhelmsson and Johansson (2009) displays an example from how empirical data can be used to derive characteristics of a system that represents properties of resilience, which is exactly what this thesis aims at. Other work that addresses the field of assessing resilience from disruptive events is e.g. Panteli et al. (2017), who presents methods of measuring resilience by using the number of tripped powerlines to define resilience metrics. Nan and Sansavini (2017) and MacKenzie and Barker (2013) uses similar ideas to measure resilience, both quite detailed methods for measuring the system, meaning that they need information that is not easily accessible. Further, they are commonly looking at single large-scale kind of events. What we could not find in our literature review, is a generic method that can be applied to empirical interruption data without the need of additional time-consuming data gathering, and that takes a broader spectrum of interruptions into consideration. What most of the above-mentioned research has in common, is the conceptualisation of systems resilience by looking at ‘functionality’ as a function of time during disruptive events, which is described in further detail in the next section.

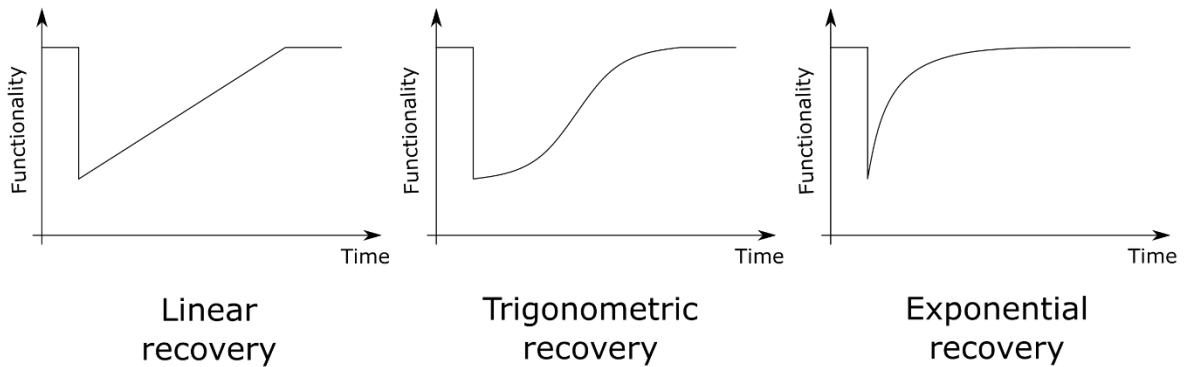
### 2.2.1 QUANTITATIVE RESILIENCE ASSESSMENT APPROACHES

Many methods exist to numerically define and quantify resilience for critical infrastructures, there seem to be no end to all the different suggestions one can quantitatively measure and define resilience. There is one thing almost all the resilience assessment methodologies have in common, which is the idea of a system’s measured ‘*functionality*’ over ‘*time*’. Whereas the emphasis is generally on measuring resilience in relation to a single specific event or a scenario (Nan & Sansavini, 2017; Panteli et al., 2017; Hosseini et al., 2016). The idea of looking at resilience as something that should relate to the measured system functionality over time, was initiated by Bruneau et al. (2003). Basically, an incident results in an immediate loss off functionality, from which the system then recovers, resulting in a triangular shape when system functionality is plotted as a function of time, see Figure 4. Bruneau et al. (2003) proposed conceptualisation is sometimes referred to as the “resilience triangle” (Panteli et al., 2017; Hosseini et al., 2016).



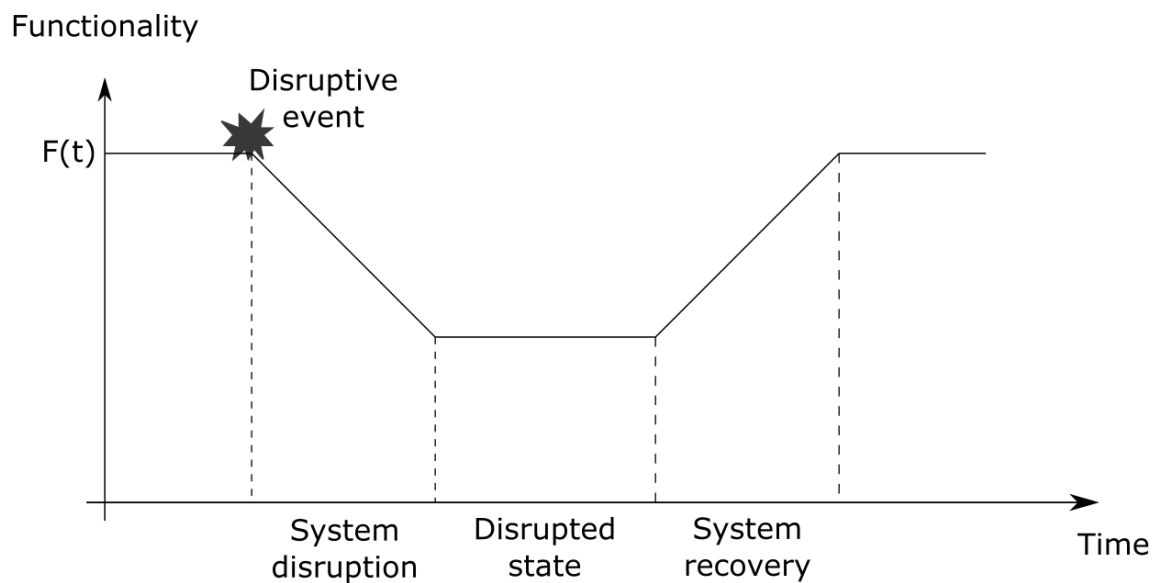
**Figure 4** Functionality  $F(t)$  plotted as a function of time, adapted from Hosseini et al. (2016).

The product of functionality loss over time is normally referred to as ‘resilience loss’ ( $R_{Loss}$  in Figure 4), and is the fundamental idea used in all the presented models and approaches. The initial drop in functionality  $F(t)$  (in this thesis we refer to this drop as Functionality Loss) can be an indicator of the system’s robustness, and the behaviour of phase from  $F(t_0)$  to  $F(T + t_0)$  indicates the system’s rapidity, recoverability and/or preparedness (G. P. Cimellaro, 2016). There are different ways to interpret the recovery-phase and analyse its behaviour to quantify better or worse resilience. Three different types of recovery-phases are suggested by G. Cimellaro, Fumo, Reinhorn, and Bruneau (2009) and shown in Figure 5, of which the exponential shape is considered the one that is most common in real events, demonstrating a well prepared and a rapid recovery of system functionality.



**Figure 5** Different recovery behaviours, of which the 'Exponential' shape indicates better recovery and the 'Trigonometric' shape indicates worse, adapted from G. Cimellaro et al. (2009).

In literature there are also depicted example of approaches where the resilience curve (sometimes referred to as functionality curve) is divided into several different phases; such as ‘original steady state’, ‘system disruption’, ‘disruptive state’, ‘system recovery’, and a ‘stable end state’ (Nan & Sansavini, 2017; Henry & Emmanuel Ramirez-Marquez, 2012). Here we have two additional phases compared the resilience curves presented in Figure 4 and Figure 5, which are the system disruption and disrupted state. System disruption, is the state in which the system’s functionality decreases more slowly from the disruptive event, hence describing a system with the ability to suppress the initial drop. Before the system then starts to recover it is in the disrupted state, which describes a system that might sustain the state of disruption for some time, normally unwantedly, before it enters the recovery phase, as seen in Figure 6.



**Figure 6** The idea of ‘System Disruption’, that leads to a ‘Disrupted State’ before recovery, adapted from Hosseini et al. (2016).

These engineering perspectives on resilience poses two fundamental questions:

- How to define the functionality? From what kind of data or observations should the functionality curve be based upon and how is that data used to derive metrics that can quantify the functionality over time (shaping the line)?
- How to define resilience from the measured functionality? When the functionality is measured and calculated, how does one derive different metrics and finally derive resilience from this information?

Here the several different ways are suggested in the literature on how to interpret and quantitatively measure resilience. One example is MacKenzie and Barker (2013) where data regarding electrical power outages is used to derive the functionality. Another example is from Nan

and Sansavini (2017) where a combination of number of tripped power lines, energy not served and the availability of some important instruments is used to derive functionality. A third example is from Panteli et al. (2017), where the number of tripped power grid lines and delivered power is used to derive functionality. A fourth example is from Vugrin, Warren, and Ehlen (2011), where different costs for repairing and recovery of petrochemical supply chains is used to derive functionality. And a final example is G. P. Cimellaro et al. (2010) where lost lives in combination with different restoring costs for hospitals is used to derive functionality. These are only some examples from approaches that measures functionality, similarly to the approach presented in this thesis. The specifics of the different suggested methodologies and how to calculate the resilience are different in them all.

Our aim is to provide a generic RAA that is utilising empirical interruption data to assess overall resilience of different types of tCIs. For the development stage of the RAA the above suggested quantitative resilience assessment methods have been used for inspiration. Hence, as the collected interruption data span long periods of time and contains hundreds and thousands of interruptions (compared to the dominating view of measuring resilience for single specific events), assessing resilience in terms of functionality over time becomes the fundamental approach and starting point for developing the RAA.

# 3 METHODOLOGY

The aim of this thesis is on assessing resilience of critical infrastructures (CIs) that falls within the category of technical, referred to as technical critical infrastructure (tCI). It was unknown from the start of the project what kind of interruption data and for how many tCIs it would be possible to retrieve data from, it was decided to approach as many tCIs as possible in the beginning of the data collection process. In summary the following tCIs we were able to attain usable data from: Electricity Transmission, Electricity Distribution, Transport Road, Transport Railway, Water Supply and Telecommunication. Attempts were also made to retrieve interruption data for District Heating, Transport Maritime and Transport Aviation, but without success. In this chapter the method used for gathering the data (section 3.1), for processing and treating the raw data (section 3.2) and the developed resilience assessment approach (section 3.3) is presented.

## 3.1 DATA GATHERING PROCESS

### 3.1.1 ILLUSTRATION OF THE DATA GATHERING PROCESS

Figure 7 demonstrates the outline of the conducted iterative data gathering process. This process was split into three different phases.

#### **PHASE 1**

Identifying technical critical infrastructures (tCIs) within Sweden that are of interest.

#### **PHASE 2**

Identifying actors, preferably at national level, that potentially collects interruption data for the respective CIs. Once identified, contact the respective actor or actors and attempt to get in-

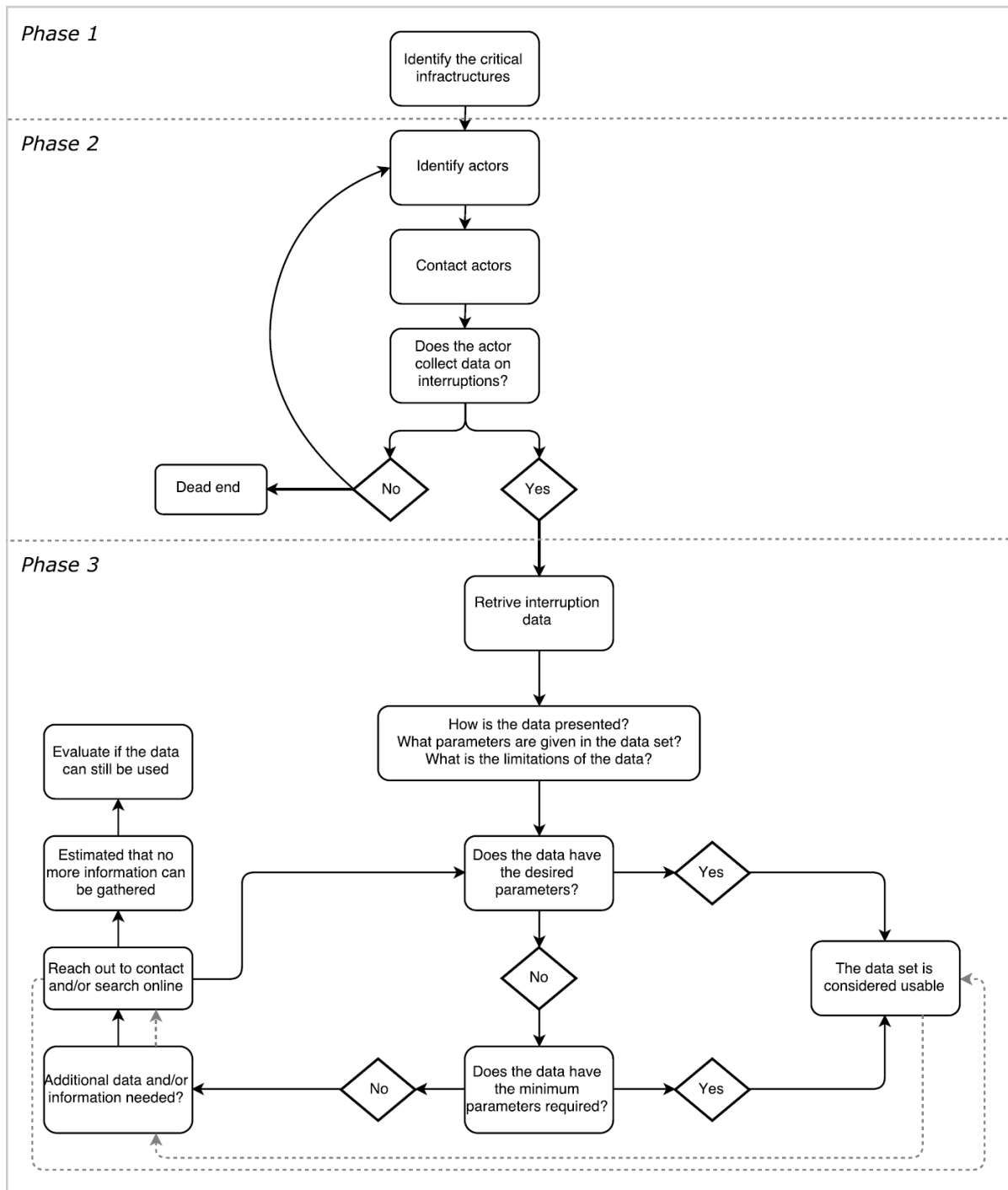
touch with appropriate department or person within the organisation. In cases where an actor is unable to assist, that actor is considered a dead end and further attempts, if possible, are made to identify another actor or actors for that respective CI that could potentially collect interruption data.

### **PHASE 3**

Retrieve the interruption data from the respective actors and examine it to gain further understanding of the quality and quantity of the data. Important points to consider are:

- i) How the data is presented? (e.g. is the data aggregated in Excel spread sheets or is it in form of incident reports that need to be manually aggregated into Excel spread sheets?)
- ii) What are the parameters given in the data set?
- iii) What are the limitations of the data?

After gaining knowledge of the respective data set, it needs to be determined if the data set has at least the minimum desired parameters needed for the Resilience Assessment Approach (RAA). If not, additional attempts are made, by the contacting the informant of the respective CI and/or search online for additional information, to gather the necessary data. If additional data is achieved it again needs to be evaluated. This is considered an iterative process. In cases where no more useful information and/or data can be gained the process is stopped.



**Figure 7 Outline of the data gathering process**

### 3.1.2 FURTHER ELABORATION ON THE DATA GATHERING PROCESS

When it came to identify and contacting actors for a specific infrastructure to inquire interruption data, this process normally involved contacting several different actors, as well as different persons within an actors' own organisations, and following suggestions of appropriate contact persons, all in the attempt to find the appropriate contact person with the knowledge and the

resources to assist with supplying the desired data. In the cases where interruption data could possibly be obtained, the contact person often needed further understanding about the aim and purpose of the thesis to comprehend what kind of specific data. There was also a need from our side to understand what kind of data the respective actor collected, to enable to formulate understandable requirements for the actor in order to retrieve adequate data. For those CIs that could offer interruption data, further explanation regarding parameters given in the data set and additional information and/or data was needed in most cases to be able to use the data.

The initial intention was to collect interruption data from actors solely at a national level, however that was not possible for all critical infrastructures (such as for Water Supply). The actors that provided interruption data that met the requirements for our resilience analysis are presented in Table 1. Additionally, Göteborgs Kretslopp och Vatten (Water Supply), VA SYD (Water Supply) and SUNET (Telecommunication Network) provided us with data. Unfortunately, these data sets did not meet the minimum requirements for our resilience analysis, thus they were excluded from further analyses (discussed further in section 4.7).

**Table 1 The actors that provided interruption data**

<b>Critical Infrastructure Sector</b>	<b>Critical Infrastructure</b>	<b>Interruption data provided by</b>
Energy supply	Electricity Transmission	Svenska kraftnätet (SvK)
Energy supply	Electricity Distribution	Energiföretagen
Transport	Transport Road	Trafikverket
Transport	Transport Railway	Trafikverket
Information and communication	Telecommunication	Post- och telestyrelsen (PTS)
Municipal technical services	Water Supply	Stockholm Vatten och Avfall (SVOA)

Once we started to receive interruption data from the different actors, we started to get a better understanding of its limitations. Consequently, our desired parameters changed over time as we needed to adapt our requirements to the recorded parameters presented in each data set, as well as all of the different data sets as a whole. Furthermore, an evaluation was needed to determine whether the provided data set contained enough parameters in order to analyse and compare the level of resilience between the different CIs. It should be noted that not all the



gathered interruption data contained enough parameters to derive a resilience metric and consequently to do a resilience comparison.

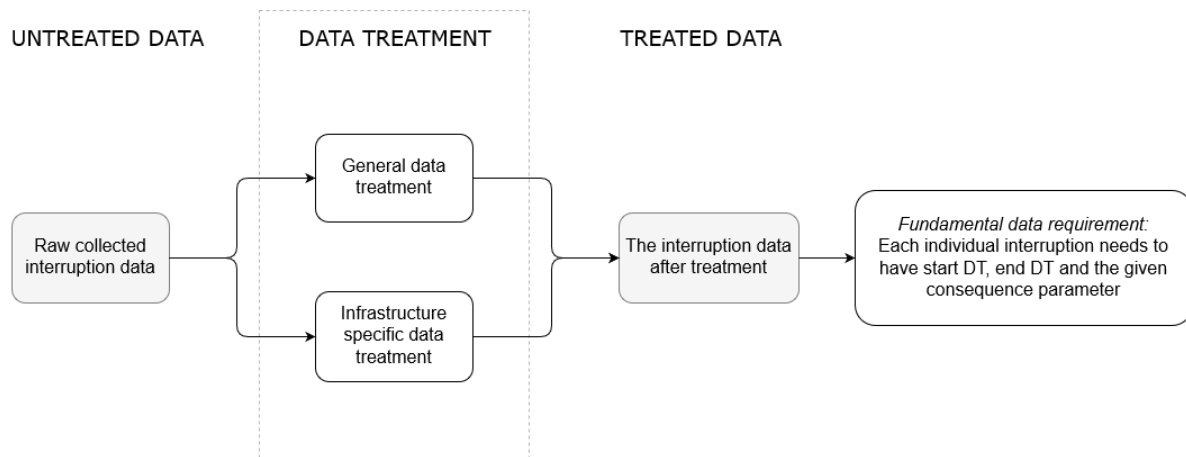
It should further be noted that the process of gathering the data ended up being a comprehensive part of the thesis work and was much more time consuming than initially anticipated. This process has resulted in more than hundred emails communications, along with dozens of phone calls, and a skype conference.

## 3.2 DATA PROCESSING

### 3.2.1 PRESENTATION

For each data set, the data presentation includes a description of the source, what kind of parameters are included and a summary of the data. In addition to that a quality assessment is performed. The quality assessment is conducted by analysing missing values or insufficient data points for the given parameters and presented in figures. The gathered data is presented in Chapter 4.

### 3.2.2 DATA TREATMENT



**Figure 8 Data treatment process consists of three phases: Untreated Data, Data Treatment, and Treated Data.**

The collected interruption data was given in Excel format for nearly all of the collected interruption data. The exception is the Telecommunication infrastructure, where the information was received in the form of individual incident reports. These reports needed to be manually transcribed into a suitable data format and stored in Excel. How we approached this is covered in section 4.6.

The software Matlab is used to transform the Excel files into a suitable format for: data treatment, calculations and to create result figures.

The data treatment process (showed in Figure 8) consists of three phases: '*Untreated Data*', '*Data Treatment*' and '*Treated Data*'. Only the parameters that are fulfilling the criteria of the RAA are evaluated. Meaning each single interruption needs to have a Start DT, End DT and minimum one consequence parameter. In the *Untreated Data* phase each single recorded interruption in the collected interruption data is evaluated and divided into three categories:

- Valid data:
  - Single interruptions containing all the required parameters for the RAA.
- Unusable data:
  - Single interruptions that can be considered containing unrealistic values, that are considered incorrect and cannot be adjusted, in one or several of the parameters that are essential for the RAA.
  - Single interruptions that completely lacks values for one or several of the parameters to meet the criteria of the RAA.
- Zero value:
  - Single interruptions given with zero duration but results in consequences, meaning the consequences are greater than zero.
  - Single interruptions that have a recorded duration but results in zero consequences.

In the *Data Treatment* phase, the treatment of data is split into two parts:

- General data treatment – Applies to all single recorded interruptions in the collected interruption data:
  - Unusable data category: Removal of single interruptions from the collected data set, if and only if, they are deemed to give an unrealistic value in any of the three parameters required for the RAA (e.g. negative values for duration or for consequences).
  - Zero value category: Removal of single interruptions containing zero values for either duration (End DT – Start DT), consequence or both. Note, *Infrastructure specific data treatment* applies here for two CIs which partly overrules this treatment step, see further in section 5.1.2 and 5.4.2.
- Infrastructure specific data treatment – A treatment of data that only applies to a specific infrastructure. This kind of data treatment is addressed in Chapter 5 under the respective CI section when it applies.

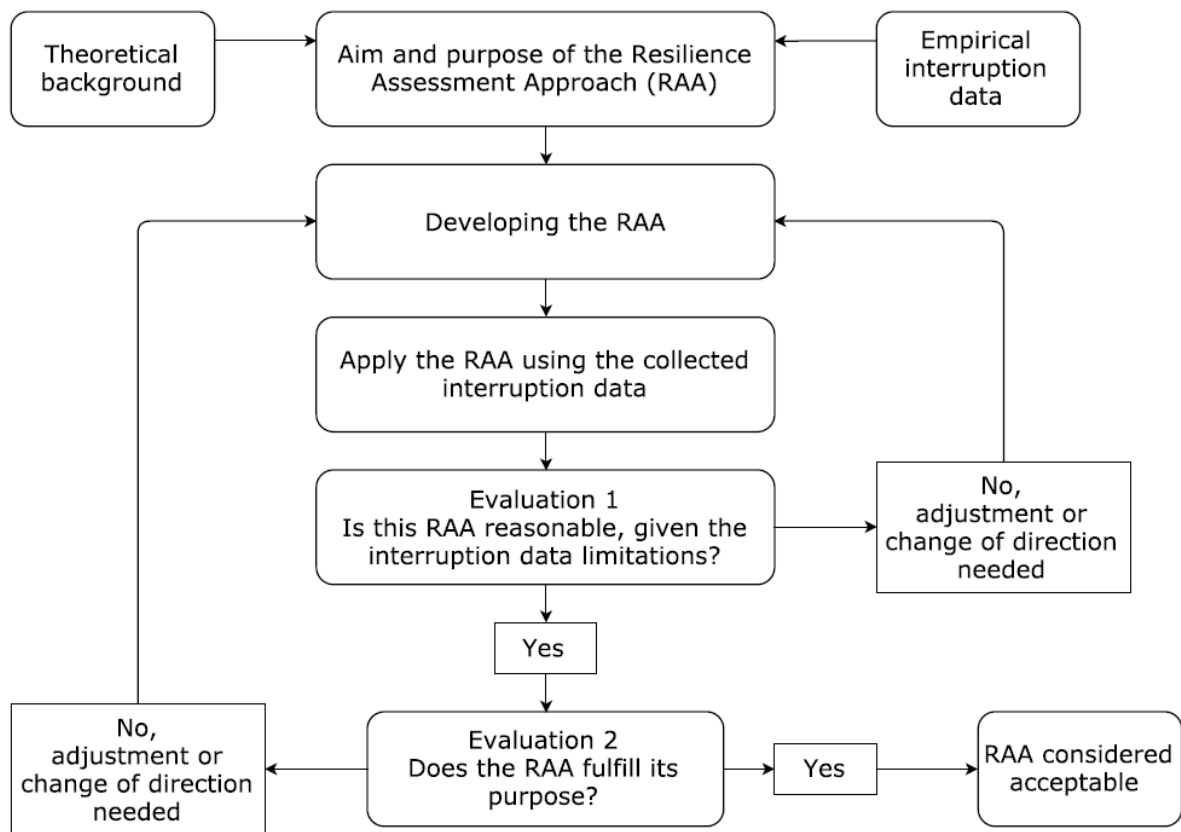
The *Treated Data* phase is when the treated data has been achieved, here are all single interruptions considered valid and fulfil the fundamental criteria of the RAA, that is each interruption is registered with Start DT, End DT and have a consequence parameter.

### 3.3 RESILIENCE ASSESSMENT APPROACH

This section presents both the process of deriving at the RAA and the RAA itself.

#### 3.3.1 PROCESS OF DEVELOPING THE RESILIENCE ASSESSMENT APPROACH

The development process for the RAA is an iterative process, see illustration in Figure 9.



**Figure 9 The process of developing the Resilience Assessment Approach**

Before developing the approach, the aim and purpose of the approach needs to be set. The theoretical background is used as input on how researchers within this field have been depicting ideas on how to measure resilience. Input from these approaches are studied to increase our understanding of the limitations and the possibilities the parameters in the collected interruption data could offer. In section 2.2 we give a brief overview of how researchers have ap-

proached resilience analysis, where a focus has been put on literature from an engineering perspective. The development phase involved testing ideas on a piece of the collected interruption data. The results from these tests were then evaluated in order to decide if it seemed to be a reasonable approach. All these steps are iterative as they involved making adjustment to the current method, some tested ideas were not fruitful and sometimes previous ideas were revitalized with minor changes. The second evaluation step was needed to make sure that the RAA fulfils its intended purpose.

The RAA presented in the following section and applied in this thesis is then end result of this process and has passed both of the evaluation steps, hence considered acceptable.

### 3.3.2 PRESENTATION OF THE RESILIENCE ASSESSMENT APPROACH

The aim of the RAA is to present a generic method that can be applied in resilience analysis of several different types of CIs at a variety of hierarchical levels by using empirical interruption data. By doing so, the different characteristics and properties of the measured states of resilience can be discussed; opening for possible ideas and fields of practical usage of such an approach.

It should be emphasised that the RAA is based on utilising empirical interruption data and is therefore naturally limited to the interruption parameters that are collected by the infrastructure owners or regulatory authorities. The interruption data is generally recorded as independent incidents and thus not much can be said about the events as a group, even though there might be a correlation between the interruptions. They are for instance not independent if they share the same root-cause (e.g. storm). However, the incidents that may be related are not necessarily easily linked together through the data provided.

The RAA can be split into two parts. The first part (section 3.3.3) is to find the resilience parameters available, in a given set of data that measures properties that can be correlated to the characteristics of resilience, doing so by choosing metrics of any given individual interruption that can easily be measured and applied on any other interruption in each set of interruption data. The second part (section 3.3.4) is where it is presented and explained how the empirical interruption data is aggregated up to a “national system level” based on unified, generic metrics. As the approach aims to measure resilience of the system as a whole, similar to a system’s thinking perspective, the system’s total level of functionality is defined by all its different parts’ level of functionality. We hope and believe that by doing so, taking all the events that results in non-delivered service into account, a wider more and multifaceted approach to measure resilience could be made possible.

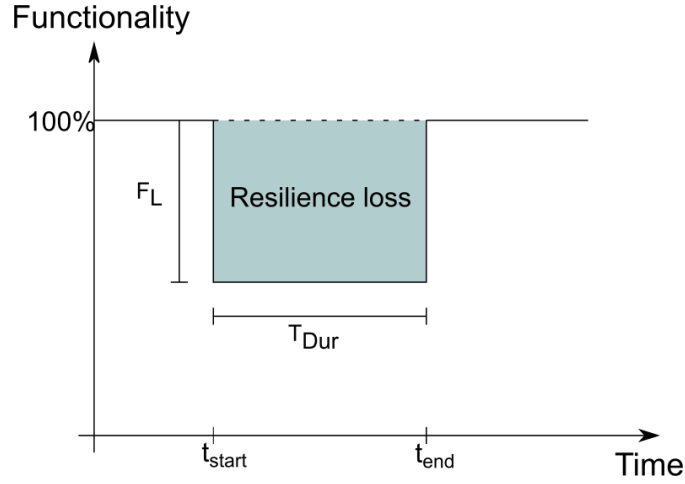
### 3.3.3 DEFINING RESILIENCE METRICS FOR AN INDIVIDUAL INTERRUPTION

As mentioned in the previous section, the collected interruption data is commonly recorded in terms of independent single events (hereby referred to as an ‘interruption’). The parameters that can collectively be withdrawn from the interruption data of all the included CIs are:

- when the interruption occurs, ‘start date-time’ (Start DT),
- when the interruption ends, ‘end date-time’ (End DT), and
- what are the consequences due to the interruption.

Overall, detailed information is lacking on how a single event behaves in terms of ‘*functionality loss*’ over ‘*time*’. That is, how fast the functionality of the system decreases (the disruptive phase), when the recovery process is initiated and how quickly the system then recovers (the recovery phase). So, the behaviour of the system functionality is then unknown in terms of ‘Functionality Loss’ ( $F_L$ ) for a single interruption. Consequently, the collected data does not reflect the more detailed ‘*resilience curves*’ (sometimes referred to as ‘functionality curve’) depicted in literature on suggested methods/approaches to measure resilience for CIs from engineering point of view (as described earlier in section 2.2.1).

If every interruption recorded in the collected data contained more detailed information regarding disruptive and recovery phase, then the behaviour of the system functionality due to a single event would perhaps better resemble the theoretical resilience curves as depicted in the scientific literature (e.g. Panteli et al., 2017; Hosseini et al., 2016; G. Cimellaro et al., 2009). Unfortunately, the collected interruption data lacks this information. For these reasons the behaviour of the functionality during a single recorded interruption in the collected data is defined with a box shaped profile, hereby symbolising the ‘Resilience Loss’ ( $R_{Loss}$ ) of the system in the thesis, see Figure 10. Overall, Functionality Loss, duration and Resilience Loss are referred to in this thesis as ‘resilience metrics’, whereas Functionality Loss and duration is a fundamental requirement for the developed RAA for each single interruption. How these metrics are generically calculated for a single interruption are presented in the following sub-headings.



**Figure 10 Functionality curve for a single interruption.** Where 100% represents the normal state of the system where it is operating as it should with out interruptions. When an interruption occurs there is a drop in the system functionality, referred to as Functionality Loss ( $F_L$ ). Each single interruption has a duration from when it starts untill the system has recovered from the interruption. The area framed by the Functionality Loss and the duration of the interruption is the Resilience Loss ( $R_{Loss}$ ) in the system due to a single interruption.

### DURATION METRIC

For a single interruption, the duration metric represents how long the interruption last, in other words the time it takes the system to recover from the event. In the collected interruption data, each interruption is generally recorded with calendar date and time when the interruption starts and when it ends. Duration is simply calculated according to Eq. 1.

$$T_{Dur} = t_{end} - t_{start} \quad \text{Eq. 1}$$

where

$T_{Dur}$ : The duration of a single interruption.

$T_{end}$ : The End DT of a single interruption.

$T_{start}$ : The Start DT of a single interruption.

In relation to usage of the term duration, in the context of this thesis the term refers both to a time vector (length of an interruption, e.g. number of hours), but it is also used to define the interruption in time-space with given Start DT and End DT (e.g. when (date) and at what time an interruption starts, and when (date) and at what time is it considered finished). Whereas, the latter is essential for the RAA.

### FUNCTIONALITY LOSS METRIC

The Functionality Loss metric ( $F_L$ ), describes how much the functionality of the system has decreased compared to its normal state, see Eq. 2 and Figure 10. To determine the Functionality

Loss, the consequences of single interruption are normalised with an appropriate time-independent baseline and should reflect the specified time-period of study. The baseline should be an indicator of the normal and full functionality state of the infrastructure and in the same unit as the recorded consequence of the interruption in the data, in order for the Functionality Loss be a unit less quote. Thus, the baseline and/or the recorded consequences for the interruption data may needed to be scaled in order to get a usable format. The generic equation for Functionality Loss is presented in Eq. 2.

$$F_L = \frac{\text{Consequence}}{\text{Baseline}} \quad \text{Eq. 2}$$

where

$F_L$ : Functionality Loss.

Consequence: The recorded consequence parameter for a single interruption in the interruption data.

Baseline: Appropriate time-independent baseline for a specified time-period of study.

For the resilience analysis in this thesis the baseline is given on annual bases.

## RESILIENCE LOSS METRIC

The Resilience Loss metric ( $R_{Loss}$ ), is the area described as the coloured box shaped area in Figure 10. As the collected interruption data is discrete, Resilience Loss of a single interruption is calculated as the sum of Functionality Loss over the duration of the interruption, see Eq. 3.

It should be noted that the Resilience Loss metric does not capture what it means if an interruption has short duration and large Functionality Loss, or vice versa, as the two can give the same result in resilience loss.

$$R_{Loss} = \sum_{t_{start}}^{t_{end}} F_L(t) \quad \text{Eq. 3}$$

where

$F_L$ : Functionality Loss of a single interruption.

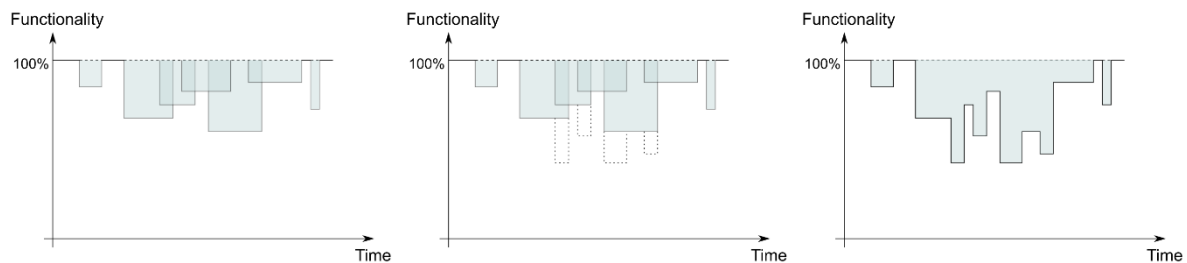
$t_{end}$ : The EndDT of a single interruption.

$t_{start}$ : The StartDT of a single interruption.

### 3.3.4 AGGREGATION TO A NATIONAL SYSTEM LEVEL

The presented RAA aims to measure resilience of a CI at a “national system level”, in other words analysing resilience of the system (the CI) as whole. As the overall CI is usually built up by several sub-infrastructures, it is thus essential to aggregate the interruption data from several sub-infrastructures that covers different geographical areas up to a national level. This kind of approach is argued to be better suited for guiding policy making and regulatory consideration at this level.

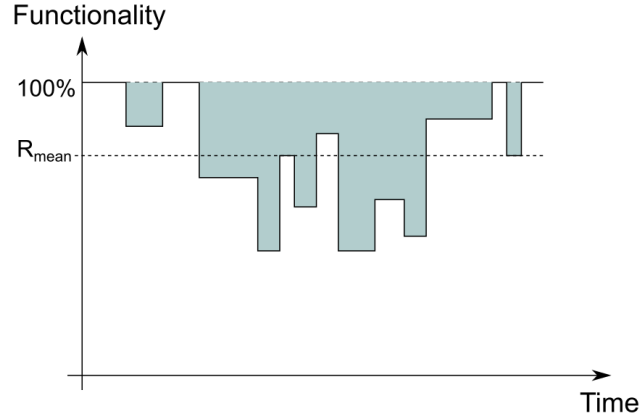
As previously mentioned, it is generally quite difficult make the connection between the recorded interruptions within a CI, to determine if they are connected or not. For this reason, each individual interruption is treated equally. That is, each single interruption is considered to place a strain on the whole system with a negative effect on the functionality during that specific time period. In the cases where two or more interruptions occur simultaneously at any given time period, these are simply added together (in other words stacked), resulting in a fictive Functionality Loss ( $F_L$ ) of the system as a whole (the “national system level”), see Figure 11. As stated in earlier in this chapter, the true behaviour of the system functionality during a single recorded interruption is unknown and is thus described with a box-shape profile. That said, the presented RAA would however still be applicable with interruption data of higher resolution, meaning more detailed information regarding the intermediate Functionality Loss behaviour during a single interruption.



**Figure 11** Illustration of how the interruption data from several sub-infrastructures (left) is aggregated to a fictive “national system level” (right), by stacking where one or more interruptions occurs simultaneously (middle).

The criteria for the RAA is that each recorded single interruption in the collected empirical data is registered with the following parameters: Start DT, End DT, and one or more consequence parameters which in turn can be transformed to Functionality Loss with an appropriate time-independent baseline (also see under *Functionality Loss Metric* in section 3.3.3). For the RAA it is important to be able to locate the recorded single interruption in time for the given time period of the collected data, as well as knowing how much the Functionality Loss is for the respective interruption. This is essential to be able to stack the collected data to fictive national system level and estimate the resilience of the whole system (the CI).





**Figure 12** Illustration of the fictive “national system level” resilience curve. Where system functionality is affected by fictive national Functionality Losses within the system over a specified time period due to series of interruptions. Where 100% represent if a system is functioning as should, that is without interruptions that lead to loss in functionality. Note in the presented equation in this section utilises quote instead of percentage). The ‘total resilience loss’ in the system is shown as the area above the curve (the coloured area), while the ‘total resilience’ is the area below the curve. Here is also visually shown the ‘resilience mean’ ( $R_{Mean}$ ), which is utilized to compare the resilience levels of different CIs.

Once the empirical interruption data has been aggregated it is possible to quantify the level of resilience and resilience loss for the respective CIs. How this is done is presented here below.

#### **TOTAL RESILIENCE AND RESILIENCE MEAN OF STREAM OF INTERRUPTION OVER SPECIFIED TIME PERIOD**

The ‘total resilience’ ( $R_{Tot}$ ) of the critical infrastructure over a specified time period is shown in Eq. 4.

$$R_{Tot} = \sum_{T_0}^{T_{end}} 1 - F_L(t) \quad \text{Eq. 4}$$

where

$F_L$  : Functionality Loss during time period  $t$ .

$T_0$  : Start time of time period.

$T_{end}$  : End time of time period.

In order to be able to compare the different CIs and to take into consideration the varying time periods the ‘resilience mean’ level ( $R_{Mean}$ ) for a given time period is calculated according to Eq. 5 and Figure 12.

$$R_{Mean} = \frac{R_{Tot}}{N} \quad \text{Eq. 5}$$

where

N : Total number of data points in time period for which the mean is calculated.

#### **TOTAL RESILIENCE LOSS AND RESILIENCE LOSS MEAN OF STREAM OF INTERRUPTION OVER SPECIFIED TIME PERIOD**

The ‘resilience loss mean’ level can thus be simply calculated according to Eq. 6.

$$R_{Loss,Mean} = 1 - R_{Mean} \quad \text{Eq. 6}$$

Note, it is also possible to calculate the resilience loss mean by first calculating the total resilience loss (see Eq. 7) and then divide it by the total number of data points in time period, N (see Eq. 8), and from there estimate the resilience mean from subtracting the resilience loss mean from one.

$$R_{Loss,Tot} = \sum_{T_0}^{T_{end}} F_L(t) \quad \text{Eq. 7}$$

where

$F_L$  : Functionality Loss during time period t.

$T_0$  : Start time of time period.

$T_{end}$  : End time of time period.

$$R_{Loss,Mean} = \frac{R_{Loss,Tot}}{N} \quad \text{Eq. 8}$$

where

N : Total number of data points in time period.

# 4 DATA PRESENTATION

*Disclaimer: Reading this chapter in depth is not entirely necessary to understand and appreciate the results, discussions and conclusions of the thesis. This chapter is giving a thorough description of the collected data, necessary to enable a complete and holistic understanding of the forthcoming chapters.*

In this chapter, the reader will be introduced to the background of the collected interruption data on which the thesis is based upon. There are many factors that can contribute to a deeper and more holistic understanding of the used data, such as knowledge about the intentions and reasons for the collecting of data and if its gathered due to legal obligations or internal audit and improvement. Hence, as a basis to establish a fundamental understanding of the developed RAA, the limitations, delimitations and background of the achieved data is presented. Each of the different infrastructures' data sets are presented with a generalised description, including information about how and from where the data was retrieved, and a descriptive background to why the data is gathered by the actor.

The original state of the achieved data for each CI is presented for documentation purposes to give a fair overview of how the raw data looked like. A description of all the parameters included in the data is given and then summarised by visualising the content in plots and graphs. A summarising table is presented for each of the obtained CI's interruption data; the first column presents the collected variable categorises, the second column lists the variables and the third column shows the adopted values for each variable. For those variables where the adopted values are plenty and not in need of detailed presentation, an exemplifying selection of the ten most occurring values are given.

The chapter finishes with an overviewsing résumé of the collected and used data, as well as the collected data that could not be used and data that could not be achieved. For documentation purposes and clarification, this is considered being of importance as there were a couple of CIs ruled out due to lack of adequate parameters in the collected data, the implications of which is further discussed in the discussion in Chapter 8.

## 4.1 ELECTRICITY TRANSMISSION, SVENSKA KRAFTNÄT

Svenska kraftnät (SvK) is the national system operator for electricity and the Swedish authority responsible for the electric power transmission system's "stem network" to be run safe, according to the environmental needs and to be cost efficient. The stem network transports high voltage power from the generating sources; such as power plants and windmills to the region networks and local networks. The stem net also delivers sold power to connected nationalities as well as it receives power bought by Sweden. It states on their homepage that,

*"The government has assigned Svenska kraftnät the task to maintain and develop the Swedish national grid for electricity. The national grid power lines transport electricity from wind, hydro and nuclear power stations to regional and local electricity networks" (SvK, 2017)*

According to Swedish and European Union regulations, all companies providing power supplies are bound by law to deliver reports of outages and disturbances since 2009 (ENTSOE, 2017; SvK, 2017; Regeringskansliet, 2009a). As a response, in 2009 SvK delivered the report "Goals for operational safety and contingency"<sup>2</sup>, where it states that all interruptions should be reported. The report does not yet contain the word resilience, but describing the concept in other words (Regeringen, 2009).

The data achieved from SvK were received as an Excel file, containing operational outages from year 2005 to 2016.

### 4.1.1 PARAMETERS

Each line of data is representing an interruption, given by 14 parameters, which are summarised and categorised in Table 2.

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<sup>2</sup> In Swedish: Mål för driftsäkerhet (English Translation Disclaimer)

**Table 2 Summary of given parameters<sup>3</sup> in the interruption data achieved from SvK**

Parameter category	Variable name	Description with adopted values or exemplification
<b>General characteristics of interruption</b>	Failure identification number	Integer
	Date	2005.01.07 - 2016.12.18
	Failure characteristics	Persistent, transient
	Initial/subsequent failure	Initial, subsequent/latent failure
	Failure type	Examples: Other network, single-phase ground failure, pole-pole failure, SSR, 3-phase short circuit, excess loading
<b>Causes of interruption</b>	Failure cause	Operation and maintenance, high voltage equipment failure, control equipment failure, subsynchronous resonance, subharmonics, external influence, thunderstorm, miscellaneous, unknown, other
	Failure sub-cause	Examples: Fire, animal, failure in other network, electronic component failure, flying vehicles incl. kites etc., leakage, glaciation, rain/moist/snow, timbering,
<b>Failing system section or component</b>	Installation component	Examples: Circuit breaker, disconnectors and grounding switches, HVDC, power transformer, overhead line, series capacitor, other high voltage components in stations
	SvK's net/other net	Home network, other network
	Voltage level [kV]	130, 220, 400, < 100, HVDC (High Voltage Direct Current)
<b>Duration and consequences</b>	From	2005.01.07 07:08
	Until	2016.12.18 07:43
	Interruption minutes	Integer, representing the interruption's duration in whole minutes
	ENS [MWh]	Integer

The consequences are quantified by the interruption's duration time and the amount of '*Energy Not Supplied*' (ENS), of which the bigger part is equal to zero. The '*Interruption minutes*' are given with a resolution of whole minutes, however each interruption also comes with a Start

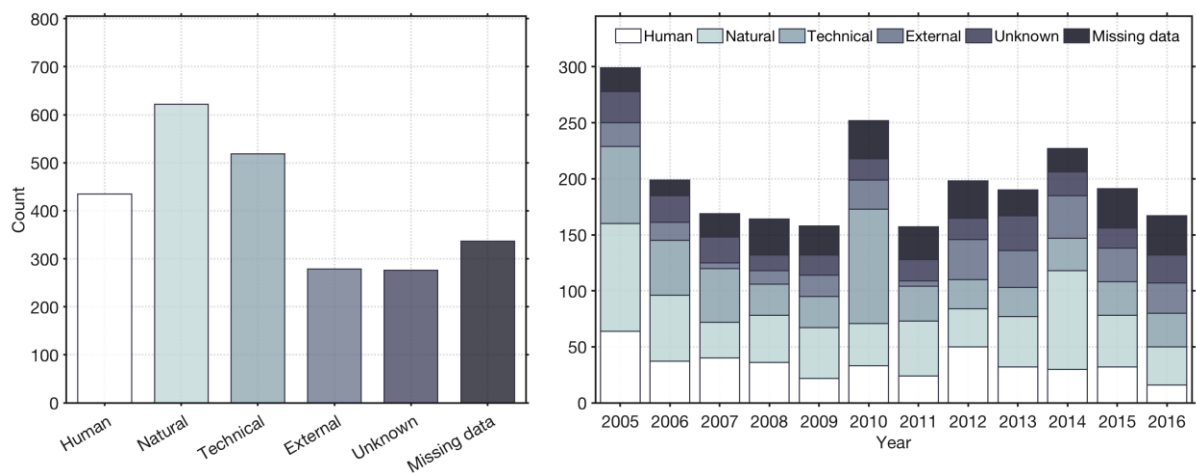
<sup>3</sup> Disclaimer for the Swedish to English translation of parameters, variables and exemplifications.

and End DT of a resolution of seconds, introducing the possibility of choosing the interruption times and duration with accuracy of whole seconds. Although, as the data is given with a pre-calculated quantity of duration in whole minutes, it might indicate that whole minutes are a good estimation of the averaged true accuracy. Each interruption also comes with a dimension that defines the consequences in terms of ENS in Megawatt hours.

Furthermore, each interruption is defined by several qualitative attributes. These are descriptions about the interruption's characteristics in terms of the causes and what part of the system that is failing. E.g., there is information given about what kind of power grid that is affected, whether it is an initial or subsequent interruption and if so, is it caused by other interconnected networks than what SvK's owns, see Table 2.

### 4.1.2 SUMMARY

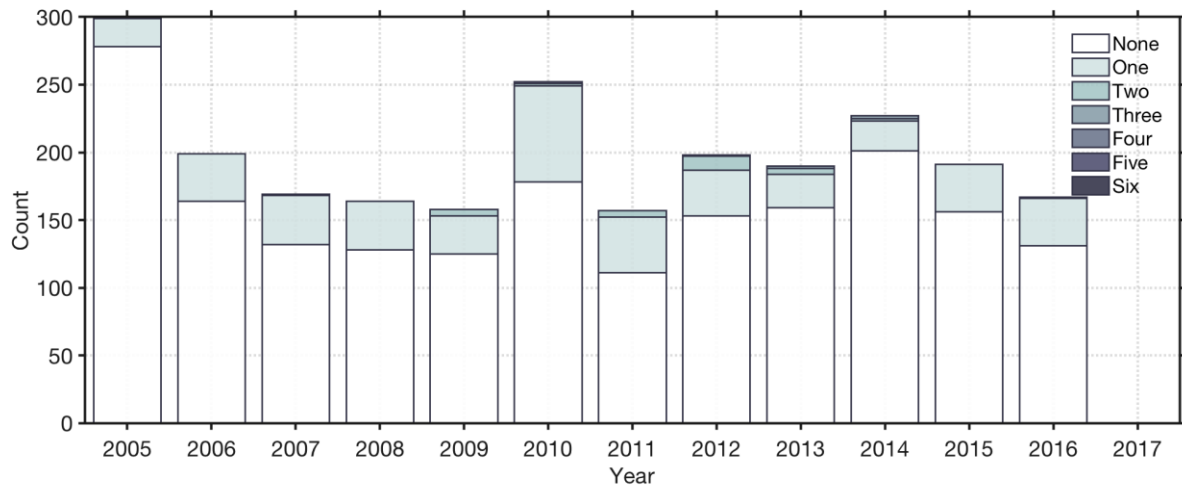
SvK presents a consistent data set where the interruptions are similarly distributed amongst causes over the years, see Figure 13. This might be an indicator for consistency and similarities in reporting interruptions. Almost one quarter of the interruptions are due to nature's powers, of which most are due to thunders storms and lighting.



**Figure 13 Summary of the Electricity Transmission infrastructure's interruptions and their causes, summarised (left) and annually (right)**

### 4.1.3 QUALITY ASSESSMENT AND LIMITATIONS

The data set received from SvK comes with some unusable data points each year, however the vast majority has all data points represented, see Figure 14. Among the bad parameters, most are just empty cells that are lacking information; almost no data is given with unrealistic or faulty numbers. Hence, this data is judged to be of very high quality and to represent characteristics of interruptions that accurately resembles reality.



**Figure 14 Number of missing parameters per year for the Electricity Transmission infrastructure**

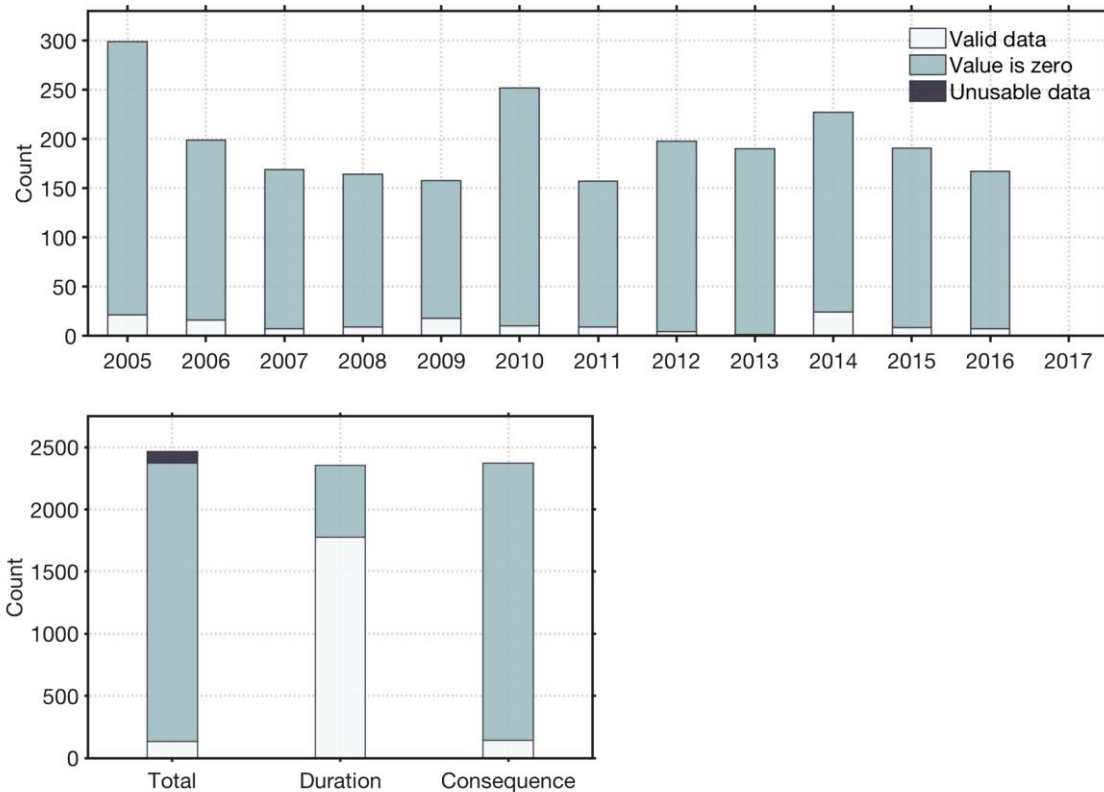
#### 4.1.4 RESILIENCE PARAMETERS

This data set is almost spotless, with only one year where there was more than ten bad parameters and two years with none out of approximately 180, see Figure 15. However, as previously mentioned and worth noticing, nearly all the ENS values are equal to zero; describing interruptions and incidents where some part of the system has failed but did not lead to any interruption of supply due to instant re-routing of power. Only six percent of the interruption result in ENS greater than zero, see Figure 15 below.

The resilience metrics from SvK's interruption data can be based on the calculated duration, derived from the given Start DT and End DT, and the amount of ENS for each interruption can be used to derive the Functionality Loss metric. However, in order to derive the Functionality Loss metric it is not enough to have the consequences as presented. In terms of the Electricity Transmission interruption data the following is needed in order to derive the Functionality Loss metric,

- The given consequence parameter ENS is not a timeless unit, meaning it is given as energy [Wh] which is time dependent, therefore the consequence parameter need to be made timeless by transforming it to power [W].
- The retrieved baseline is the total averaged Swedish power consumption.

In section 5.1 a detailed description of how both duration and Functionality Loss metrics are derived for the interruptions of Electricity Transmission is given.



**Figure 15 Usability of the interruption data for Electricity Transmission infrastructure, aggregated annually (above) and summarised by total interruptions, duration metric and the consequence resilience parameter (below).**

## 4.2 ELECTRICITY DISTRIBUTION, ENERGIFÖRETAGEN

Energiföretagen is a relatively new Swedish trade association, operating since 2016. Though their main task is to ensure and maintain its members' commercial terms, they also focus on developing the Swedish power system to keep it up to date with the development of new demands and environmental needs. Energiföretagen continuously gather and analyse interruption data from their members and are bound to do so according to the same laws as SvK, see section 4.1 above. The statistics of this data is summarised and presented by Tapper (2016) in the so called "DARWin-reports", which are annually published by Energiföretagen (Energiföretagen, 2017b, 2017a). With almost 100 member companies, this data represents nearly 90% of Sweden's total end user's. The interruption data from Energiföretagen were received as Excel files, separated by year for unplanned interruptions for the years 2005 to 2016.



## 4.2.1 PARAMETERS

Each line of data is representing an interruption, given by 13 parameters, summarised and categorised in Table 3 below.

**Table 3 Summary of given parameters<sup>4</sup> in the interruption data achieved from Energiföretagen**

Parameter category	Variable name	Description with adopted values or exemplification
<b>General characteristics of interruption</b>	Start date	2005.01.04
	Start time	hh.mm Examples: 12.32, 11.3, 15 Notes: time written with decimals. Exact hours are not written like 12.00 but as an integer 12
	End date	2016.12.31
	End time	hh:mm, see Start time above
<b>Causes of interruption</b>	Failure cause	Examples: Unknown, faulty production or component, fallen tree due to wind, thunder, fuse breakage, digging, lacking maintenance, wind, overload, snow or ice load
	Interruption type	Disruption
<b>Failing system section or component</b>	Disconnecting site	220 kV Backbone network; $\geq 220$ kV own region net; 132, 66, 45, 36 and 22 kV region network; 24, 12 and $< 10$ kV distribution network; 0.4 kV low voltage network
	Failure site	$\geq 220$ kV home region network; 132, 66, 45, 36 and 22 kV region network; expired 22kV region network; 24, 12 and $< 10$ kV distribution network; 0.4 kV low voltage network; relief facilities
	Network	Home network, customer installation high voltage, customer installation low voltage, unknown, merged, overlying network
	Installation component	Examples: Unknown, overhead line unisolated, ground cable, fuse- or apparatus-box, bifurcating- or cabling-cabinett, overhead line isolated, pole station, distribution centre, overhead bundled cable line, encapsulated transformer

<sup>4</sup> Disclaimer for the Swedish to English translation of parameters, variables and exemplifications.

<b>Duration and consequences</b>	Interruption time	hh.mmm, representing the sum of all customer's outage durations  Examples: 375.57, 0.3, 6.029 Notes: whole hours are written as integers, the first two decimals resemble minutes. Eg. 0.3 is equal to 30 minutes and 375.57 is equal to 375 hours and 57 minutes. If there is a third decimal, this resembles one tenth of a minute, that is 6 seconds. So 6.029 is equal to 6 hours two minutes and 54 seconds.
	No. high voltage customers affected	Integer
	No. low voltage customers affected	Integer

The consequences are derived from of the number of high and low voltage customers affected by each interruption and the duration is easily calculated by the Start and End DT. Another time parameter is the '*Interruption time*', which is given pre-calculated as the total sum of all customers' factual interruption times, high and low voltage customers alike; both contributing equally to the total. This parameter tends to be lower than the calculated *Interruption time*, which is because of reconnected customers whom receive their power before the interruption is fixed for all, that is

$$\text{Interruption time given} = \sum \begin{matrix} \text{All the customer's actual interruption times,} \\ \text{given by Energiföretagen} \\ \text{(both high and low voltage customers)} \end{matrix}$$

≠ (close to always less than or equal to)

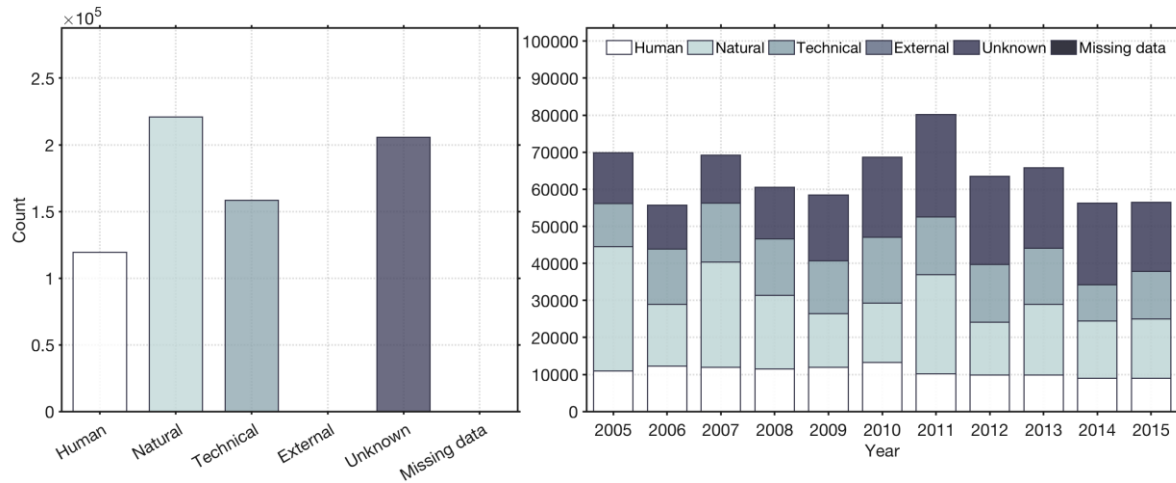
$$\begin{aligned} &\text{Interruption time calculated} \\ &= \left( \sum \begin{matrix} \text{High and low} \\ \text{voltage customers} \end{matrix} \right) \times \begin{matrix} \text{Duration} \\ \text{(end time – start time)} \end{matrix} \end{aligned}$$

Worth mentioning is that the parameters received from Energiföretagen are similar to the ones from SvK, especially the qualitative parameters (see rows under '*Failing system section or component*' in Table 3). This can be considered likely as they are both subject to the same regulations and all companies are using the same templates and guidelines to report the interruptions (SvK, 2013b).

#### 4.2.2 SUMMARY

This is an impressive collection of data, with almost 700 000 logged interruptions over eleven years. The quote of failure causes that are human, technical or natural, are much like SvK's. As could be expected of Energiföretagen's associated companies that distributes power to

much finer local networks; networks where the power lines are more integrated in complex urban environments, adding up many more unknown failure causes compared to SvK. On the other hand, there are no given interruptions that can be connected to other networks, so part of the SvK's unknown interruptions could potentially belong in the category 'other networks'.

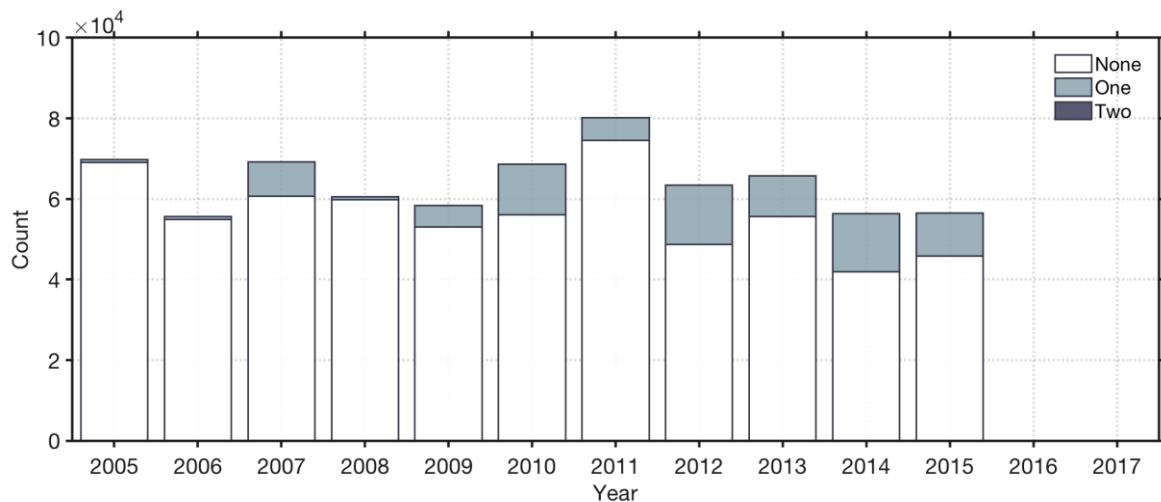


**Figure 16 Summary of the Electricity Distribution infrastructure's interruptions and their causes, summarised (left) and annually (right)**

#### 4.2.3 QUALITY ASSESSMENT AND LIMITATIONS

The data set received from Energiföretagen is around ten times larger than SvK's in terms of total number of interruptions. Considering this, it must be said that the amounts of bad or lacking data are few in numbers, empty cells and missing values do occur, but rarely.

Of just over 700 000 given interruptions, none of the interruptions miss more than two of the total 13 parameters, see Figure 17 below. Hence, this data is judged to be of high quality and to represent characteristics of interruptions that accurately resembles reality.



**Figure 17 Number of missing parameters per year for the Electricity Distribution infrastructure**

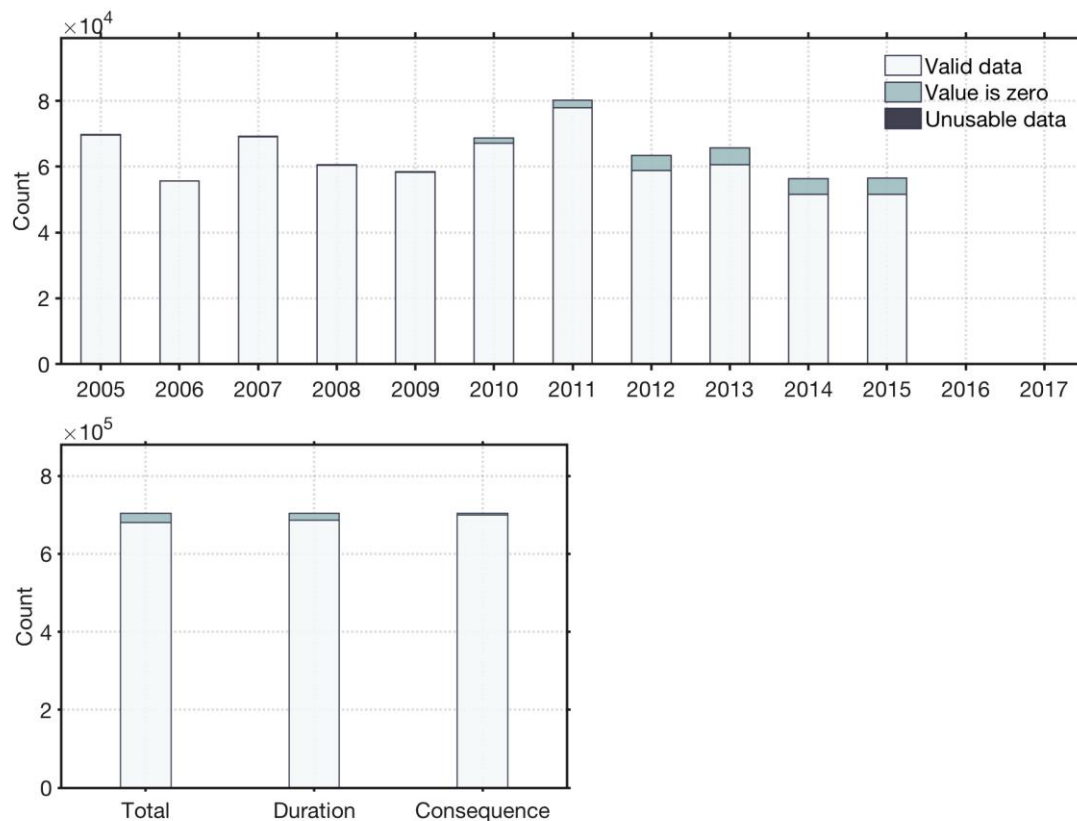
#### 4.2.4 RESILIENCE PARAMETERS

The Electricity Distribution interruption data, compared to the Transmission data, does not come with the same number of data points where duration or consequences are equal to zero, representing statistics of interruptions that most often leaves customers without power for some time (see Figure 18 below). The number of parameters missing for the resilience metrics are zero after adjusting some obvious errors, which is impressive for such a big data set. The number of outages resulting in any non-delivered energy (ENS) to end customers is much greater in the data achieved for the Electricity Distribution infrastructure when comparing with the Electricity Transmission interruption data. This implies some initiating ideas about that Electricity Transmission infrastructure being more resilient. As SvK is delivering high voltage power from the main production sources to Energiföretagen's affiliated companies to distribute locally, thus it could be expected to find less outages from an actor such as SvK.

Looking at the parameters from a resilience perspective, the Start DT and End DT parameters are used to derive the duration metric. The consequence parameters are given by the number of (high and low voltage) customers affected which is used to derive the Functionality Loss metric. In terms of the Electricity Distribution interruption data the following is needed in order to derive the Functionality Loss metric:

- A baseline, given as the total number of customers of the companies that report interruptions to Energiföretagen.

In section 5.2 a detailed description of how both the duration and the Functionality Loss metrics are derived for the interruptions of Electricity Distribution.



**Figure 18 Usability of interruption data for the Electricity Distribution infrastructure, aggregated annually (above) and summarised by total interruptions, duration metric and the consequence parameter (below).**

## 4.3 TRANSPORT ROAD, TRAFIKVERKET

Trafikverket<sup>5</sup> is the public body/authority responsible of the long-term infrastructure planning of road-, railway-, shipping- and aviation-operations; as well as building and working with maintenance of the road- and railway-systems in Sweden (Trafikverket, 2017). The data received from Trafikverket derives from a project called “*Total traffic stop*”<sup>6</sup> (TTS), where traffic jams are registered when there is an unplanned total stop of traffic on any given road in Sweden. A situation of long ques where the traffic is nearly standing still, but some cars still may pass, it is not registered as a TTS. Only while the cars are unable to pass or turn away the stop is classified as TTS; as soon as the situation allows cars to slowly pass by again, the total stop should be revoked and registered as ended. On larger roads, where the two directions are completely separated, a stop is classified as total stop only if all the lanes in one direction are in full stop. For roads where the two directions are not separated, all lanes in all directions must

<sup>5</sup> In English: The Swedish Transport Administration

<sup>6</sup> In Swedish: Totalstopp i trafiken (English Translation Disclaimer)

be in full stop for the ‘*Situation ID*’ to be classified as, and registered in, TTS. The interruption data for Transport Road infrastructure spans the time period of 2016 – June 2017.

### 4.3.1 PARAMETERS

Each line of data is representing an interruption, given by 30 parameters, summarised and categorised in Table 4 below. An interruption in this data, a TTS, is made from the sum of all pieces of information reported about a specific TTS.

**Table 4 Summary of given parameters<sup>7</sup> in the interruption data achieved from Trafikverket**

Parameter category	Variable name	Description with adopted values or exemplification
<b>General characteristics of interruption</b>	Year	2016 and 2017
	Month	Integer, 1 to 12
	Situation ID	Integer
	Object history ID	Integer
	Start time	2016-01-13 16:00:00
	End time	2017-06-14 16:14:03
	Situation type	Description of the cause of failure, adopted values are: nature and traffic caused
	Redirection description	More detailed description of the redirectioning, empty if no redirectioning occurs
	First situation text	Accident, towing, stationary vehicle, fallen tree, accident involving heavy vehicle, obstacle on the roadway, road closed, flood, objects on the roadway, closed, accident involving dangerous goods, falling ice, severe fire, rockslide
	First additional text	road closed, road blocked, blocked, closed
	Impact	Not given, none, light, heavy, very heavy,
	Description	Text written by traffic manager to further describe the situation
<b>Failing system section or component</b>	Location text	Information about the location of the situation

<sup>7</sup> English Translation Disclaimer for parameters, variables and exemplification

	Road of great importance	Yes (else empty)
	Urban road	Yes (else empty)
	Heavy vehicle involved	Yes (else empty)
	County number	Interger, county ID Nr
	County name	Written name of county, example: Skåne län
	Road number	Road ID Nr
	Xpkt	9 digit interger, coordinates in a system called Sweref99
	Ypkt	9 digit interger, coordinates in a system called Sweref99
<b>Duration and consequences</b>	Gross duration [min]	Interger, duration in minutes from “start time” to “stop time”
	Net duration [min]	Interger < 720, more accurate duration where redirection of traffic duration is taken into account
	Start time, redirection	Date and time of redirection, 2016-01-12 16:54:50 (Empty if no redirection is stated)
	Affected directions	Determines if one or both directions are affected by a full stop, adopted values: 1, 2
	ADT (Averaged daily traffic)	Interger. A parameter calculated by complex road traffic measurements, to give the averaged daily traffic load of the given road section.
	Palpability	Interger. Sum of pre-calculated vehicle hours affeted by TTS
	ADT truck	Interger. ADT for trucks and heavy vehicles
	Duration class	Classification number, adopted values: 25, 2, 1
	Length [m]	Interger. Calculated length of waiting car

The parameters achieved from Trafikverket are plenty, and for the bigger part, the parameters are made to classify the reported total stops in traffic and considered uninteresting for our understanding of the data analysis at hand; for example, the ‘*Impact*’ and the coordinates of the accident (see ‘*Xpkt*’ and ‘*Ypkt*’) and other location descriptions.

Each interruption is the sum of many pieces of reported information, of which each is identified with a *Situation ID*, and they all add up to one ‘*Object history ID*’. Specific *Situation IDs* and individual information about those are excluded from this data set, which is made up by the summarised versions, *Object history ID*. The consequence of each interruption is calculated

through the ‘*Averaged daily traffic*’ (ADT), a number that is extensively gathered by Trafikverket for nearly every part of all Swedish roads. ADT defines the traffic density, which is specific to a local part of the road and sometimes even specific to the given traffic direction; a given ADT represents the averaged amount of traffic that passes the chosen road section during 24 hours. From the ADT and the duration, the so-called ‘*Palpability*’ is calculated, a parameter that estimates the number of vehicles affected by the TTS. To estimate the *Palpability* the day is divided into five parts, of which a given percentage of the ADT is assumed to pass hourly within each part. For example, between 16:00-18:00 during commuting traffic, 13% of ADT is calculated to pass each hour. Between 00:00-07:00, during low traffic, it is said to pass 1% hourly and so on. To perform the *Palpability* calculations, two duration quantities are introduced, the so-called ‘*Net duration*’ and ‘*Gross duration*’. The *Net duration* is the one used for calculating *Palpability*. The ‘total’ duration, between the first registration of the TTS and the last (‘*Start time*’ and ‘*End time*’) is called *Gross duration*. The *Net duration*, made to be more accurate and realistic, is calculated from the Start time to the ‘weighted end time’. That is, whichever occurs first of the following:

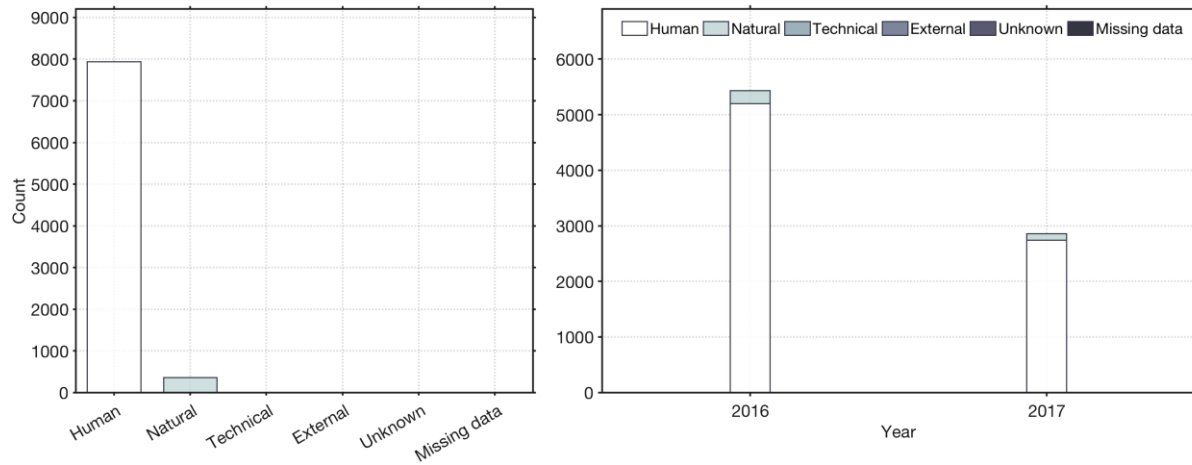
- When the ‘*Start time, redirection*’ occurs (if it does),
- At ‘*maximum net duration*’, 240 minutes on urban roads and 720 minutes on country roads,
- The given end time ( $Net\ duration = Gross\ duration$ ).

The *maximum net duration* is made to avoid too long and unrealistic durations. For example, if a road is affected by a TTS for days because of a flood or heavy snowfall, it is assumed that the traffic will redirect and the cuing vehicles will cooperate to enable passage away with or without help of emergency services.

### 4.3.2 SUMMARY

One of the main differences with Transport Road data compared to the interruption data for the other infrastructures is its limited time span. Unfortunately, this type of data has only been gathered since 2016, which only gives us the possibility of one and a half year of data to work with. Where most of the other data we received stretches for some ten years, this only reveals the last piece, which will make it more difficult to differ between trend and coincidence. As could be expected from the Transport Road infrastructure, almost all interruptions are due to human errors, see Figure 19.

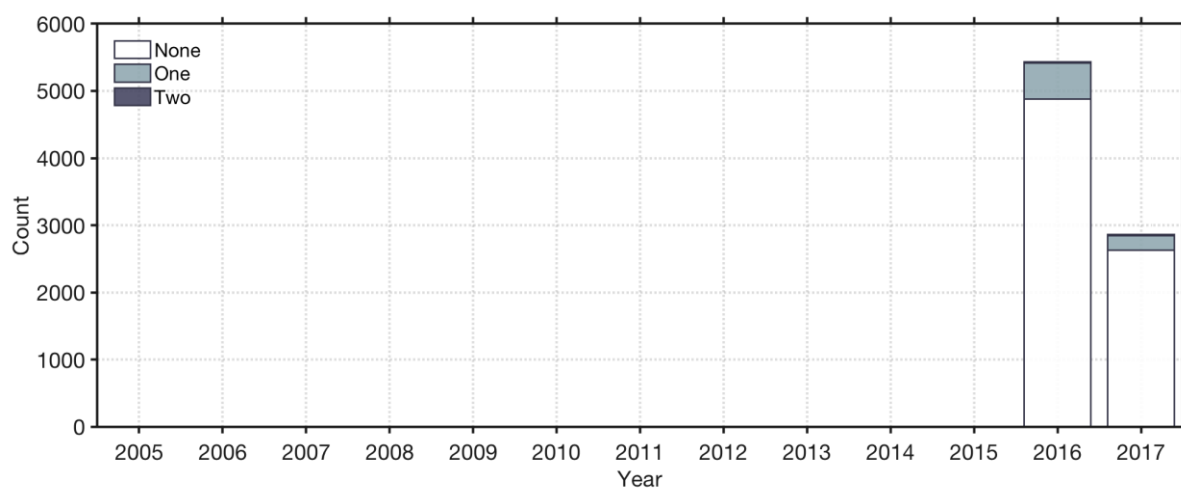




**Figure 19 Summary of the Transport Road infrastructure's interruptions and their causes, summarised (left) and annually (right)**

### 4.3.3 QUALITY ASSESSMENT AND LIMITATIONS

To count the number of lacking parameters here is difficult, as this data comes with empty cells where other would log something. Empty cells are seen in yes-no questions where the answer is not yes and for some parameters where no information should be given. This sometimes makes it difficult to realise if blank cells are lacking data or intentionally left empty, hence, the number of missing parameters might be slightly underestimated. That said, out of 8300 only a few lacks the minimum data needed, of which no one misses more than two parameters, see Figure 20 below.



**Figure 20 Number of missing parameters per year for the Transport Road infrastructure**

There are some key factors that shapes the data received from Trafikverket that should be clarified. To start with, there is a lower threshold of minimum five minutes; any situation that

would have classified as a total stop but falls below a duration of five minutes will not be registered as TTS. Also, any road that has not yet been analysed and lacks an assigned ADT is completely excluded from this data, as well as stops that are registered incorrectly so that the correct ADT cannot be applied.

To calculate and assign ADT for a given point on a road, a complex statistical calculation procedure is performed. This is made with consideration of traffic density variations amongst weekends, holidays, seasons and weekdays so that daily differences are averaged and included in the ADT constant. Then, while calculating *Palpability*, the same ADT is used regardless of which day it occurs. Only hourly differences over the day is taken into account, being the only factor that differ the two incidents of equal duration and location (read under section 4.3.1). This will contribute to over- and underestimations depending on when the incident occur. With large data quantities, they should contribute equally much and cancel each other out, which hopefully is our case. However, if only variations in traffic density is taken into account and not the variations in prevalence (occurrence of accidents), meaning that it is assumed that the number of incidents are directly proportional to the number of passing cars on a given piece of road, it is possible that this introduces a bias. Since the ADT behaves the same every day the whole year, while probably not equally many accidents occur every day during the whole year. It could be more probable that accidents occur during some parts of the year or some part of the day, e.g. during winter conditions (in Scania).

To conclude, this data is judged to be of good quality regarding most of the parameter values are available. However, the given consequence (the *Palpability*) are a made through rough estimations, which is judged to bring high uncertainties in terms of affected cars. It is also uncertain how and how accurately the TTS are logged. Given that a tree falls on a random Swedish road where the local community solves the situation, this could result in a fair number of affected cars, however it is hard to imagine how it could be logged in TTS.

#### 4.3.4 RESILIENCE PARAMETERS

The *Palpability* is chosen as the resilience parameter to represent the consequence of this data set, as it is the parameter that most closely estimates the number of affected cars for a given interruption. The given End DT is incorrect to use for calculating the duration metric since the *Palpability* is calculated from the given *Net Duration*. Hence, End DT is recalculated as,

$$End\ DT = Start\ DT + Net\ Duration \quad Eq. 9$$

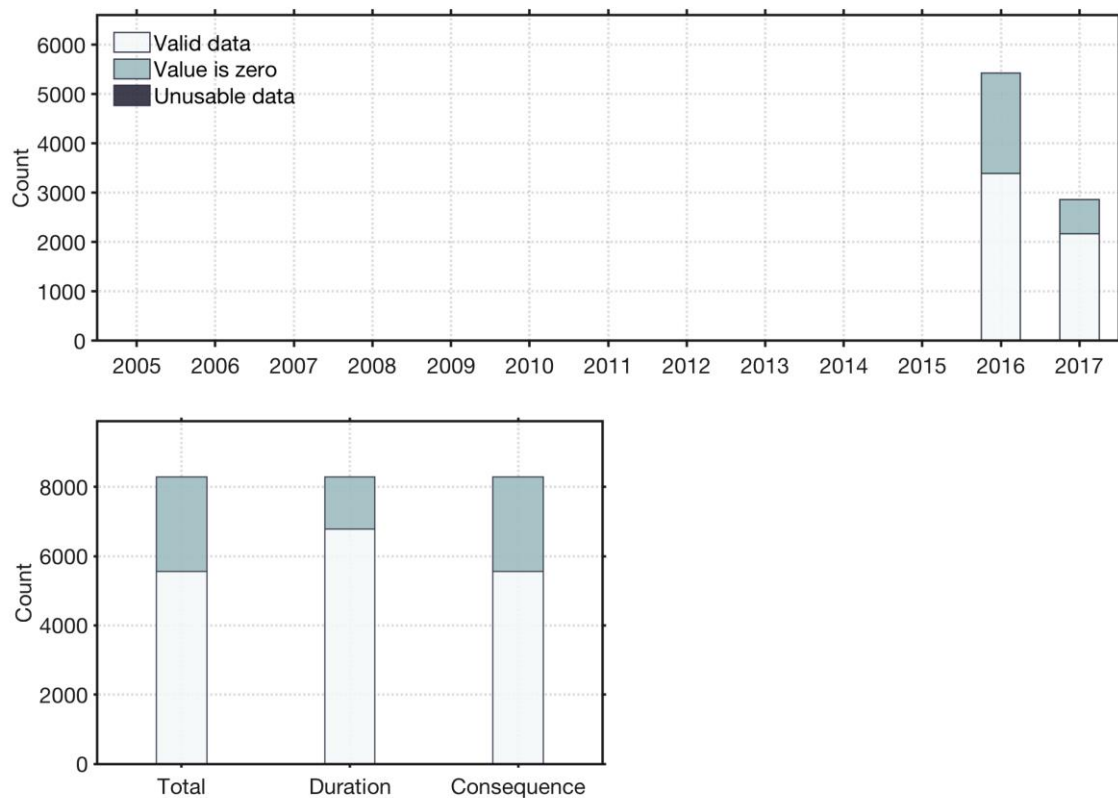
This is why there are that many interruptions that have zero values in terms of duration, see Figure 21. Which also is reflected in the consequences, as the *Palpability* is proportional to the

*Net Duration*. All *Net Durations* that are equal to zero will result in the consequences (the *Palpability*) to equal to zero.

In term of the Transport Road interruption data the following is also needed in order to derive the Functionality Loss metric:

- The retrieved baseline, as the consequence parameter (*Palpability*) represents the number affected cars, we need the total number of cars in the system as a baseline.

In section 5.3 a detailed description of how both the duration and the Functionality Loss metrics are derived for the interruptions of Transport Road.



**Figure 21 Usability of the interruption data for the Transport Road infrastructure, aggregated annually (above) and summarised by total interruptions, duration metric and the consequence parameter (below).**

## 4.4 TRANSPORT RAILWAY, TRAFIKVERKET

As previously mentioned in section 4.3, Trafikverket<sup>8</sup> is the public actor responsible for road-, railway-, maritime- and aviation operations, as well as constructing and maintenance of the road- and railway system in Sweden.

Receiving usable data for the Transport Railway infrastructure turned out to be harder than anticipated, not the least since we were told from Trafikverket while gathering the data for Transport Road infrastructure, that it is to be expected that the data for the Transport Railway infrastructure to be better and easier accessible data compared to Transport Road.

There has not been found any information about juridical responsibilities for data gathering, that said the logged delays are used to determine which part is to carry the responsibility and burdened with a fee for the delay(s) (Trafikverket, 2013).

The received data for the Transport Railway infrastructure comes from the statistical service department at Trafikverket and was received as Excel files, with yearly data spanning from 2012-2016.

### 4.4.1 PARAMETERS

Each line of data is representing the sum of all delayed trains that are logged with the same root cause, i.e. delays that are given the same '*Delay ID*'. Each interruption is given by 20 parameters, which are summarised and categorised in Table 5 below.

**Table 5 Summary of given parameters<sup>9</sup> in the interruption data achieved from Trafikverket**

Parameter category	Variable name	Description with adopted values or exemplification
<b>General characteristics of interruption</b>	Delay ID	Interger, six or seven digits starting with capital H Spanning from H783305 to H2124505
	Delay Nr	Delay ID without prefix 'H'
	Start date	2012.01.01 - 2016.12.31
	Start time	13:37

<sup>8</sup> In English: The Swedish Transport Administration

<sup>9</sup> Disclaimer for the Swedish to English translation of parameters, variables and exemplifications.

	End date	2012.01.01 - 2017.05.30
	Prognosed end date	2012.01.01 – 2018.11.30
	Prognosed end time	13:38
	Cause code	Examples: JJF -, JDE -, JTP -, DPS 01, DPR 03, JTP 13, DTB -, OUT -, DTT
	Delay cause level 1	Railway company, Operational management , Infrastructure, Accidents/ Incidents and external factors
	Delay cause level 2	Terminal/Platform Management; No Data from JF; Delayed from Depot; Towing/motor car; Personnel; Prioritization; Signaling facilities; Driver personnel; Congestion railway yard; Railway superstructure
	Delay cause level 3	-; Incorrect Handling/Decision; Priority Management; JF Wish; Machine Error; Track Exchange; Door Error; System Restart; Signal; Signal Switch; RBC and Line Blocking System
<b>Failing system section or component</b>	Delay location	Examples: Stockholm C, Göteborgs c, Malmö Godsbangård, Malmö c, Hallsbergs rangerbangård, Hässleholm, Hallsbergs pbg, Nässjö c, Bodens c, Norra bantorget
	Delay area	Examples: Cst, G, Mgb, M, Hrbg, Hpbg, Hm, N, Bdn, Nbt
	Causing train Nr	Train number responsible for the registered Delay ID
<b>Duration and consequences</b>	Number of cause-requiring additional-delays	Sum of stored delays that needs to be logged. Interger, spanning from 0 to 17097
	Number of cause-reported additional-delays	Sum of all ‘cause-requiring additional-delays’ that has been logged to the given Delay ID. No case has been found where this value differs from ‘Number of logged delays’
	Number of train disturbances	Interger, most often less than the ‘Number of logged delays’ Spanning from 0 to 6948
	Registered derived delay minutes	Sum of all derived extra delay time due to given Delay ID
	Registered additional delay minutes	Sum of all delay minutes for the trains registered under the same Delay ID

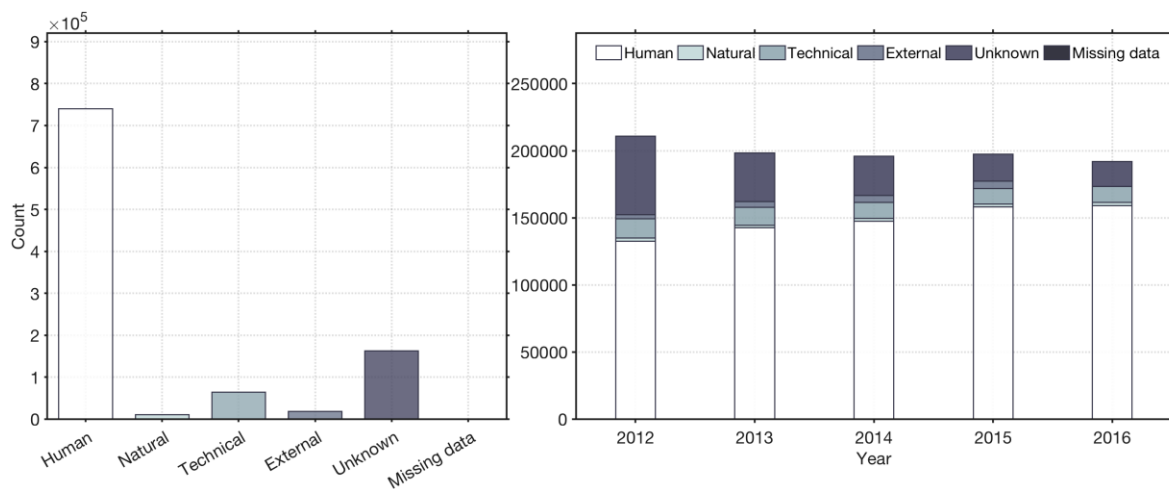
As could be expected, the system for logging train delays is both huge and complex. No dedicated documentation has been received to clarify the process and the arisen questions been communicated over phone. If correctly understood, a train that is delayed for more than three minutes when passing a given measurement point (usually located at train stations) generates

a ‘Cause-requiring additional-delay’. The *Cause-requiring additional-delay* will maintain until it is manually logged, thus given a root failure cause as well as a ‘Causing train Nr’, if there is a train to blame. Once a delay has been reported and given a *Delay ID*, it is stored as a ‘Cause-reported additional-delays’ (CRAD).

Given a train that is delayed by  $x$  minutes, this train will only generate new CRAD if it is delayed more than  $x$  when it passes a measurement point. So, if a train is delayed 2 minutes according to schedule from measurement point A, then it is delayed by 15 minutes according to schedule from measurement point B and lastly it is delayed 20 minutes according to schedule from measurement point C; that train would have 0 ‘Registered additional delay minutes’ (RADM) and 0 CRAD from point A, then from point B it would have 13 RADM and 1 CRAD and another 5 RADM and 1 CRAD from point C, making the total sum of 18 RADM and 2 CRAD.

#### 4.4.2 SUMMARY

The Transport Railway data covers five years and comes with approximately million logged *Delay IDs*, which is the sum of three million registered CRADs. The number of *Delay IDs* are on a stable level, at just about 200 000 per year, see Figure 22. The bigger part of the interruptions are due human errors and the ratio of unknown causes is continuously improving.



**Figure 22 Summary of the Transport Railway infrastructure’s interruptions and their causes, summarised (left) and annually (right)**

#### 4.4.3 QUALITY ASSESSMENT AND LIMITATIONS

It is considered that the delays in Transport Railway data are logged accurately. However, the delays are floored minutely, and there is a threshold of three minutes, which basically excludes all trains delayed less than four minutes (3:59 to be exact). As mentioned, the party that is

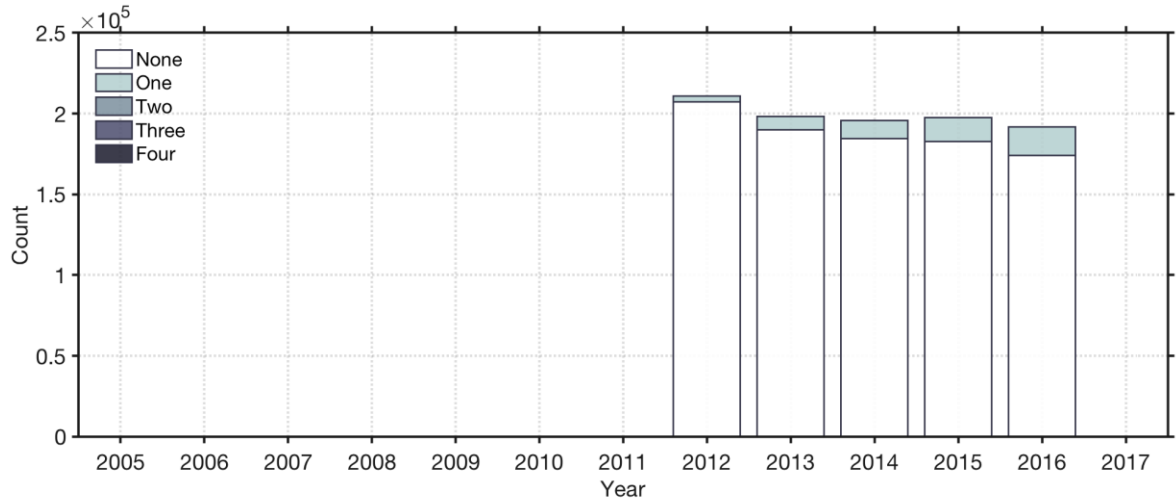
deemed responsible for a delay is punished by a fine, which makes for strong economic interests in its accuracy and nearly the entire system seems to be measured and logged digitally in real time. These are factors that are argued to contribute well to this data set's quality. Since the logged failure cause (in Table 5 referred to as '*Delay cause*') is the final judgement of whom carries the guilt, it is not strange that only six *Delay IDs* of a million comes without a logged failure cause.

It is hard to define interruptions from this data as it only includes delays and no cancelled trains are logged. The ultimate indicator for railway interruptions would be logged system interruptions, when train traffic is failing completely, and no trains can run. We were told, however, that no such data is stored. This leaves a big gap of uncertainty in this data set, as it only logs delays. This means that given an incident on a railway track with only one track, where no trains can pass and are all cancelled for a certain time, it might not give justified consequences (the CRAD) in a data set where only delayed trains are registered.

Furthermore, trains can only be logged to a certain amount of fixed delay causes (given by three levels, see Table 5) and are not logged to a "real cause", i.e. given a storm that affects big parts of the country and equally much the railway system, it is quite uncertain how probable it is that all the interruptions connected to this storm will be given the same *Delay ID*.

Another flaw is the fact that almost all *Delay IDs* are given the same Start- and End DT. This makes it difficult to assess for how long a train keeps a delay. Since CRAD is only registered for the measurement points with measured additional CRAD, it will not take in to consideration for how long it carries this delay. For example, given a train A that is delayed an hour from the start and keeps this delay during a whole route of ten hours; then given a train B, that gets stuck in the end of its route which results in it being delayed for an hour between the two last measurement points (to its end station). In this data set train A and train B will most probably show up with the equal Start- and End DT and therefore it is impossible to differ between the two, as they will result in the same CRAD and will therefore be counted for equally.

Out of just over below one million interruptions given in the data, there are only a few interruptions that lacks values for the defined data parameters, of which no single interruption misses more than four parameters, see Figure 23 below. Overall, this data is judged to be of high quality and represents the characteristics of interruptions that accurately resembles reality in terms of train delays, however how well it resembles interruptions remains uncertain as it does not include cancelled trains.



**Figure 23 Number of missing parameters per year for the Transport Railway infrastructure**

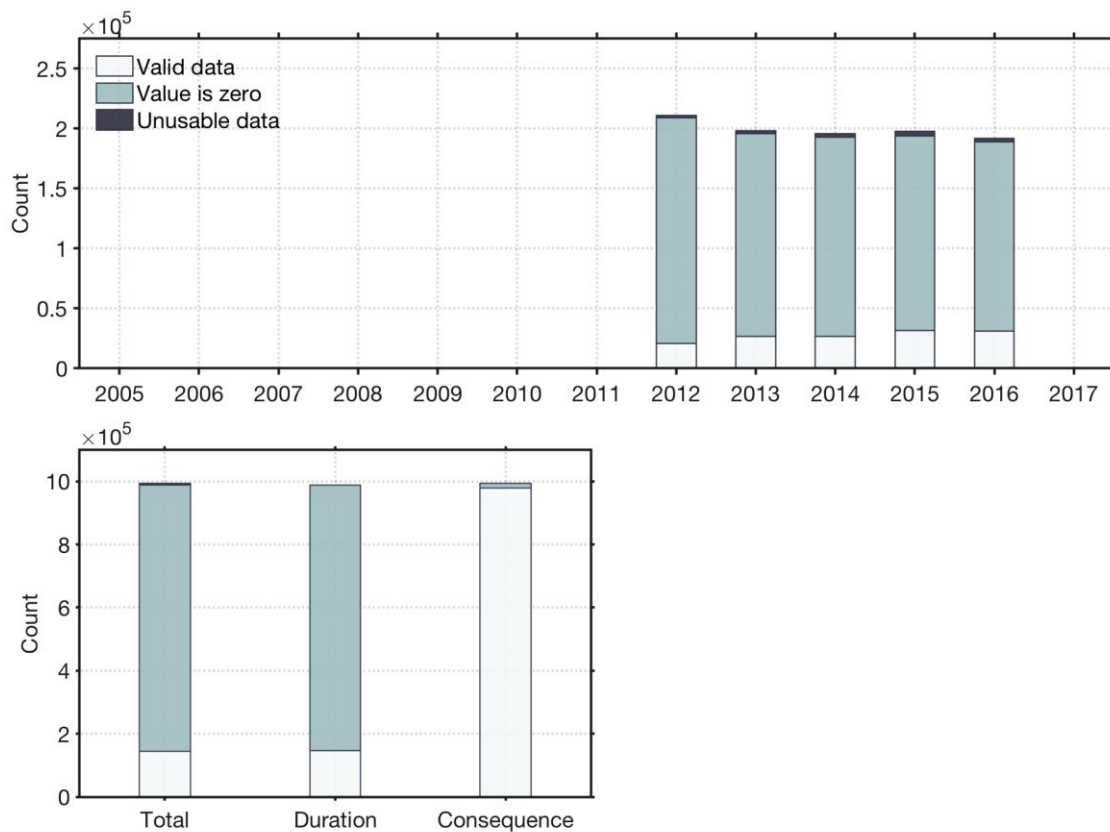
#### 4.4.4 RESILIENCE PARAMETERS

To determine resilience parameters was tough for the Transport Railway infrastructure, as there is no obvious parameter given in the data that resembles consequences. Additionally, almost all values come with an incorrect duration value of zero, see Figure 24 (bottom). That is the Start DT and End DT was the same in majority of cases. Initially the number of RADM was expected most useful consequence measurement. However, it was ruled out since a baseline could not be derived for the delay minutes. In the end, the only parameter deemed adequate to resemble consequences is the CRAD for each interruption. The Start- and End DT are used to calculate the duration metric. In terms of the Transport Railway interruption data the following is also needed in order to derive the Functionality Loss metric:

- The retrieved baseline, which represents the number of annual departures in the system.

In section 5.4 a detailed description of how both the duration and the Functionality Loss metrics are derived for the interruptions of Transport Railway. Furthermore, as the bigger part of all interruptions resulted in zero duration, we needed to figure out the End DT of those *Delay IDs* (interruptions). How this was done is also covered in section 5.4.





**Figure 24 Usability of the interruption data for the Transport Railway infrastructure, aggregated annually (above) and summarised by total interruptions, duration metric and the consequence parameter (below).**

## 4.5 WATER SUPPLY, STOCKHOLM VATTEN OCH AVFALL

Stockholm Vatten och Avfall (SVOA) is the main distributor of drinking water and runs the wastewater treatment for Stockholm city and the municipality of Huddinge (SVOA, 2015). SVOA gathers data of disruptions in the water interruption caused by service and reparations of broken piping for internal audit.

The collected data set from SVOA stretches from 2007 to 22<sup>nd</sup> May 2017 and provided in Excel format.

### 4.5.1 PARAMETERS

SVOA does not present their interruptions in the same manner as other interruption data that was achieved in the form of Excel file in the way the data is tabulated. The most common way, the interruption data is presented, is a table where each row resembles an interruption, defined by a certain number of fields or cells containing the defined parameters, characteristics and descriptions. However, SVOA's interruptions have most values gathered in one column, where

one disruption, or ‘*Work order ID*’ is represented by several lines of different but still unified parameters. Some interruptions are defined by fewer lines than others, introducing some uncertainties about whether the data is lacking unintentionally or if it is intentionally stored differently. That said, some patterns are found that explains the differences that are more easily taken into account; e.g. after two years the data changes behaviour and slightly different parameters are stored (see Figure 26 - Figure 27 below). In total, each interruption can be given by 11 different parameters, however structural alterations of how the data is stored were made in middle of 2009; where prior to alterations the stored data is given by 7 parameters and post alteration by 9 parameters, see Table 6 below.

**Table 6 Summary of given parameters<sup>10</sup> in the interruption data achieved from SVOA**

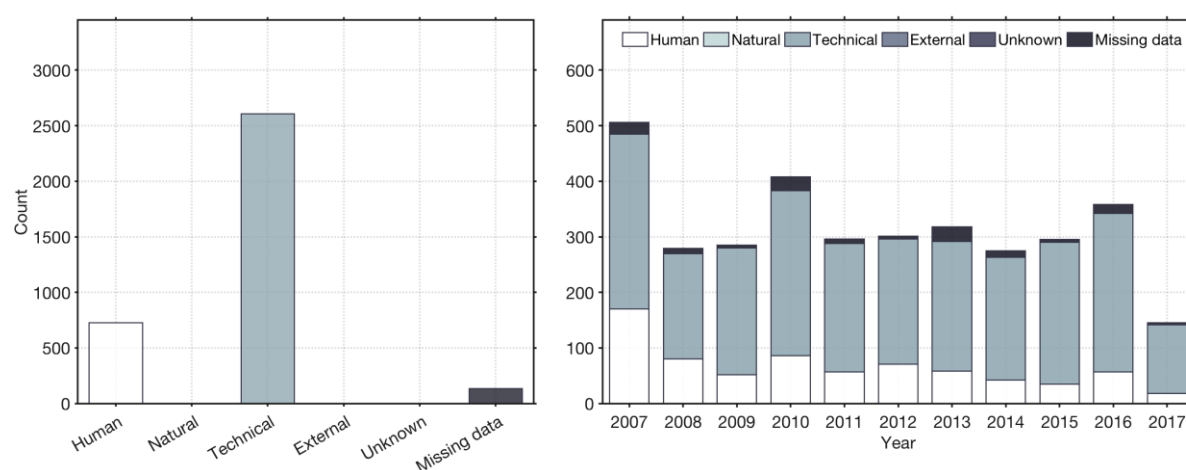
Parameter category	Variable name	Description with adopted values or exemplification
<b>General characteristics of interruption</b>	Work order ID	Interger
	Start date and time	From 2007-01-02 07:17:09 to 2017-05-22 13:19:53
	Failure cause	Leak, pipe rupture; leak; leak, joint; leak, chemical corrosion; leak, crack; leak, excavation/digging; rupture, sewer; unsealed gasket; examination; preventive maintenance; failure on cover/lid; block.
	Time ambitions fulfilled?	Yes, no ambitions set, no
<b>Failing system section or component</b>	Work order type	Repair of distribution-pipe, repair of main water pipe, repairation service
<b>Duration and consequences</b>	Duration [h]	Duration in hours, interger (up until 12 <sup>th</sup> June 2009)
	Total user-hours without water [h]	Interger (up until 12 <sup>th</sup> June 2009)
	Hours without water [h]	Interger (after 12 <sup>th</sup> June 2009)
	Number of users	Interger (after 12 <sup>th</sup> June 2009)
	Length [m]	Interger (after 12 <sup>th</sup> June 2009)
	Asphalt area [m <sup>2</sup> ]	Interger (after 12 <sup>th</sup> June 2009)

<sup>10</sup> Disclaimer for the Swedish to English translation of parameters, variables and exemplifications.

Before 12<sup>th</sup> June 2009 the data set gives slightly different information and is in general of much lower quality. During this time, the consequences are given by the parameter called ‘*Total user-hours without water*’ (the summarised duration of the affected users), which easily transforms to number of users when divided by duration. Unfortunately, both parameters are seldom present for those interruptions. However, after 12<sup>th</sup> June 2009 the data set’s quality increases drastically. ‘*Duration*’ and *Total user-hours without water* is replaced by ‘*Hours without water*’ and ‘*Number of users*’, and two new parameters are introduced: ‘*Length*’ and ‘*Asphalt area*’, describing societal effects of the consequences of pipe repairing and excavation in an urban environment.

## 4.5.2 SUMMARY

This data represents piping that SVOA for any given reason decides to repair, which forces them to cut the water pressure for some customers. Water distribution piping networks are often old and there is a constant leakage flow from which substantial quantities of produced water is lost (Malm, 2011). Leakages and damaged piping does not lead to water outage in most cases, not until the water pressure needs to be turned off for pipe replacements or reparations. It is first then, when the water is turned off, that connected customers will experience the interruption. From this perspective, the large proportion of Technical disruptions seems to be legitimate, when close to all are due to broken piping (see Figure 25).



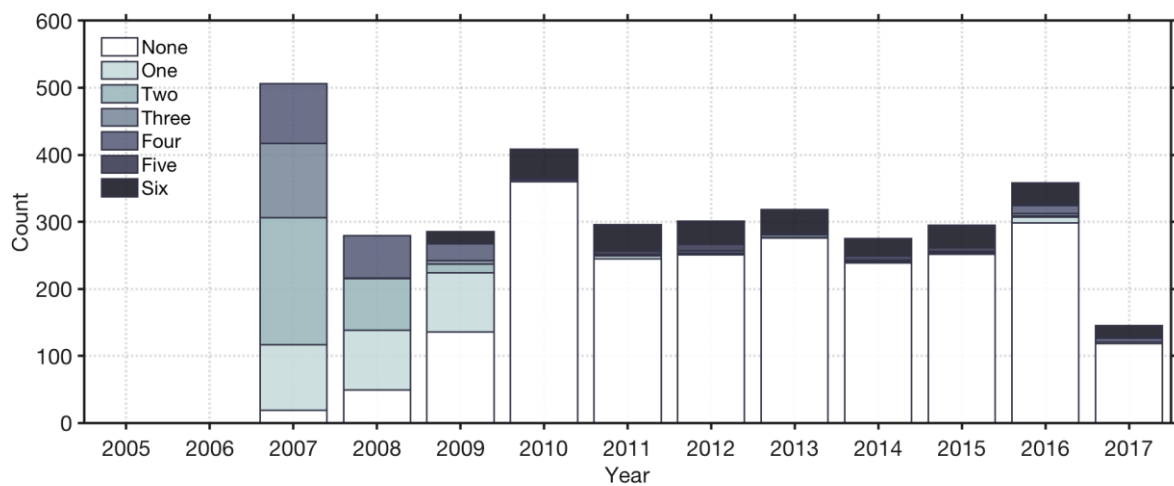
**Figure 25 Summary of the Water Supply infrastructure’s interruptions and their causes, summarised (left) and annually (right)**

## 4.5.3 QUALITY ASSESSMENT AND LIMITATIONS

It seems like damaged piping seldom leads to changes in water quality or interruption, but only to higher consumption needs to compensate for the losses of water in the system due to spilled water. Since we are informed that the only interruptions in SVOA’s system are due to these

repairs, this data is argued to be a good representation of reality. It is worth mentioning that we were told that never during the time period of this data set has there been any type of interruption that resulted in undrinkable water qualities. According to SVOA, a big part of *Number of users* is derived from the national population registration, giving the exact number of persons living at the affected addresses, adding up to the numbers accuracy. When this information is not used, we are told that an averaged number of habitants per household is used.

As mentioned in the summary above, there are indications that suggests this data being of high quality in terms of representing reality. Looking at the number of missing parameters in Figure 26 below, it seems as the data after 12<sup>th</sup> June 2009 (when changes in the data structures were made, see section 4.5.1 above) is of fine quality, where almost all interruptions are given with all parameters.



**Figure 26 Number of missing parameters per year for the Water Supply infrastructure**

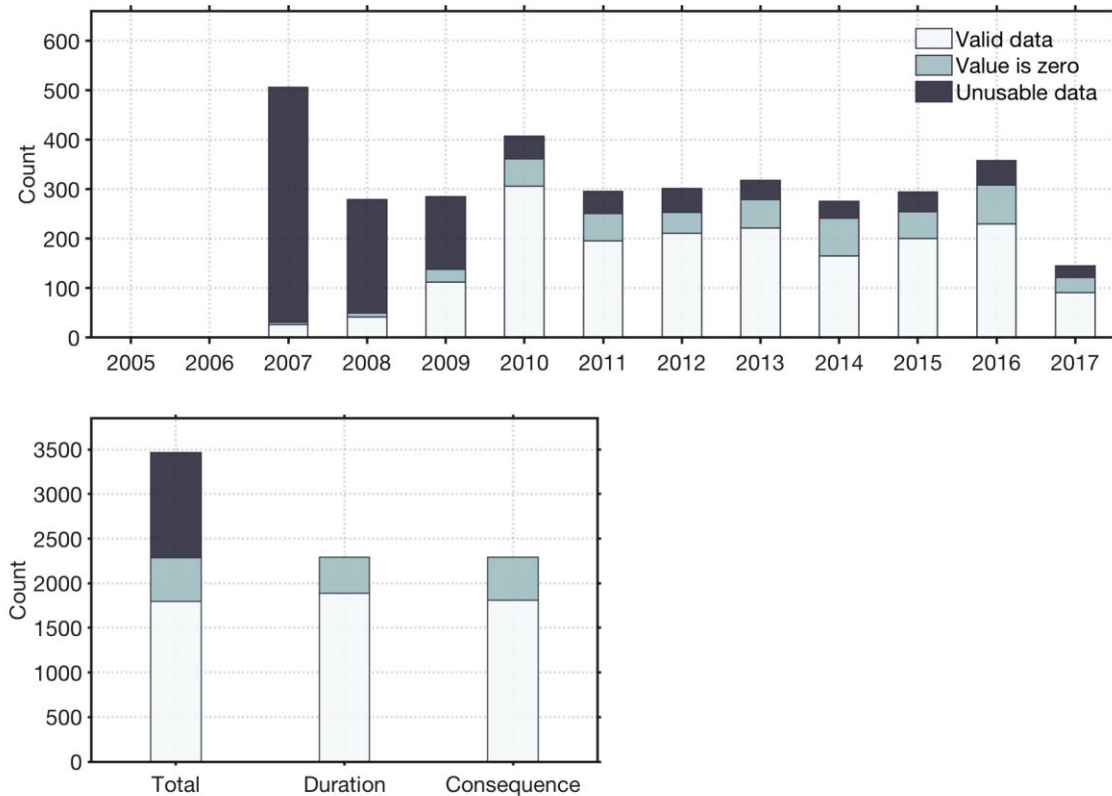
#### 4.5.4 RESILIENCE PARAMETERS

The data after the change in 2009 comes with both resilience parameter in the vast majority of cases. Some interruptions come with zero duration or consequence, which might be inaccurate data or explained by other reasons. Since broken pipes does not seem to generate many or any spontaneous interruptions, we suggest that it sometimes might be possible to depressurise only such part of a water piping system, that it enables repair without leaving any customers without water. This could potentially explain the interruptions that results in no consequences, see Figure 27.

The Start DT together with the given duration gives the exact duration with Start- and End DT as in the previous data sets. The number of affected customers is used as consequence parameter for the Functionality Loss metric. In terms of the Water Supply interruption data the following is also needed to derive the Functionality Loss metric:

- The retrieved baseline, which is represented by the total number of customers of SVOA.

In section 5.5 a detailed description of how both the duration and the Functionality Loss metrics are derived for the interruptions of Water Supply.



**Figure 27 Usability of the interruption data for the Water Supply infrastructure, aggregated annually (above) and summarised by total interruptions, duration metric and the consequence parameter (below).**

## 4.6 TELECOMMUNICATION, POST- OCH TELESTYRELSEN

The Swedish Post and Telecom Authority<sup>11</sup> (PTS) is the public agency that is responsible for monitoring both electronic communications (including the Internet, telephony and radio) and postal sectors in Sweden. Where its overall goals is to secure communication, effective use of resources and long-term sustainable competition and consumers benefits (PTS, n.d.-b).

Since July 2011 electronic communication operators are obligated to report disruptions and interruptions that fall under the criteria of threshold (see Table 7) according to PTS (n.d.-b,

<sup>11</sup> In Swedish: Post- och telestyrelsen

2012) regulation 8 § PTSFS 2012:2 regarding reporting of disruptions or interruptions of great significance (PTS, 2013).

**Table 7 Threshold values. The table is adapted from PTS's (2012) regulation**

<b>Time occurrence of the disruption or interruption</b>	<b>Estimated extent of disruption or interruption</b>
≥ 1 hour	≥ 150 000 subscriptions or ≥ 15 000 km <sup>2</sup> joint affected area or ≥ 50% capacity loss
≥ 2 hour	≥ 30 000 subscriptions or ≥ 5 000 km <sup>2</sup> joint affected area or ≥ 30% capacity loss
≥ 6 hour	≥ 5 000 subscriptions or ≥ 2 500 km <sup>2</sup> joint affected area or ≥ 50% capacity loss
≥ 24 hour	≥ 2 000 subscriptions or ≥ 1 000 km <sup>2</sup> joint affected area or ≥ 10% capacity loss

The data achieved from PTS was in from of incident reports which needed to be aggregated to an Excel format manually. The time period of the data is from mid-August 2011 to the beginning of March 2017. It is important to take note that part of the information in the incident reports are masked as it is considered to be covered by secrecy law (Regeringskansliet, 2009b). The masking varies a lot from report to report, both in terms of how much is masked and what.

#### 4.6.1 PARAMETERS

The Telecommunication data parameters are not gathered and presented in same manner as for the other CI, as the original information regarding disruptions and interruptions (in this thesis we do not distinguish between the two and refer to them simply as interruptions) is not presented in tabulated format. Operators are obligated to provide specific information about the incidents in accordance to PTS (n.d.-b, 2012) regulation 3§ - 7§ PTSFS 2012:2. PTS (2013) has also published a document to aid the telecommunications companies to interpret the regulation. This document gives detailed information on what information it should include, but there is no clear information on how it should be displayed. The operators' freedom in answer-

ing the questions, reflects how the incident reports are written and how differently the consequences are reported. This makes it more complicated to transcribe the data and to define unified parameters.

Parameters are presented in Table 8 below, which are based on how we decided to withdraw the information regarding interruptions from these incident reports. Due to the complexity of transcribing the data, we limited ourselves to three sub-Telecommunication infrastructures: Broadband Services, Fixed Telephony, and Mobile Communication.

**Table 8 Summary of parameters based on information available in the incident reports achieved from the Telecommunication infrastructure.**

Parameter category	Variable name	Description with adopted values or exemplification
<b>General characteristics of interruption</b>	Start date & time	2012.07.29 17:23
	End date & time	YYYY.MM.DD hh:mm, see Start date & time above
	Affected municipality	Given municipality where the interruption had an affect
	Affected county	Given county where the interruption had an affect
	All of Sweden affected	Yes or No
<b>Causes of interruption</b>	Failure cause	Human, Technical, External, Natural, Unknown, Missing data
<b>Consequences for IP-based infrastructure services</b>	Customers (number of affected customers, subscribers)	Integer
	Geographical area [km <sup>2</sup> ]	Integer
<b>Consequences for Fixed Telephony</b>	Customers (number of affected customers, subscribers)	Integer
	Geographical area [km <sup>2</sup> ]	Integer
<b>Consequences for Mobile Communication</b>	Customers (number of affected customers, subscribers)	Integer

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Mobile sites (number of affected 2G, 3G and 4G mobile sites)	Integer
Geografical area [km <sup>2</sup> ]	Integer

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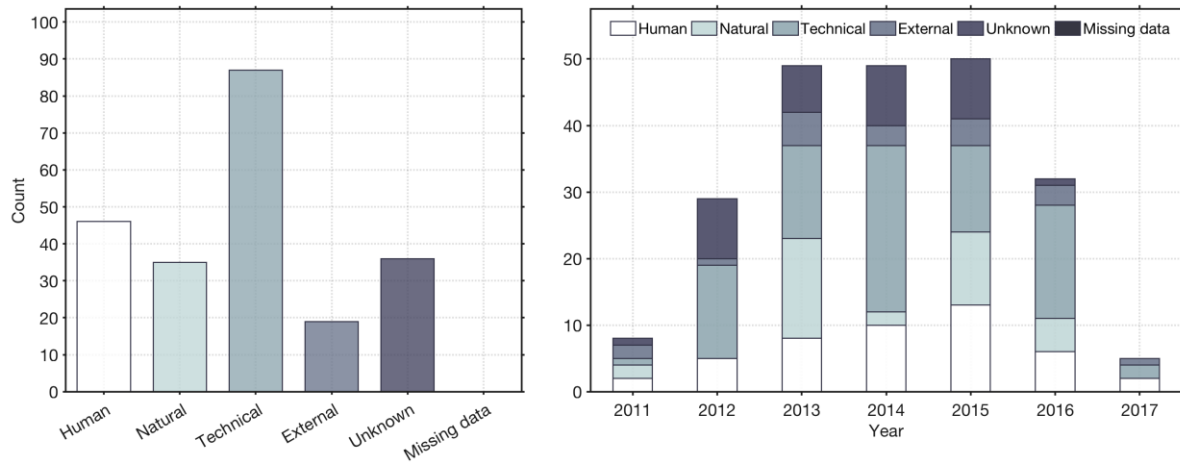
For clarification, interruptions that switches between going down and coming up again are treated as individual interruptions and given the same consequence parameter, if and only if it is clearly stated in the incident report. This is done to not over estimating the duration of the interruption, as the system had function in between. Furthermore, we do not distinguish between customer, subscriptions, connection; thus, we call it customer. In terms of affected mobile sites referrers to any of the mobile site types 2G, 3G and 4G. Regarding the interruptions where the consequence parameter was available, if it was expressed in a range we adopted the maximum value.

#### 4.6.2 SUMMARY

The data set is aggregated manually (as previously mentioned), which was done by reading and analysing 366 incidents documents, resembling what became a data set of 223 interruptions. As can be seen in Figure 28, the number of incidents the first three years is steadily increasing, which might the result of an implementation process, to then be on steady level for three years and then decrease again. The decrease in the end is probably because that we did not receive the latest reports, as we only received reports that had already been masked at some point before we asked for them. It should be noted that the same cause related interruption may affect one or more sub-Telecommunication infrastructure, depending on the services/infrastructures are provided/operated by the Telecom operator.

It is understandable that the reports need to be masked to protect the exposed companies and for the safety of the nation, but the irregularity in the masking makes it questionable. Some reports are completely unmasked, in others the masked information is in parts that were left unmasked in some cases and vice versa.





**Figure 28 Summary of the Telecommunication infrastructure’s interruptions and their causes, summarised (left) and annually (right)**

### 4.6.3 QUALITY ASSESSMENT AND LIMITATIONS

There is quite a lot of missing data in the masked reports, which makes it difficult to define the parameters. From what can be gathered from the unmasked information, the data is very accurate. However, in many cases the data values that are relevant to the intended purpose of this thesis is masked or partially masked. Assumptions has been made to increase the number of usable interruptions. That said, when there is not enough information available to draw reasonable parameter values for the interruptions the data value/s must be treated like they are missing. In some reports, parts of the masked information were given, e.g. where the numbers of affected customers were masked, the areas are sometimes mentioned. In these cases, the population of the affected areas (municipalities or regions) and the given carriers market share in terms of customers has been used to estimate the number of affected customers.

In total, this is one of the most inaccurate data set as so many incidents are left unknown, both as we cannot be sure that we have all the incident reports, but also the unknown number of lacking incidents due to the threshold value for reporting. However, there are still some incidents to use, and for the three years 2013-2015 it seems to be on a stable level, which we believe is an indicator on that we might have most of the raw data (reports) for this period, missing parameters or not.

### 4.6.4 RESILIENCE PARAMETERS

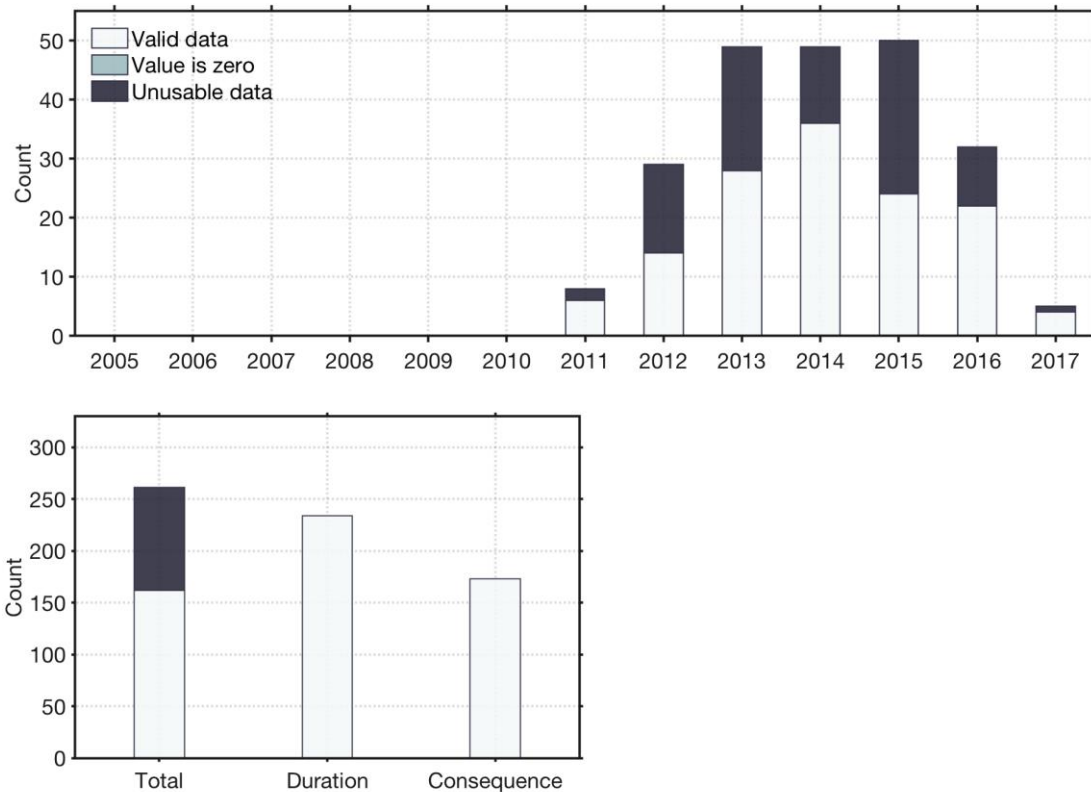
It should be stated now, that we decided to group the consequence categories based on type of sub-Telecommunication infrastructure to make the work of extracting and aggregate the information given in the incident reports more manageable. We defined three consequence categories. The first category is IP-based infrastructure (hereby referred to as Telecommunication Broadband Services) and refers to fixed internet and broadband connections via dial up modem,

cable, fibre or xDLS, but also services such as IP-based telephony and IPTV. This is done as some incident reports talk about broadband service without specifying clearly which part of it and/or how the consequences are distributed between them. The second category is mobile communication (hereby referred to as Telecommunication Mobile) and refers to mobile call, data, MMS, SMS and mobile broadband. The third category is fixed telephony (hereby referred to as Telecommunication Fixed Telephony) which includes PSTN and ISDN, IP-based phone is not included here even though it is considered as fixed telephony (PTS, n.d.-a).

The interruptions durations are accurately stated by Start- and End DT, and available for almost all incidents, see Figure 29. The consequences are given as either affected '*Geographical area*' or number of affected '*Customers*'. With the exception of Telecommunication Mobile which has an extra category, that is the number of affected '*Mobile sites*'. The consequences are only one part of deriving the Functionality Loss metric. In term of the three sub-Telecommunication infrastructure the following is also needed in order to derive the Functionality Loss metric:

- The retrieved baselines of the total number of users for the three Telecommunication sub-infrastructure
- The retrieved baseline of total number of mobile sites

In section 5.6 a detailed description of how both the duration and the Functionality Loss metrics are derived for the interruptions of the three sub-Telecommunication infrastructures.



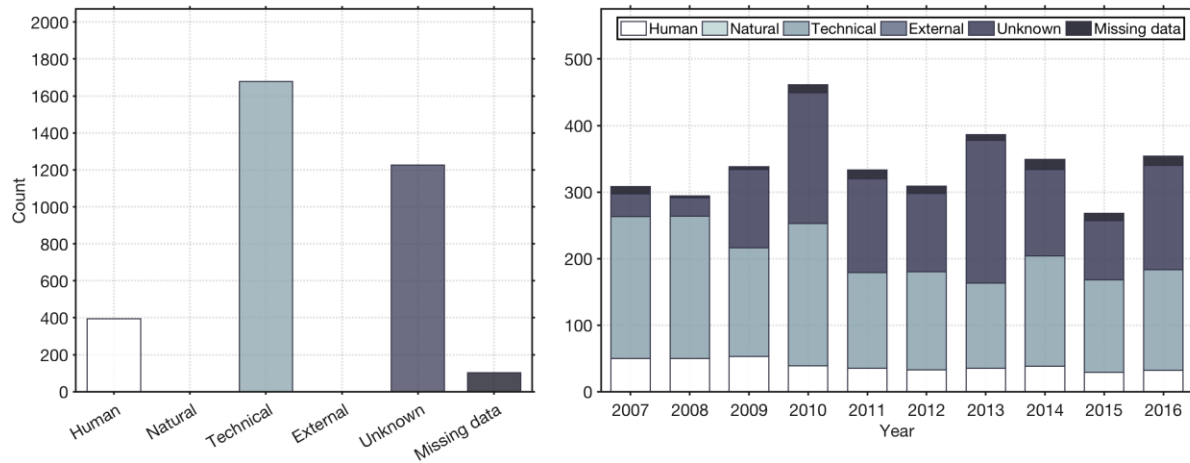
**Figure 29 Usability of the interruption data for Telecommunication infrastructure (aggregated for the three Telecommunication sub-infrastructure), aggregated annually (above) and summarised by total interruptions, duration metric and the consequence parameter (below).**

## 4.7 INSUFFICIENT DATA QUALITY

For documentation purposes and for a general overview of the data collection efforts with respect to interruption data for different infrastructures, the data received but could not be used is shortly presented here.

### 4.7.1 WATER SUPPLY, GÖTEBORG KRETSLOPP OCH VATTEN

Göteborg Kretslopp och Vatten offered a very complete data set, see Figure 30. Unfortunately, it only comes with Start DT and it does not come with any parameters that describes consequences. Without duration and quantifiable consequences of an interruption, the data is unusable for the purpose of this thesis.



**Figure 30 Summary of Göteborg Kretslopp och Vatten's interruptions and their causes, summarised (left) and annually (right)**

#### 4.7.2 WATER SUPPLY, VA SYD

The interruption data achieved from VA SYD was not of sufficient quality. It displays the number of water leakages both in the main distribution pipeline and service pipeline during 2016 on a monthly basis. It also shows the total number of leakages per year for 2012-2016 for these two types of pipelines. The data applies to the municipalities of Malmö, Lund, Burlöv, and Eslöv. The interruption data is in PDF format, where the number of leakages are presented both in tables and figures.

This data does not contain any information regarding timeframe for each individual interruption and a consequence parameter. Thus, this interruption data set is excluded as it lacks information on the basic parameters to fulfil the purpose of this thesis.

#### 4.7.3 TELECOMMUNICATION, SUNET

SUNET stands for Swedish University computer Network. It owns and operates a data communication network. The interruption data is recorded in monthly reports where the incidents are logged per calendar date they occur, with short description of what happened. This applies to both planned and unplanned interruptions. Then the month is summarised in a table where the number of incidents are aggregated in accordance to specific component (e.g. hardware, software, link and routing) and the total duration of the grouped events is given in terms of planned and unplanned event. This table then summarises the duration in terms of total duration of unplanned, and respectively planned; and then it summarises the total duration of all incidents (planned and unplanned) in terms of the specific components. After evaluation of the

received data from SUNET it is determined that the data set do not fulfil the requirement of the RAA and therefor excluded.

## 4.8 SUMMARY

In the pursuit of attempting to gain access to suitable interruption data for the different types of CIs, while not knowing if respective actors would reply or have access to the data we needed, resulted in a rather extensive outreach. In this chapter we have presented the interruption data that we got access to, both in terms of the data that fulfilled the requirement criteria of our RAA and the interruption data that did not meet the fundamental criteria of the approach. We want to emphasise that we also attempted to get interruption data for other CIs as well, such as aviation, maritime and district heating. In Table 9 we have summarised the communicated infrastructures and the respective actor that we either got interruption data or attempted to obtain interruption data from. The table also summarise the collected interruption data it terms of the fundamental criteria of the RAA, that the data includes the resilience parameters needed for the resilience metric, that is Start DT, End DT and one or more consequence parameters.

**Table 9 Summary of the communicated infrastructures. The colour code refers to the collected interruption data in relation to the fundamental criteria of our RAA. That the collected data set has Start DT, End DT and quantitative consequence parameter. Green means the parameter is given; yellow means the parameter can be derived from another given parameter in the data set; and red means that the parameter is not given.**

Infrastructure	Organisation	Answer data	Data available	Start DT	End DT	Quantifiable consequences
Electricity Transmission	Svenska kraftnät	Yes	Yes			
Electricity Distribution	Energiföretagen	Yes	Yes			
Electricity Distribution	E.ON	No				
District Heating	Kraftringen	No				
District Heating	Energiföretagen	Yes	No			
Water Supply	Svenskt Vatten	Yes	No			
Water Supply	Stockholm Vatten och Avfall	Yes	Yes			
Water Supply	Göteborg Kretslopp och Vatten	Yes	Yes			
Water Supply	VA SYD	Yes	Yes			
Transport Road	Trafikverket	Yes	Yes			
Transport Railway	Trafikverket	Yes	Yes			
Transport Aviation	Luftfartsverket	Yes	No			
Transport Aviation	Swedavia	Yes	No			
Transport Aviation/Maritime	Transportstyrelsen	Yes	No			
Transport Maritime	Sveriges Hamnar - transportföretagen	Yes	No			
Telecommunication All	PTS	Yes	Yes			
Telecommunication Network	SUNET	Yes	Yes			

# 5 RESILIENCE METRICS

The resilience metrics duration and Resilience Loss is estimated in accordance to Eq. 1 and Eq. 3 (see RAA in section 3.3.3), for each individual interruption. As for the Functionality Loss metric the generic representation is given in Eq. 2 (see RAA, section 3.3.3), that said how it is actually estimated varies between infrastructure to infrastructure. Therefore, a further elaboration on how the Functionality Loss is derived is covered here.

## 5.1 ELECTRICITY TRANSMISSION

The interruption data regarding the Electricity Transmission infrastructure in Sweden contains the minimum parameters for deriving the resilience metrics. The time parameters of when each individual interruption starts, and when it ends are given, as well as the duration of the interruption. In the resilience assessment we calculated the duration with the start and end times given and did not use the given duration. There is given one consequence parameter and that is ENS (*Energy Not Supplied*).

Regarding the consequence parameter, during analysis of the interruptions we noticed that there are many interruptions that have zero duration and zero consequences. However, there were also some interruptions that have zero duration which lead to ENS. According to SvK (Hampus Bergquist, e-mail, 2017-11-28) interruptions with zero duration minutes are interruptions that last under a minute. This is for interruptions that are automatically corrected (which normally takes in the order of milliseconds to seconds). In cases that lead to ENS, this is a result of when switching is required but there are no available lines to take over the load from the disconnected line. SvK's power grid is a mesh network in about 80-90% of Sweden, thus the remaining power lines, those that are not faulted and are still in operation, can in most cases take over the load of the faulted powerline, hence leading to zero ENS (in comparison with

alternative routes for road traffic when a road is closed). The interruptions with duration of zero minutes and zero consequences are not included in the resilience assessment (i.e. a interruption that does not lead to any consequences), as SvK is the only actor that does this uniformly in their interruption data. For the cases where the interruptions have the duration of zero minutes but associated with an ENS greater than zero we give them duration of one minute, so the Functionality Loss can be derived and analysed. The duration of one minute is chosen as that is the lowest resolution for time in our implemented analysis approach.

### 5.1.1 DERIVING RESILIENCE METRICS FROM THE COLLECTED INTERRUPTION DATA

The metrics are derived in accordance to the generic equations presented in section 3.3.3.

#### **DURATION METRIC**

Though the duration is given in the interruption data, we use the Start DT and End DT of the interruption to calculate the duration of the interruption.

The duration is derived from the given timeframes for each interruption in the given interruption data, in accordance to Eq. 1 (in section 3.3.3).

#### **BASELINE**

The average hourly power consumption over one year in Sweden is utilized as the baseline for calculating the Functionality Loss in the system. The baseline is retrieved from publicly available data on SvK's (2016b) homepage. The data presents the exact hourly energy consumption, that is per clock hour, and is given with the accuracy of  $\text{MWh} \times 10^{-6}$  (Wh) from July 2010 to date, before July 2010 the accuracy is  $\text{MWh} \times 10^{-2}$ . The data given by SvK is the exact energy consumption, where imported/exported energy and non-consumed energy is not taken into account (SvK, 2016a, 2015, 2014, 2013a, 2011, 2010, 2009, 2008, 2007, 2006, 2005).

A timeless baseline was achieved by summarising the total energy hourly consumption over one year and divide it with the total hours in one-year, see Eq. 10. Having a timeless baseline means that the baseline does not change over one year, that is it is on average valid during any time point during the year.

As the energy consumption comes with such a high resolution, meaning it is given per hour, this baseline is considered to be of high accuracy.



### PRESENTATION OF THE BASELINE METRIC

$$P_{avg} = \frac{\sum E(\text{hourly consumption over a year})}{T_{Dur,baseline}(\text{year of interruption})} \quad \text{Eq. 10}$$

where

$P_{avg}$ : Average power consumption for given year (MW).

$\sum E(\text{hourly consumption over a year})$ : Sum of the hourly consumption during a year (MWh).

$T_{Dur,baseline}(\text{year of interruption})$ : Total hours in one year, there are on average 8760 hours in one year. Start and end time of for the calculated annual average, that is 00.00 first of January and 24.00 31<sup>st</sup> of December the year given by the measured interruption.

### FUNCTIONALITY LOSS METRIC

The issue with the ENS consequence parameter is that it contains a time parameter, it has the unit of MWh. Therefore, before the Functionality Loss can be derived the ENS needs to be transformed to 'Power Not Supplied' (PNS). That is done by averaging ENS over the duration of the interruption, see Eq. 11.

$$PNS_{avg} = \frac{ENS}{T_{Dur}} \quad \text{Eq. 11}$$

where

$PNS_{avg}$ : Power Not Supplied, averaged (MW)

ENS: Energy Not Supplied (MWh)

$T_{Dur}$ : The time duration of an interruption (h)

The Functionality Loss ( $F_L$ ) is then derived by dividing averaged PNS with the baseline, see Eq. 12.

### *PRESENTATION OF THE FUNCTIONALITY LOSS METRIC, $F_L$*

$$F_L = \frac{PNS_{avg}}{P_{avg}} \quad \text{Eq. 12}$$

where

$F_L$  : Functionality Loss

$PNS_{avg}$  : Average Power Not Supplied for given interruption (MW)

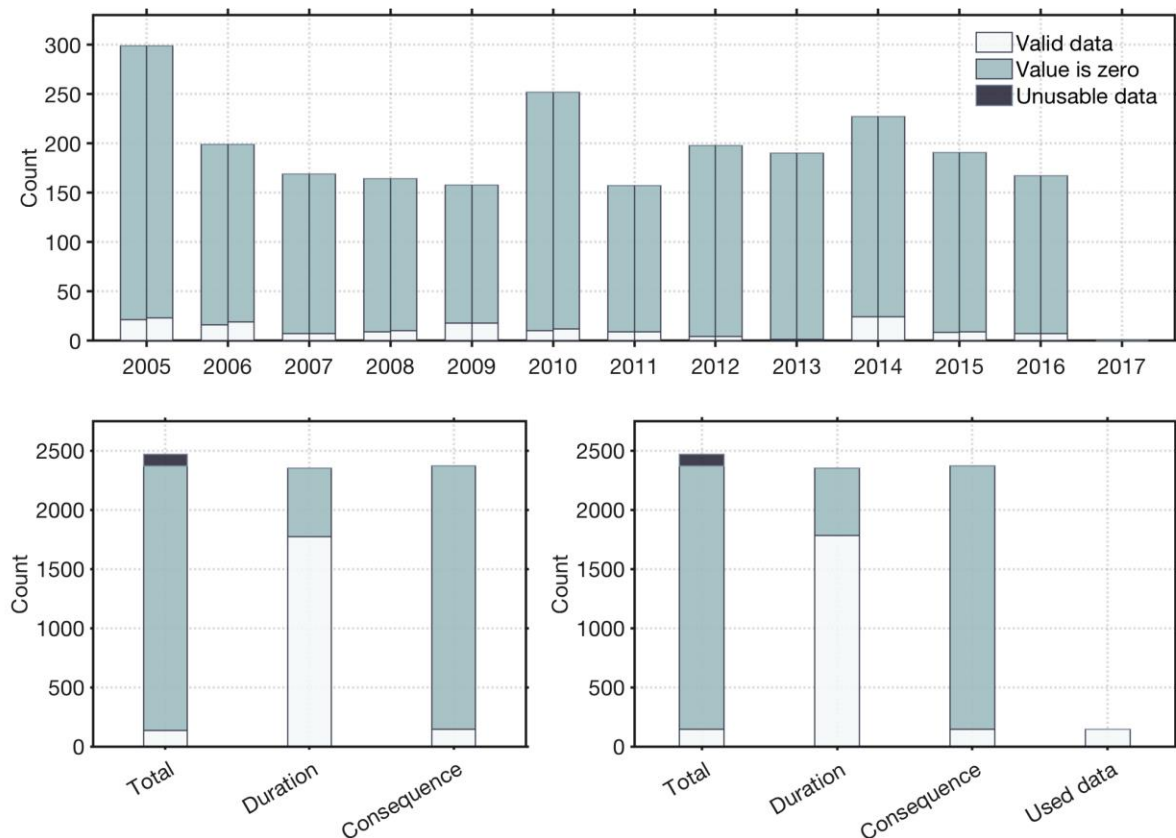
$P_{avg}$  : Average system power consumption when interruption occurs (MW)

### 5.1.2 DATA TREATMENT

The bigger part of the data treatment for the Electricity Transmission has been to remove the interruptions that did not lead to any power loss (zero consequences). In the data there were found two bad values with negative durations (End DT was before Start DT), one with six hours negative duration that was removed and the other one was an obvious error and was consequently corrected and included in the data. Some values were found that had an ENS greater than zero, but with zero duration<sup>12</sup>. All these values were given a duration of one minute (the lowest value our resolution of whole minutes allows), in accordance to previous explanation. In Figure 31 a summary and comparison of the untreated data and the data after treatment. Furthermore, it demonstrates the portion of interruptions in the data that is used in the resilience analysis of this thesis.

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<sup>12</sup> Zero is not a defined duration for a produced amount of energy



**Figure 31 Summary and comparison of the untreated and treated data for the Electricity Transmission infrastructure. The data is aggregated annually (above), where each bar is split by untreated data (left side) and treated data (right side). The data is also summarised by metric (below), showing untreated data (bottom-left side) and treated data (bottom-right side). Where the treated data has an extra clarifying bar, summing up the total used data.**

### 5.1.3 VALIDITY OF THE METRICS

The validity for the resilience metrics are very high for the Electricity Transmission data. All values for calculation of the interruption duration, consequence and baseline that that are used comes from highly accurate numbers. No values have been estimated with the exception of the few interruptions that came with undefined durations of zero (energy production is not defined for zero duration).

## 5.2 ELECTRICITY DISTRIBUTION

The interruption data regarding the Electricity Distribution infrastructure offered more than the minimum requirement for calculating the resilience metrics. The Start DT and End DT for the interruption are present, along with three consequence parameters. The consequence that area presented are: *Interruption time*, *No. of high voltage customers affected*, and *No. of low voltage customers affected*. For resilience assessment, the *Interruption time* parameter is not included.

Though it is considered as interesting parameter, as it is number of high- and low voltage customer that were affected during the duration of the interruption. This parameter is quite similar to what we refer to as Resilience Loss. However, no similar parameter is present in the interruption data for the other CIs and therefore it is excluded.

There were no issues with deriving the resilience metrics for Electricity Distribution.

## 5.2.1 DERIVING RESILIENCE METRICS FROM THE COLLECTED INTERRUPTION DATA

### **DURATION METRIC**

The duration is derived from the given timeframes for each interruption in the given interruption data, in accordance to Eq. 1 (in section 3.3.3).

### **BASELINE**

The baseline is the total number of customers of the electricity distribution companies that report interruptions to Energiföretagen, see Eq. 13. This number includes both high- and low voltage customers. It was not possible obtain a baseline that is separated according to high- and low voltage customers. The baseline data is presented on annual basis, for same years as the corresponding interruption data, that is 2005 – 2015. The data is provided by Energiföretagen (Matz Tapper, e-mail, 2017-04-26).

### *PRESENTATION OF THE BASELINE*

$$N_{tot,customers} \quad \text{Eq. 13}$$

where

$N_{tot,customers}$  : Average number of customers for the given year the interruption occurs.

### **FUNCTIONALITY LOSS METRIC**

Functionality Loss of each individual interruption is determined by the number of high- and low voltage customers affected divided by the baseline which is the average number of customers during a given interruption year, see Eq. 14.

### PRESENTATION OF THE FUNCTIONALITY LOSS METRIC, $F_L$

$$F_L = \frac{N_{affected\ customers}}{N_{tot,customers}} \quad \text{Eq. 14}$$

where

$F_L$  : Functionality Loss of individual interruption.

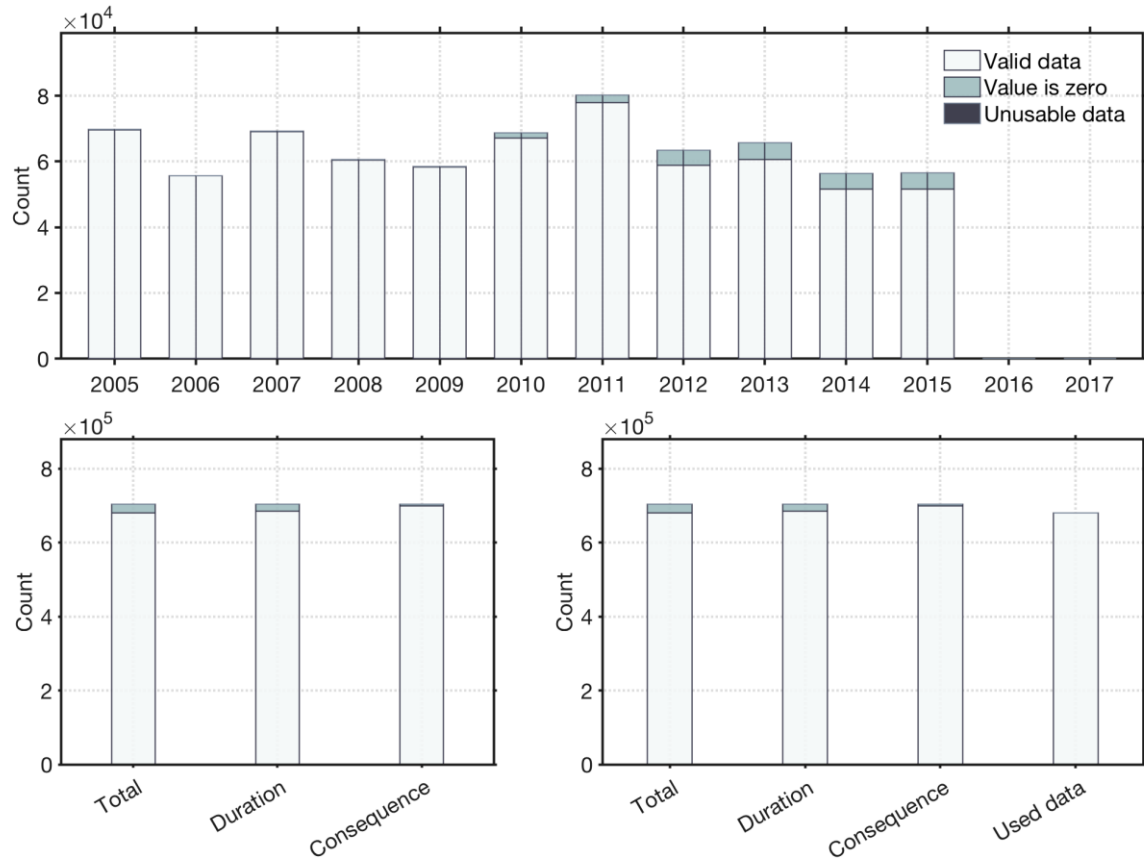
$N_{affected\ customers}$  : Number of affected customers during the respective interruption.

$N_{tot,customers}$  : Average number of customers the year the respective interruption occurs.

## 5.2.2 DATA TREATMENT

No unusable data given in the data set, however some values with zero duration were removed. Some fifty incorrectly labelled End DT were found, where the date did not change for the interruptions that started or ended at midnight (at the time 00:00 the date should change, as the new day begins). This results in correct end time, but the date is 24 hours early, resulting in negative durations with a correct absolute value; 24 hours were added to those values.

Some values were considered faulty that had the duration of just above one year (in one case tree years), which is extremely rare data set. Hence, when End DT values are found that happens to be almost precisely one year after Start DT, they have been judged as incorrect and given a new end date the correct year. Very close to all values were used as they were given as can be seen in Figure 32, but the treated data is not enough to be separated from the untreated treated bars. Furthermore, the figure demonstrates the portion of interruptions in the data that is used in the resilience analysis of this thesis.



**Figure 32 Summary and comparison of the untreated and treated data for the Electricity Distribution infrastructure.** The data is aggregated annually (above), where each bar is split by untreated data (left side) and treated data (right side). The data is also summarised by metric (below), showing untreated data (bottom-left side) and treated data (bottom-right side). Where the treated data has an extra clarifying bar, summing up the total used data.

### 5.2.3 VALIDITY OF THE METRICS

The metrics for the Electricity Distribution infrastructure are considered to be highly valid. The baseline is given as the total number of customers, given to us by Energiföretagen and the durations seem to be very accurate. The uncertainties are introduced when the given *Interruption time* (see Table 3) was not used. The consequences are calculated from the total number of customers affected multiplied with the duration, which in most cases is equal to the given *Interruption time*. However, sometimes some customers are gradually connected which is taken into account in the given *Interruption time*, but we estimated those interruptions with the interruptions' total duration, which in general with overestimate the consequences, hence also the resilience loss.

## 5.3 TRANSPORT ROAD

The interruption data for the Transport Road infrastructure contains a couple of duration and consequence parameters (see section 4.3). The given time related parameters are: Start DT and End DT of the interruptions, *Gross duration* and *Net duration*. The parameters used are Start DT and *Net duration*. *Gross duration* is not utilised for the resilience assessment. As a measure of consequence, the estimated number of affected cars for each interruption is used, the *Palpability*.

### 5.3.1 DERIVING RESILIENCE METRICS FROM THE COLLECTED INTERRUPTION DATA

#### DURATION METRIC

Here the duration metric is represented by the Start DT and *Net duration*, according to Eq. 9 even though the generic duration metric is given with Eq. 1 (in the section 3.3.3).

#### BASELINE

The average number of vehicles in the system is estimated from numbers regarding traffic volume and the total length of the national road network, see Eq. 15. The system is here defined as the total Swedish road network. The baseline data is estimated from a number presented in a report regarding total road length for 2015, made by the Swedish Transport Administration (Trafikverket, 2016). The numbers given in that report are from 2015-12-31 and there have not been any published reports on road length since. It is assumed that there have not been any significant changes regarding road length in the national road network since 2015 and that these figures can represent the baseline for the time period of the interruption data.

#### PRESENTATION OF THE BASELINE

$$N_{tot,vehicles} = \frac{Traffic\ volume}{Total\ road\ length} \quad \text{Eq. 15}$$

where:

$N_{tot,vehicles}$  : Average number of vehicles in the system

Traffic volume: Total number of vehicle km per year

Total road length: The total length of the national road network in km

## FUNCTIONALITY LOSS METRIC

The Functionality Loss is derived from the *Palpability*, a pre-calculated estimation of the number of vehicles affected by a given TTS. By dividing the *Palpability* with the baseline, a quote received as an estimation of how big part of the estimated numbers of vehicles is affected by interruptions, see Eq. 16.

*PRESENTATION OF THE FUNCTIONALITY LOSS METRIC,  $F_L$*

$$F_L = \frac{Palpability}{N_{tot,vehicles}} \quad \text{Eq. 16}$$

where

$F_L$ : Functionality Loss of an individual interruption

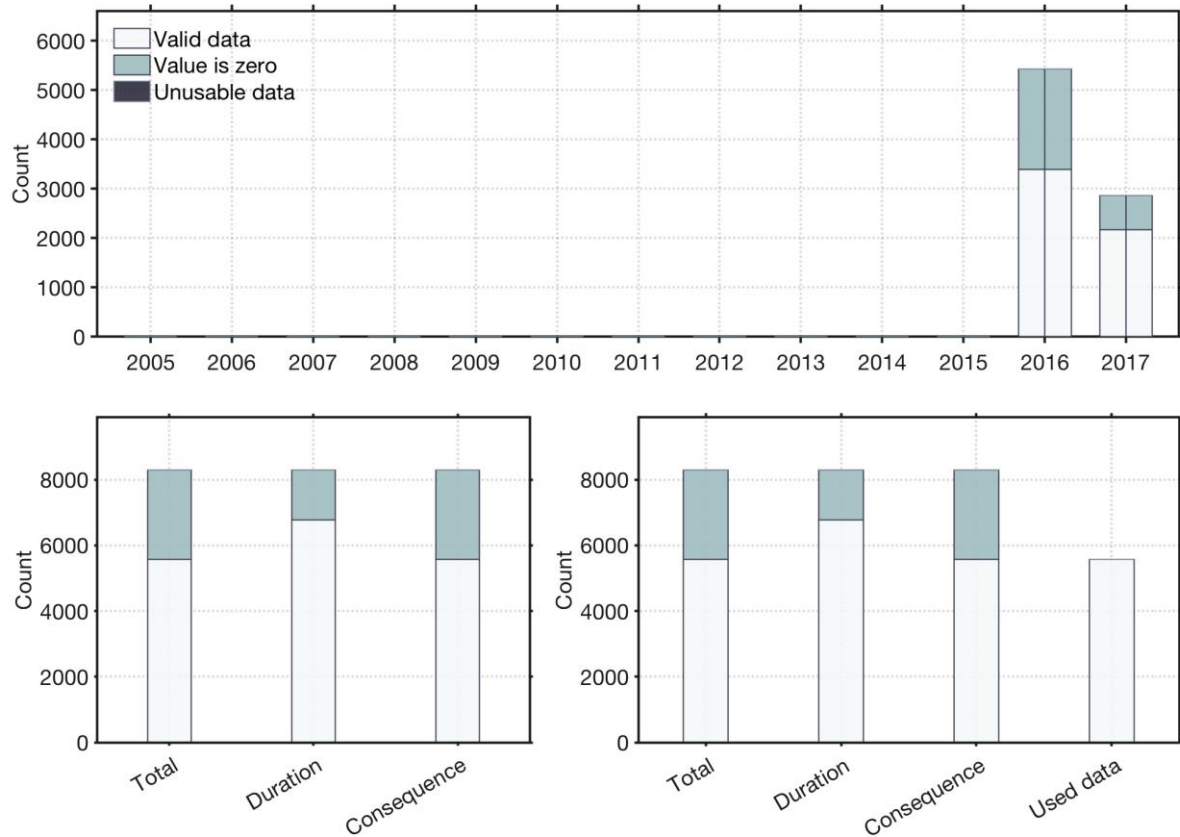
Palpability: Number of affected vehicles for a given interruption

$N_{tot,vehicles}$ : Averaged number of vehicles in the system (i.e. the total Swedish road network for)

### 5.3.2 DATA TREATMENT

No bad or unrealistic data is given, however one third of the interruptions had zero duration or consequence and was therefore removed from the data set, see Figure 32. Furthermore, the figure demonstrates the portion of interruptions in the data that is used in the forthcoming resilience analysis.





**Figure 33 Summary and comparison of the untreated and treated data for the Transport Road infrastructure. The data is aggregated annually (above), where each bar is split by untreated data (left side) and treated data (right side). The data is also summarised by metric (below), showing untreated data (bottom-left side) and treated data (bottom-right side). Where the treated data below has an extra clarifying bar, summing up the total used data.**

### 5.3.3 VALIDITY OF THE METRICS

The accuracy of the metrics from the road data are judged to be highly uncertain, as they are all rough estimations. The system that calculates the durations of interruptions is of unknown accuracy. When fully functioning, the system should be updated with accurate traffic information in real time. However, the data also comes with a maximum duration value that is applied when the *Net duration* received by the reporting system is unrealistically long, i.e. when the system seems to be failing. This indicates a system that sometimes over-estimate the durations of interruptions. As the duration is directly correlated to the *Palpability* (number of affected cars), which also is a highly uncertain average, the uncertainties are overall judged to be high. Furthermore, the baseline is estimated from the expected total number of cars running in the system, which is a highly uncertain estimation.

## 5.4 TRANSPORT RAILWAY

There were couple of difficulties of deriving the resilience metrics for the Transport Railway interruption data. As a consequence parameter for the interruptions, the number of registered delays (CRAD) is utilised. The Start DT and End DT are given in the interruption data, however the vast majority of the interruptions are given with the same Start DT and End DT, resulting in zero duration for these interruptions. How this issue was dealt with is covered under section 5.4.2.

### 5.4.1 DERIVING RESILIENCE METRICS FROM THE COLLECTED INTERRUPTION DATA

#### **DURATION METRIC**

The duration is calculated according to Eq. 1 (in section 3.3.3).

#### **BASELINE**

The baseline is here represented by the number of annual departures in the system. That said, we only have the number of departures in the system for one year which is from 2012. We utilise extrapolation to estimate the annual of annual departures in the system for the other years the interruption data spans, see Eq. 17.

The 2012 baseline is normalised and weighted by utilising the sum of all transported km per year for railway traffic (Trafikanalys, 2017), with 2012 as index year.

#### *PRESENTATION OF THE BASELINE*

$$\bar{N}_{MP}(\text{year} = Yr) = \text{Hourly Average} \left( \sum MP(2012) \times \frac{\text{Train km}(Yr)}{\text{Train km}(2012)} \right) \quad \text{Eq. 17}$$

where

$\Sigma MP(2012)$ : is the total sum of passed “measurement points” by all trains in all Sweden for year 2012 ( $\approx 38 \times 10^6$ ).

$\bar{N}_{MP}(\text{year} = Yr)$ : is the scaled hourly average of passed “measurement points” by all trains in all Sweden for year (Yr).

#### **FUNCTIONALITY LOSS METRIC**

The Functionality Loss is derived from the given interruption’s consequence parameter CRAD (Cause-reported additional-delays) which is then averaged hourly, see Eq. 18. This hourly averaged CRAD is then divided by the hourly average of the total number of departed measurement points in the system for the given year, see Eq. 19. I.e. the hourly averaged number of

additional delayed measurement points (CRAD) is divided by the average number of departed measurement in the whole system (all Sweden).

#### PRESENTATION OF THE FUNCTIONALITY LOSS METRIC, $F_L$

$$\overline{CRAD}_{interruption} = \frac{\sum CRAD (interruption)}{Duration(hours)} \quad \text{Eq. 18}$$

$$F_L = \frac{\overline{CRAD}_{interruption}}{\overline{N}_{MP} (year = Yr)} \quad \text{Eq. 19}$$

where

$F_L$ : Functionality Loss of individual interruption.

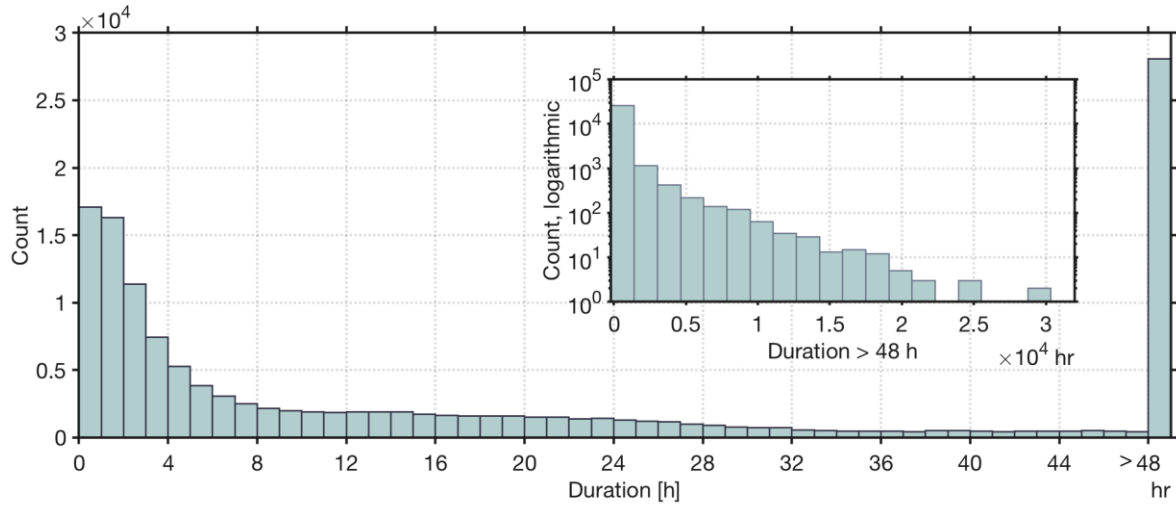
$\sum CRAD (interruption)$ : The sum of passed ‘measurement points’ where any train has received additional delay registered to the Delay ID (the interruption)

$\overline{CRAD}_{interruption}$ : Hourly average of passed ‘measurement points’ for an interruption.

### 5.4.2 DATA TREATMENT

The Transport Railway data is the data in need of most manipulation, as it has one essential flaw as previously stated, that nearly all End DT values are incorrect. Nearly all *Delay IDs* are given with the same Start DT and End DT, i.e. resulting in duration that are equal to zero.

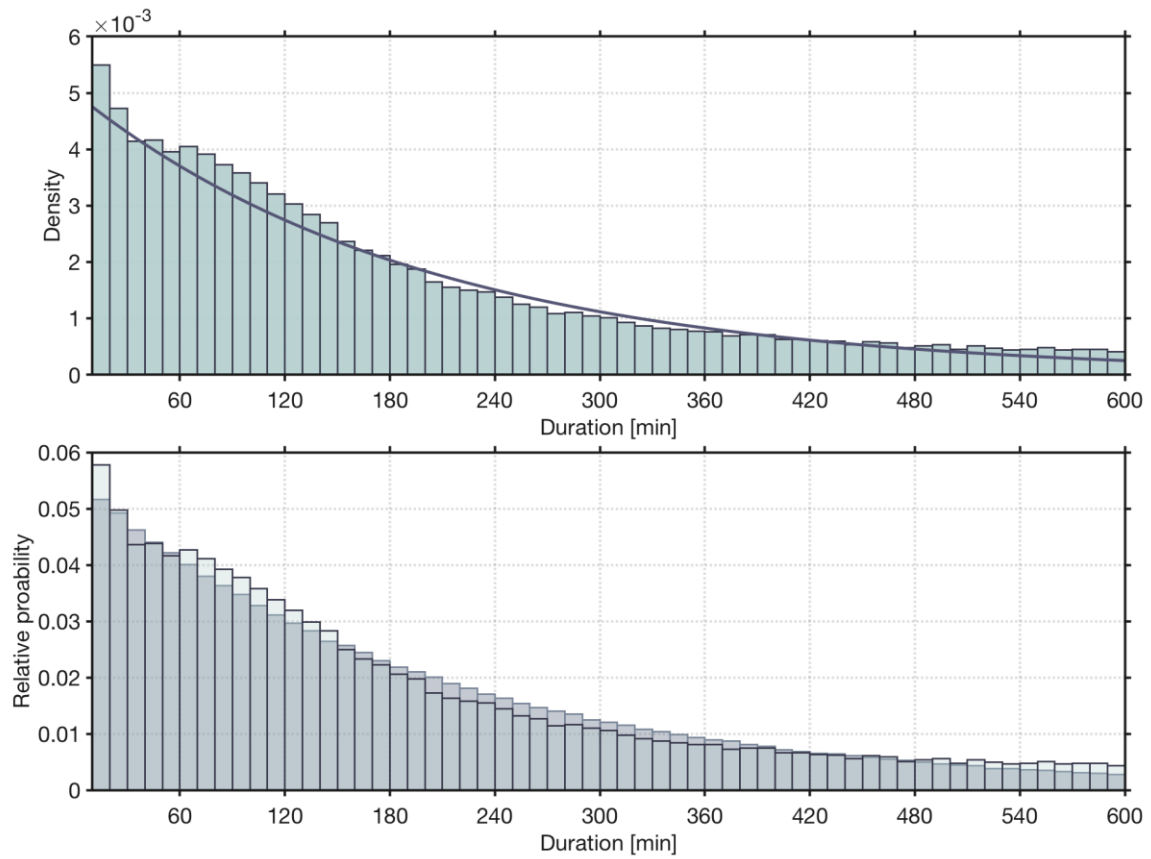
Many of the given durations are less than some of its included interruption’s CRADs, meaning that the given duration of the *Delay ID* is shorter than some of its delays. However, a *Delay ID*’s End DT is not defined for durations that are less than any included single train’s total delay (CRAD); the duration of an interruption cannot be shorter than any of its included delays trains, meaning those values are also incorrect. With this knowledge, all available interruption durations that are greater than zero and less than 10 minutes has been considered faulty, and will be given a new End DT. No correlations could be found between the duration and CRAD (or any other consequence-parameter) for the *Delay IDs* with correct durations, otherwise such a correlation would be appropriate to use for estimation of the incorrect End DTs. Instead, the durations of the correctly given *Delay IDs* are analysed in order to get an estimate for the *Delay IDs* with incorrect End DTs, see Figure 34. A few of the zero-values have an estimated End DT, which usually is given for the *Delay IDs* that lasts for several days, weeks or months; these values are adopted as End DT when available.



**Figure 34 Histogram of durations longer than 10 minutes for the Transport Railway data**

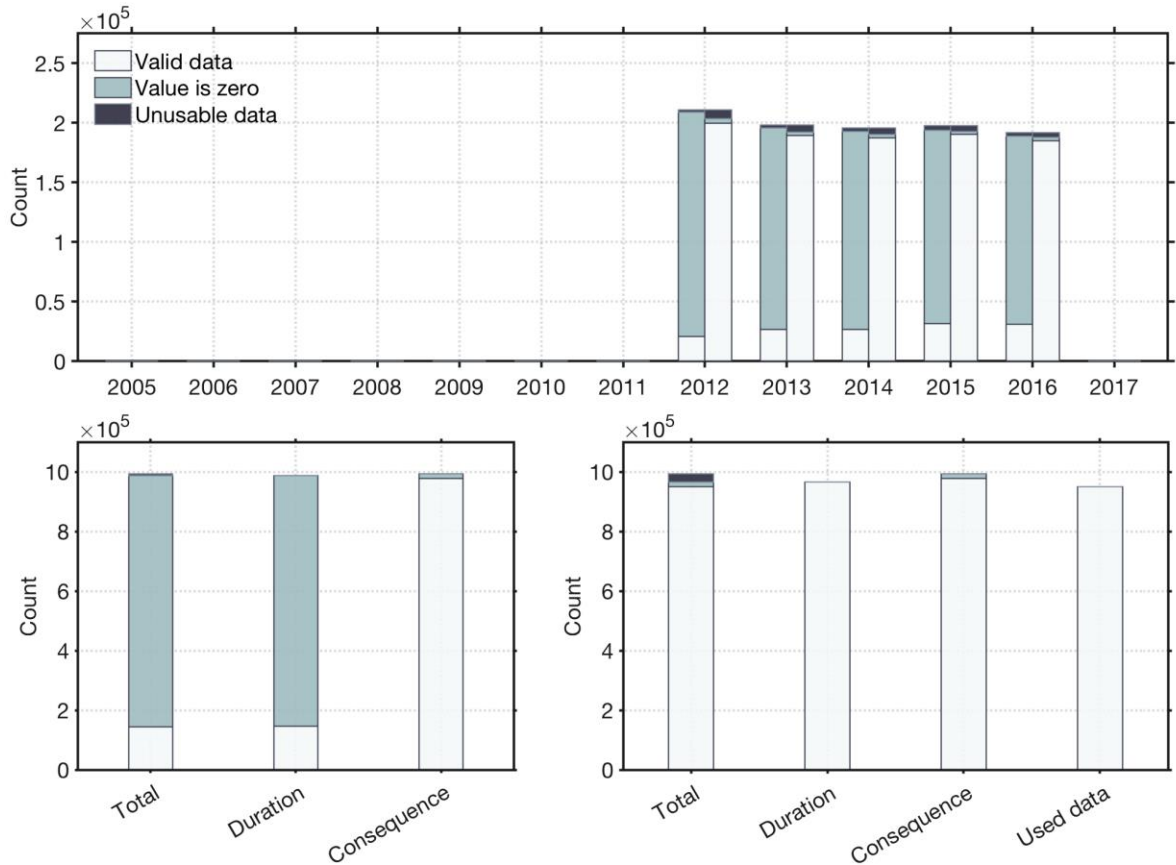
As seen in Figure 34, the interruptions' that are correctly logged have durations that are quite evenly spread out, for thousands of hours. From the look of this data however, it seems possible to find a correlation with a stochastic process. If so, such a correlation can be used to generate the incorrect End DT values by stochastically randomise them. In doing so, it does not seem fair to estimate very long durations for the unknown End DT we want to generate. It does not seem very likely that these correct durations are all representable for the parts of the data set with incorrect End DT, as longer delays are deemed more probable to be correctly logged. Therefore, only delays that are longer than 10 minutes but shorter than 10 hours are used as basis for further analysis. This data is then used to estimate a probability density function (PDF); when fitted with an exponential distribution an accurate correlation is found (see Figure 35, top histogram). The properties of the fitted exponential function is then used to stochastically randomise the missing values. These values are plotted in a histogram as a function of the relative probability, see the bottom Figure 35.<sup>13</sup>

<sup>13</sup> The relative probability is used as the randomised values are much greater in number and would have looked un-proportionally large in a regular histogram.



**Figure 35 Probability density function of the valid durations less than 10 hours with the fitted exponential function curve (top). The same valid durations from the data is also plotted together with the stochastically randomised values, in the histogram of relative probability (bottom).**

A summary of the values before and after the data treatment is found in Figure 36 below. Furthermore, the figure demonstrates the portion of interruptions in the data that is used in the resilience analysis of this thesis.



**Figure 36 Summary and comparison of the untreated and treated data for the Transport Railway infrastructure. The data is aggregated annually (above), where each bar is split by untreated data (left side) and treated data (right side). The data is also summarised by metric (below), showing untreated data (bottom-left side) and treated data (bottom-right side). Where the treated data below has an extra clarifying bar, summing up the total used data.**

### 5.4.3 VALIDITY OF THE METRICS

The CRAD is a highly valid number. The given baseline is also estimated to be accurate, however the validity of using delayed trains as consequence parameter for interruptions is not considered high. With more than eight out of ten stochastically estimated durations and no cancelled trains, the validity of this data as a representative of Transport Railway interruptions, is deemed to be highly uncertain.

## 5.5 WATER SUPPLY

As previously mentioned in Chapter 4, the data is of better quality after June 12<sup>th</sup>, 2009. For this reason, we exclude the all data prior July 1<sup>st</sup>, 2009. The argument for starting from July 1<sup>st</sup> instead of the 12<sup>th</sup>, is both to start at a beginning of a month instead of in the middle of the month, as well as July represents the beginning of new annual quarter.

The interruption data for Water Supply contains the minimum parameters for deriving the resilience metrics. The time parameters that are given are Start DT and duration (referring to the parameter *Hours without water*) which is given in hours. There is no End DT present in the interruptions data. The consequence parameter is *Number of users* that are affected.

### 5.5.1 DERIVING RESILIENCE METRICS FROM THE COLLECTED INTERRUPTION DATA

#### DURATION METRIC

Though the generic duration metric is given with Eq. 1 (in section 3.3.3). As previously stated, the End DT is not given in the interruption data, for that reason the given duration is utilised. Both in terms of the interruption duration, as well as estimating the End DT.

#### BASELINE

Number of system users is used to represent the baseline, where 95% of the total inhabitants of Stockholm and Huddinge municipalities are connected to the actor's drink water distribution network, see also Eq. 20. It should be noted that industries, hotels, schools and work places are not included (Erik Karlsson, e-mail, 2017-07-18). The total number of inhabitants for Stockholm and Huddinge municipalities on annual basis is retrieved from Statistics Sweden (SCB, n.d.)

#### PRESENTATION OF THE BASELINE

$$\begin{aligned} N_{tot,system\ users} & \\ &= 95\% \text{ of inhabitant of Stockholm and Huddingen municipalities} \end{aligned} \tag{Eq. 20}$$

where

$N_{tot,system\ users}$ : Number of users that are connected to the actor's water distribution network per year.

#### FUNCTIONALITY LOSS METRIC

The Functionality Loss is determined by the *Number of users* that are affected by the interruption divided by the annual number of total users of the system when the interruption occurs, see Eq. 21.

### *PRESENTATION OF THE FUNCTIONALITY LOSS METRIC, $F_L$*

$$F_L = \frac{N_{affected\ users}}{N_{tot,system\ users}} \quad \text{Eq. 21}$$

where

$F_L$  : Functionality Loss of individual interruption.

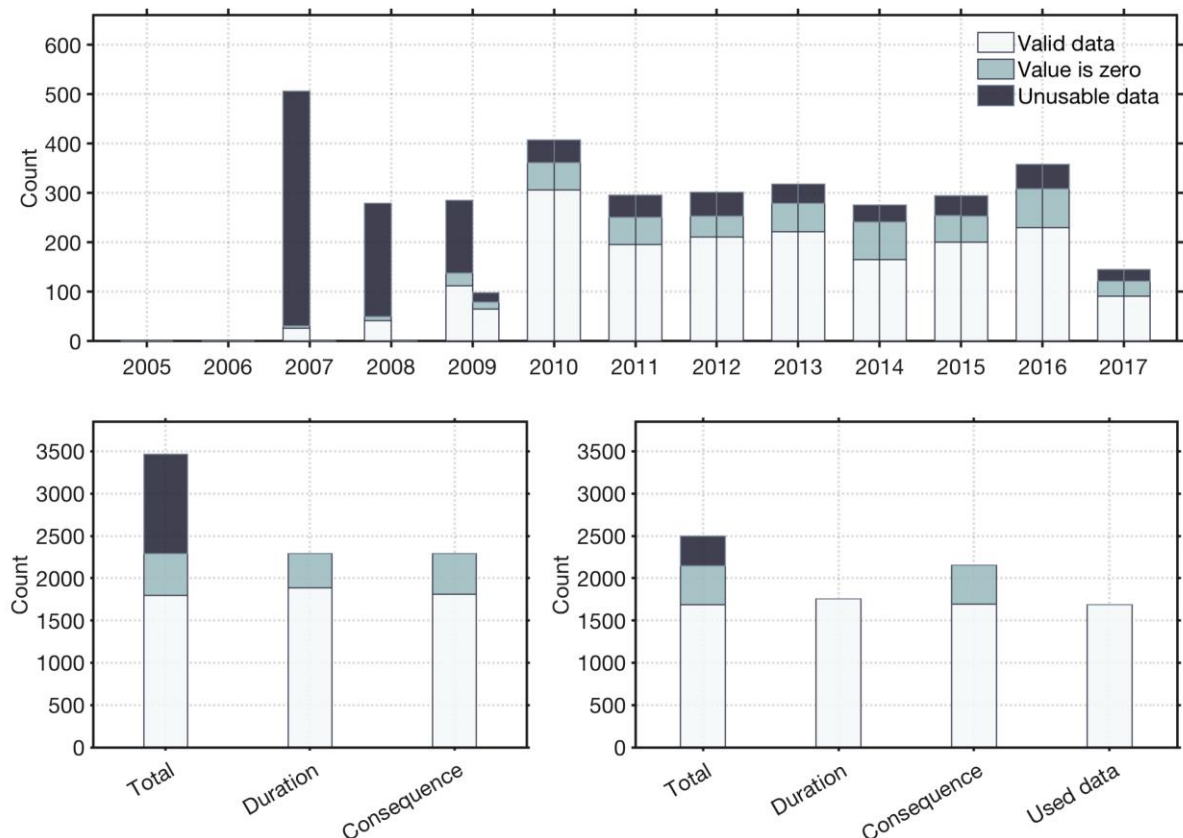
$N_{affected\ users}$  : Number of users that are affected by the interruption.

$N_{tot,system\ users}$  : Number of users that are connected to the actor's water supply infrastructure for a given year of interruption.

### 5.5.2 DATA TREATMENT

The main part of the data treatment for Water Supply was to remove all interruptions occurring before July 2009, as there was not enough usable data, see Figure 37. The remaining data treatment was to delete interruptions that lacked the required information to withdraw the resilience metrics. Furthermore, Figure 37 demonstrates the portion of interruptions in the data that is used in the resilience analysis of this thesis.





**Figure 37 Summary and comparison of the untreated and treated data for the Water Supply infrastructure.** The data is aggregated annually (above), where each bar is split by untreated data (left side) and treated data (right side). The data is also summarised by metric (below), showing untreated data (bottom-left side) and treated data (bottom-right side). Where the treated data below has an extra clarifying bar, summing up the total used data. Note that the treated data does not include values prior to July 2009.

### 5.5.3 VALIDITY OF THE METRICS

The Functionality Loss metric and the duration metric for the Water Supply interruption data are judged to be very accurate, the uncertainties are introduced with the less certain baseline. Our contact at SVOA judged an estimated baseline of 95 % of the population of the area Stockholm and Huddinge municipality, to be accurate. That in turn, will add some uncertainties to the derived Functionality Loss metric. However, overall the validity of these metrics is deemed to be high. The uncertainties are proffered being in the baseline rather than in the consequence parameter, that way it contributes with an equal bias between all interruptions Functionality Loss metric (changes annually).

## 5.6 TELECOMMUNICATION

As previously mentioned, it proved difficult and time consuming to aggregate the relevant information from the incident reports from PTS, especially in terms of the consequences. There were various difficulties with extracting the relevant consequence parameters and here are couple of the them listed; firstly, multiple ways to express the same consequences. Secondly, some of the consequences were difficult to place as they do not fit the general format, such as number of customer or mobile sites. Lastly, the information is masked. This is not a limited list.

On the positive side, out of all the CIs the information is most detail from PTS, the problem is to make sense of the data and aggregate it, and that the information given is not uniformly given in the same way. The Start DT and End DT (which gives the interruption durations) is not so difficult to extract from the incident reports and in the majority of the interruptions the duration is present. It was even possible in some of the cases to have some of the in-between parameters during the duration of the interruption. More explicitly, e.g. in some cases the peak time where the consequences where the highest was given, and in other cases step by step time points and corresponding consequences values during that timepoints. However, minority of the Telecommunication interruptions contained this level of details. Furthermore, none of the other CI interruption data sets have that level of detail, where commonly only the Start DT and End DT (or duration) and the maximum consequences are given.

As previously mention in section 4.6, we focus three sub-infrastructures from the Telecommunication infrastructure, which are Telecommunication Mobile, Telecommunication Broadband Services, and Telecommunication Fixed Telephony. The Telecommunication infrastructure is the only CI where we have decided to analyse sub-infrastructure separately instead of analysing them as a group in the resilience analysis. This is both due to the complexity of aggregating the interruption data, as well as difficulties of establishing a joint baseline.

Common consequence parameter between the sub-infrastructures is number of *Customers* that are affected by the interruptions. However, Telecommunication Mobile also expresses consequences in terms of affected *Mobile sites*.

### 5.6.1 DERIVING RESILIENCE METRICS FROM THE COLLECTED INTERRUPTION DATA

#### **DURATION METRIC**

The duration metric is calculated according to Eq. 1 (in section 3.3.3).

## **BASELINE**

There are couple of baselines for the Telecommunication infrastructure, as the interruption data expresses different types of sub-infrastructure/services. Appropriate baselines needed to be found for each sub-infrastructure on annual basis.

For Telecommunication Mobile there are two base lines, the first baseline is total number of mobile sites, in other words the mobile masts, per given year in Sweden, see Eq. 23. We do not divide between 2G, 3G, and 4G, this is because of how differently the information is presented in the incident reports. The data for the mobile sites baseline is aggregated from PTS reports (PTS, 2017a, 2016, 2015), which is available for 2013-2016. The second baseline is number of subscribers, see Eq. 22. The selection of which of the baseline used depends on how the consequences are expressed for each interruption for a year.

The baseline for both Telecommunication Fixed Telephony and Telecommunication Broadband Services is represented by the number of customers with fixed telephone services (excluding IP-based phone), respectively the number of customers with fixed broadband services (that includes the Internet, IP-based phone, and IPTV), see Eq. 22.

The baseline data regarding number of customers for Telecommunication Mobile, Telecommunication Fixed Telephony and Telecommunication Broadband Services are all retrieved from PTS (2017b) Statistics Portal database which is publicly available. PTS's Statistics Portal database offers among other things detailed information over all customers of Swedish telecom companies and their subscription services.

### *PRESENTATION OF THE BASELINES*

All three sub-infrastructure share the baseline calculations derived from the total number of users, see Eq. 22.

$$N_{tot,customers}(Year = Yr) \quad \text{Eq. 22}$$

where

$N_{tot}$  : Total number of registered subscriptions of studied sub-infrastructure during the given year (Yr) of interruption.

### *TELECOMMUNICATION MOBILE SPECIFIC*

As previously mentioned above, Telecommunication Mobile utilises two forms of baseline as this sub-infrastructure expresses its consequences in two ways. When the consequence for interruptions are expressed in terms of affected *Mobile sites* then this baseline applies and is given by the total number of sites the given year of the interruption, see Eq. 23.

$$N_{tot, mobile\ sites} \quad \text{Eq. 23}$$

where

$N_{tot, mobile\ sites}$  : The total number of mobile sites for given year of interruption.

### FUNCTIONALITY LOSS

A generic formula for all the sub-Telecommunication sub-infrastructures for the calculation of Functionality Loss is given in Eq. 24.

*PRESENTATION OF THE FUNCTIONALITY LOSS METRIC,  $F_L$*

$$F_L = \frac{N_{affected}}{N_{tot, system}} \quad \text{Eq. 24}$$

where

$F_L$  : Functionality Loss of individual interruption.

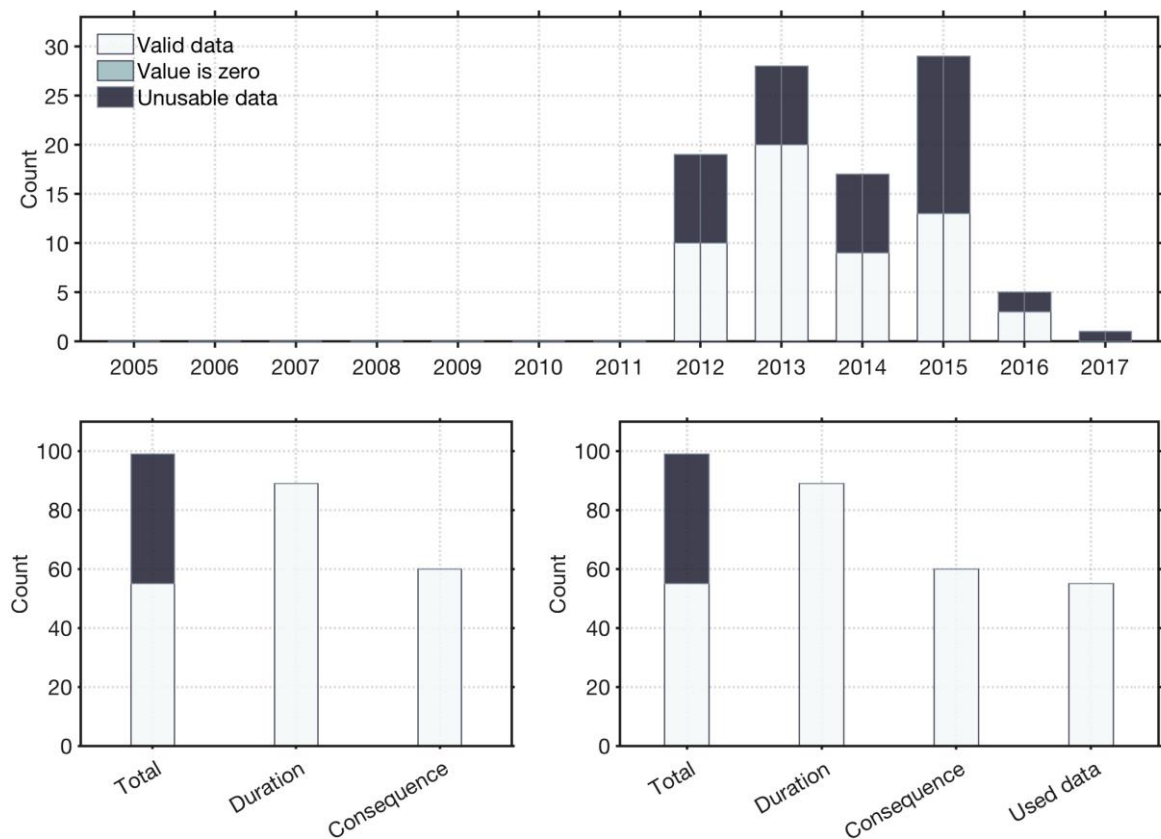
$N_{affected}$  : The number of customers or sites affected.

$N_{tot, system}$  : Total number of customers connected to the respective actor for given year, or total number of (Mobile) sites.

## 5.6.2 DATA TREATMENT

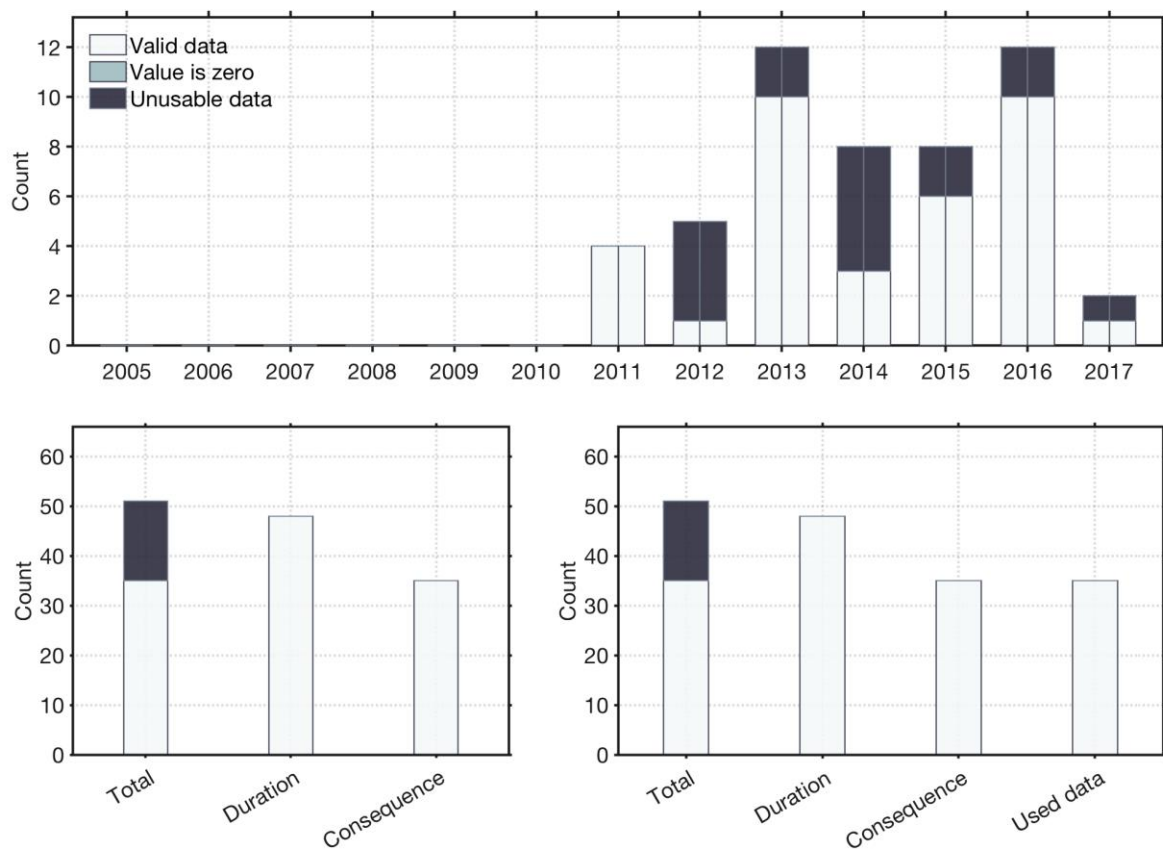
Nothing is done with the Telecommunication interruption data except dividing the different interruptions and their consequences between the different sub-infrastructures, and then removing the interruptions that lacks the information to meet the criteria of deriving the resilience metrics, see Figure 38 for Telecommunication Mobile, Figure 39 for Telecommunication Fixed Telephony and Figure 40 for Telecommunication Broadband Services. Furthermore, the portion of interruptions for each respective sub-infrastructure that is utilised in the resilience analysis in this thesis can be seen in these figures.

## TELECOMMUNICATION MOBILE



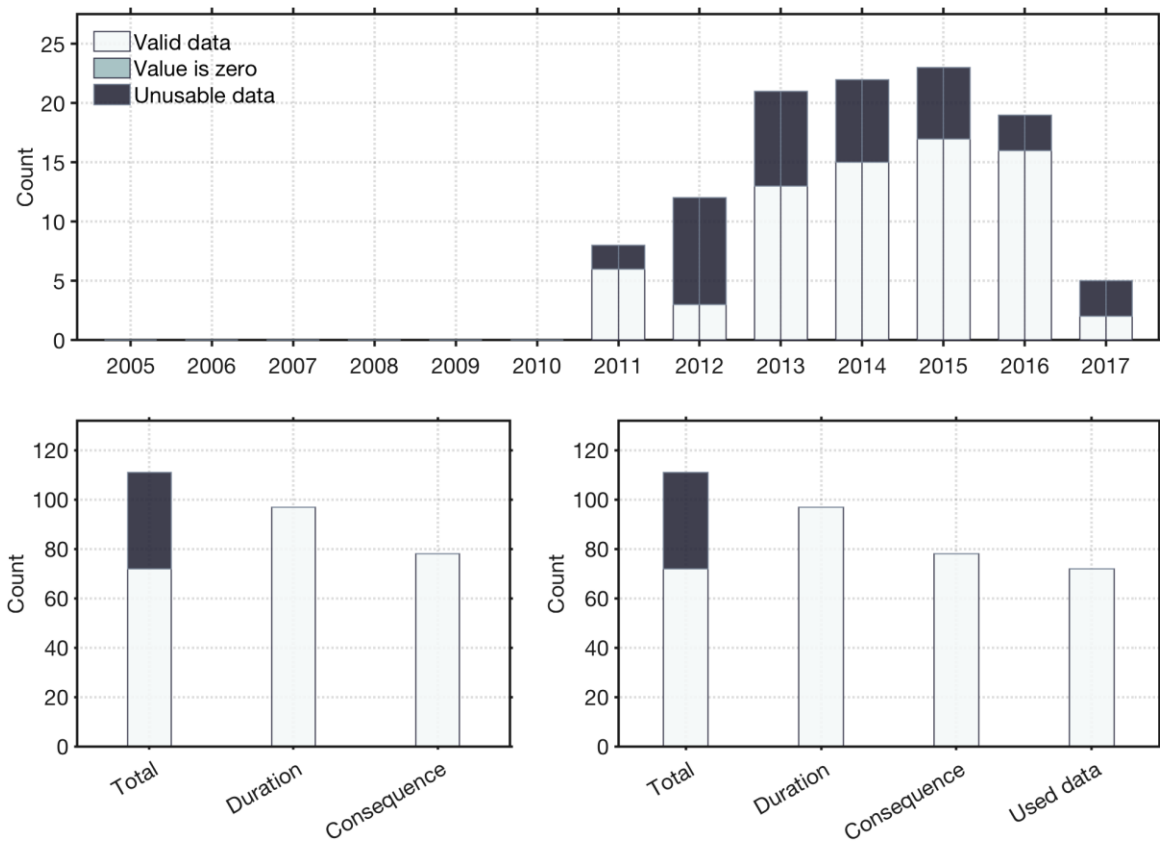
**Figure 38 Summary and comparison of the untreated and treated data for the Telecommunication Mobile infrastructure. The data is aggregated annually (above), where each bar is split by untreated data (left side) and treated data (right side). The data is also summarised by metric (below), showing untreated data (bottom-left side) and treated data (bottom-right side). Where the treated data below has an extra clarifying bar, summing up the total used data.**

## FIXED TELEPHONY



**Figure 39 Summary and comparison of the untreated and treated data for the Telecommunication Fixed Telephony. The data is aggregated annually (above), where each bar is split by untreated data (left side) and treated data (right side). The data is also summarised by metric (below), showing untreated data (bottom-left side) and treated data (bottom-right side). Where the treated data below has an extra clarifying bar, summing up the total used data.**

## BROADBAND SERVICES



**Figure 40 Summary and comparison of the untreated and treated data for the Telecommunication Broadband Services infrastructure. The data is aggregated annually (above), where each bar is split by untreated data (left side) and treated data (right side). The data is also summarised by metric (below), showing untreated data (bottom-left side) and treated data (bottom-right side). Where the treated data below has an extra clarifying bar, summing up the total used data.**

### 5.6.3 VALIDITY OF THE METRICS

When the interruption parameters are not masked, both the consequence parameter and the duration metric are highly accurate. The baselines that are used are also highly accurate. The assumptions made of the unmasked data is uncertain. As those reports only states the affected areas, it is not known if there are more accurate consequences stated in the masked text. As we have assumed all customers for a given carrier to be affected in those areas stated, probability is that they are somewhat overestimated. Given that we have received all reports, the uncertainties from missed data is introduced by the masked data and the bias caused by the threshold for reporting.

## 5.7 SUMMARY AND CONCLUSION OF THE METRICS

All data has successfully been transformed into the generic metrics of Functionality Loss and calendar duration. The validity of the different parameters differs, but the final data with all estimated values included is deemed to result in resilience calculations that are representative for the respective tCI.



# 6 RESILIENCE ASSESSMENT OF INDIVIDUAL CRITICAL INFRASTRUCTURES

In this chapter we present the results for each studied CI.

## *THE NATIONAL SYSTEM LEVEL:*

For each infrastructure, the interruption data has been aggregated in accordance to the RAA and presented. The table data and sub-figure marked with ‘A’ demonstrates the total functionality loss in the system over time with the accuracy of minutes. The other sub-figures show the functionality loss with respect the interruption causes (i.e. sub-samples of the total functionality loss). Human causes are marked ‘H’, natural ‘N’, technical ‘T’, external ‘E’, and causes that are unknown or missing are marked ‘U’. With these sub-figures it is possible to visualize how much each type of interruption contributes to the total functionality loss over time. This gives an indication of to what extent the different interruption causes contributes to the total functionality loss of the system.

## *ANNUAL RESILIENCE LEVEL:*

For each infrastructure, depending on the availability of data, the annual mean resilience level and mean resilience losses has been calculated in accordance to the RAA and presented in tables.

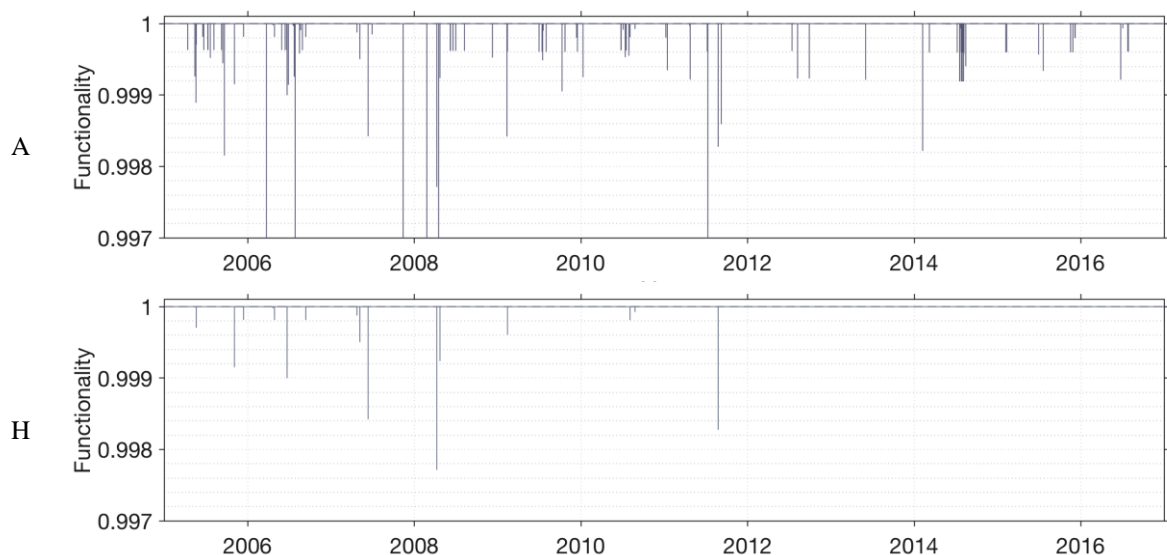
Note, the tabulated values presented in the chapter are given with three significant decimals with the exception of numerical table values of resilience which is given with five decimals in order of better displaying the difference in resilience, this also applies to table values in section 7.2.

## 6.1 ELECTRICITY TRANSMISSION

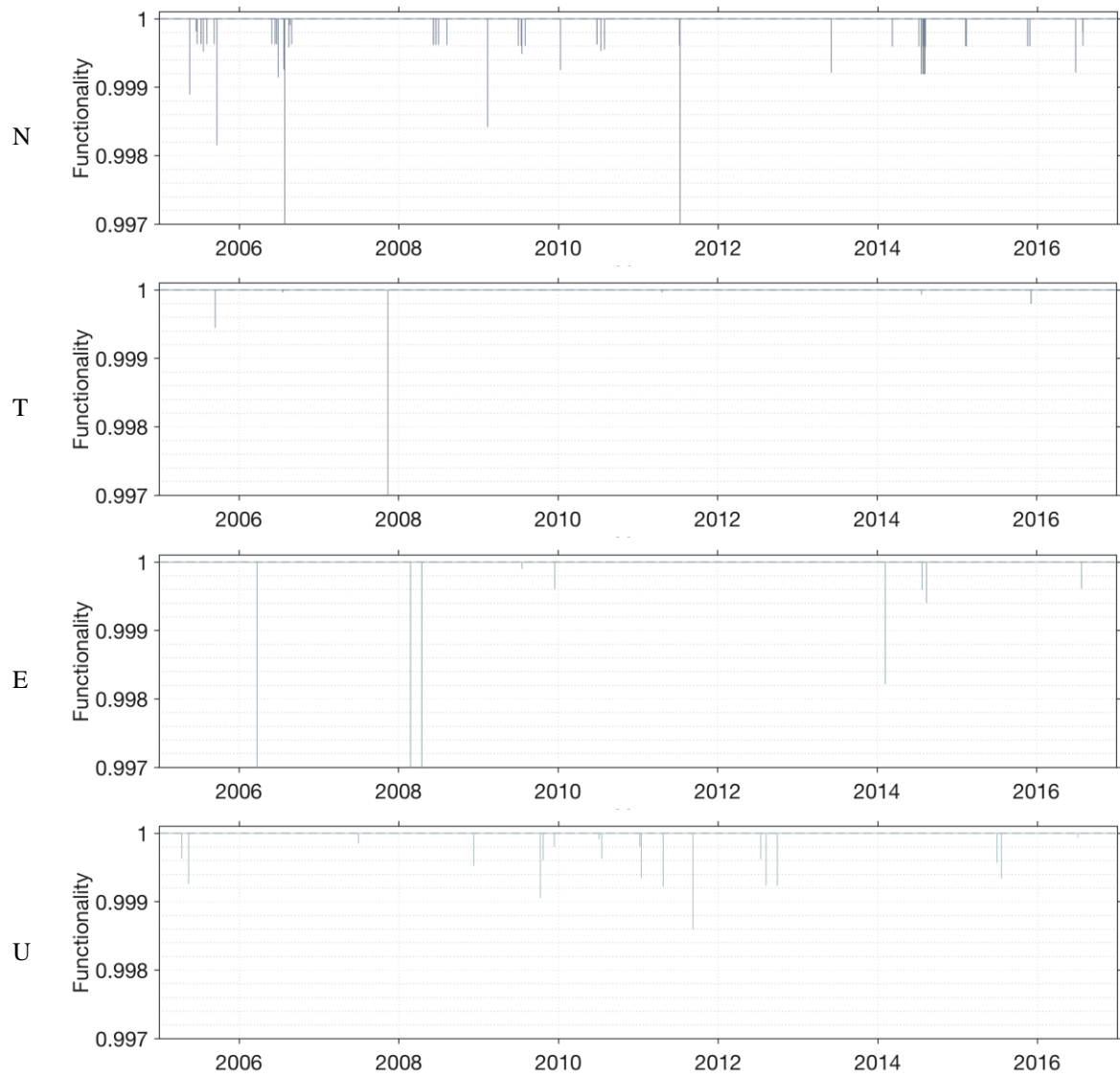
### 6.1.1 THE NATIONAL SYSTEM LEVEL RESILIENCE OF ELECTRICITY TRANSMISSION

Figure 41 demonstrates the functionality of the Electricity Transmission infrastructure at a national system level over the time period of the data and given data availability. The findings demonstrate that the infrastructure does not experience frequent interruptions, generally long-time intervals between with examples of almost a whole year.

Table 10, as complement to Figure 41, gives an indication of which interruption causes that contribute most to the total losses of the functionality level of the infrastructure. The interruption cause resulting in the largest impact on the electricity transmission infrastructure are related to external causes. The functionality loss in the system generated by external causes are few, but they result in a high mean functionality loss and resilience loss compared to the other causes. However, the mean duration is the lowest comparing to the other causes. Technical causes and then natural causes are second and third contributors. Compared to the other interruption causes, the technical failure causes have the second highest impact in terms of mean functionality loss and resilience loss in the system, however, it has the highest mean duration of interruptions at the national system level. Furthermore, functionality loss in the system generated by technical interruption causes are generally not many. Natural interruption causes tend to affect the functionality of the system more frequently than other causes.



*Cont.*



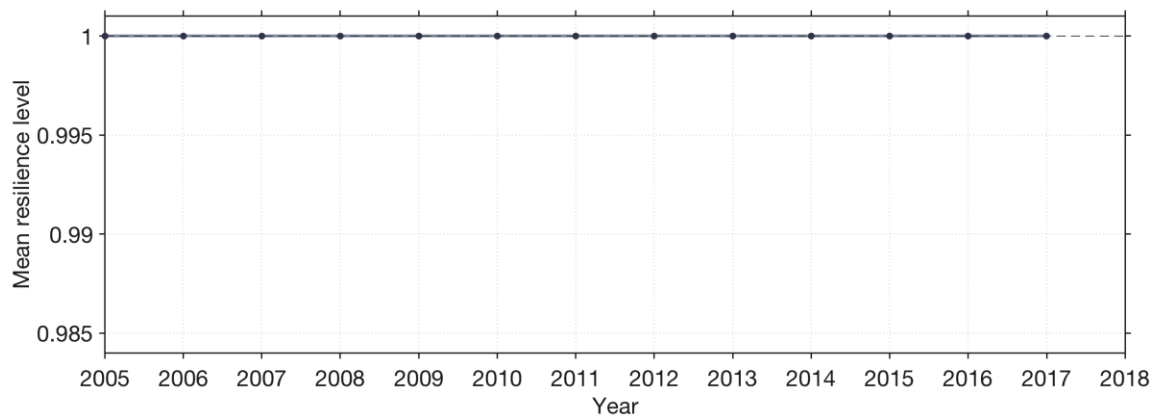
**Figure 41 Resilience curve for Electricity Transmission during the time period 2005-2016. All values are first plotted as reference (A), then categorised according to the generic interruption causes: (H) human, (N) natural, (T) technical, (E) external and (U) unknown/missing data. A dashed line is plotted as reference, displaying a fully functional system. The vertical axes are given a unified value of (0.997) for better resolution. Extreme values falling outside of the displayed bounds are presented for accounting purposes as [Date (maxFL)]: 2006-03-23 (0.045), 2006-07-27 (0.006), 207-11-13 (0.011), 2008-02-24 (0.012), 2008-04-16 (0.008) and 2011-07-10 (0.008).**

**Table 10 Overall resilience values of the generic interruption causes for Electricity Transmission. A: The total functionality of the system at a national system level. The generic interruption causes: H: human, N: natural, T: technical, E: external and U: unknown/missing data.**

Cause	Duration (h)			FL			Resilience Loss			Resilience
	Mean	Var	Max	Mean (10 <sup>-3</sup> )	Var (10 <sup>-6</sup> )	Max (10 <sup>-3</sup> )	Mean (10 <sup>-6</sup> )	Var (10 <sup>-6</sup> )	Max	
<b>A</b>	2.23	76.5	67.3	0.512	8.05	44.5	0.216	0.000963	0.0445	1.00000
<b>H</b>	0.288	0.227	1.85	0.254	0.257	2.29	0.0325	0.0000492	0.00229	1.00000
<b>N</b>	0.718	11.9	23.3	0.290	0.690	8.44	0.050	0.0000529	0.00844	1.00000
<b>T</b>	18.4	617	67.3	0.389	3.70	10.6	0.0465	0.0000563	0.0106	1.00000
<b>E</b>	0.145	0.0320	0.567	2.76	83.8	44.5	0.0602	0.000796	0.0445	1.00000
<b>U</b>	2.35	27.0	20.0	0.190	0.102	1.41	0.0270	0.00000856	0.00141	1.00000

## 6.1.2 ANNUAL RESILIENCE LEVELS OF ELECTRICITY TRANSMISSION

In Figure 42 the calculated annual mean resilience level for the Electricity Transmission system is given. In Table 11 detailed accounts of the annual mean resilience level, mean duration of the given year, along with mean functionality loss per year and mean resilience loss is given. From Figure 42 it is hard to discern any changes of the mean resilience level over the years as is it very close to one, although Table 11 reveals that there are some minor variations.



**Figure 42 Annual resilience level of Electricity Transmission**

**Table 11 Resilience values for Electricity Transmission per year**

Year	Duration (h)			FL			Resilience Loss			Resilience
	Mean	Var	Max	Mean (10 <sup>-3</sup> )	Var (10 <sup>-6</sup> )	Max (10 <sup>-3</sup> )	Mean (10 <sup>-6</sup> )	Var (10 <sup>-6</sup> )	Max	Mean
<b>2005</b>	0.53	5.82	11.6	0.217	0.123	1.85	0.0309	0.0000247	0.00185	1.00000
<b>2006</b>	5.14	255	67.3	1.47	51.1	44.5	0.774	0.00423	0.0445	1.00000
<b>2007</b>	9.66	575	64.0	0.894	7.32	10.6	0.306	0.00089	0.0106	1.00000
<b>2008</b>	0.0733	0.011	0.333	1.23	9.49	12	0.596	0.00575	0.012	1.00000
<b>2009</b>	2.30	47.1	26.0	0.203	0.105	1.58	0.0423	0.0000174	0.00158	1.00000
<b>2010</b>	0.297	0.623	2.77	0.174	0.0498	0.75	0.0462	0.00000795	0.00075	1.00000
<b>2011</b>	3.11	32.9	17.6	0.727	3.74	8.44	0.377	0.000464	0.00844	1.00000
<b>2012</b>	5.07	98.7	20.0	0.215	0.114	0.768	0.051	0.0000196	0.000768	1.00000
<b>2013</b>	0.0167	0	0.0167	0.262	0.206	0.786	0.0015	0.00000118	0.000786	1.00000
<b>2014</b>	0.82	12.7	17.6	0.238	0.122	1.78	0.139	0.0000734	0.00178	1.00000
<b>2015</b>	2.58	24.5	15.3	0.163	0.0469	0.662	0.219	0.0000599	0.000662	1.00000
<b>2016</b>	0.681	3.01	4.62	0.159	0.0589	0.785	0.00834	0.00000280	0.000785	1.00000
<b>All years</b>	2.23	76.5	67.3	0.512	8.05	44.5	0.216	0.000963	0.0445	1.00000

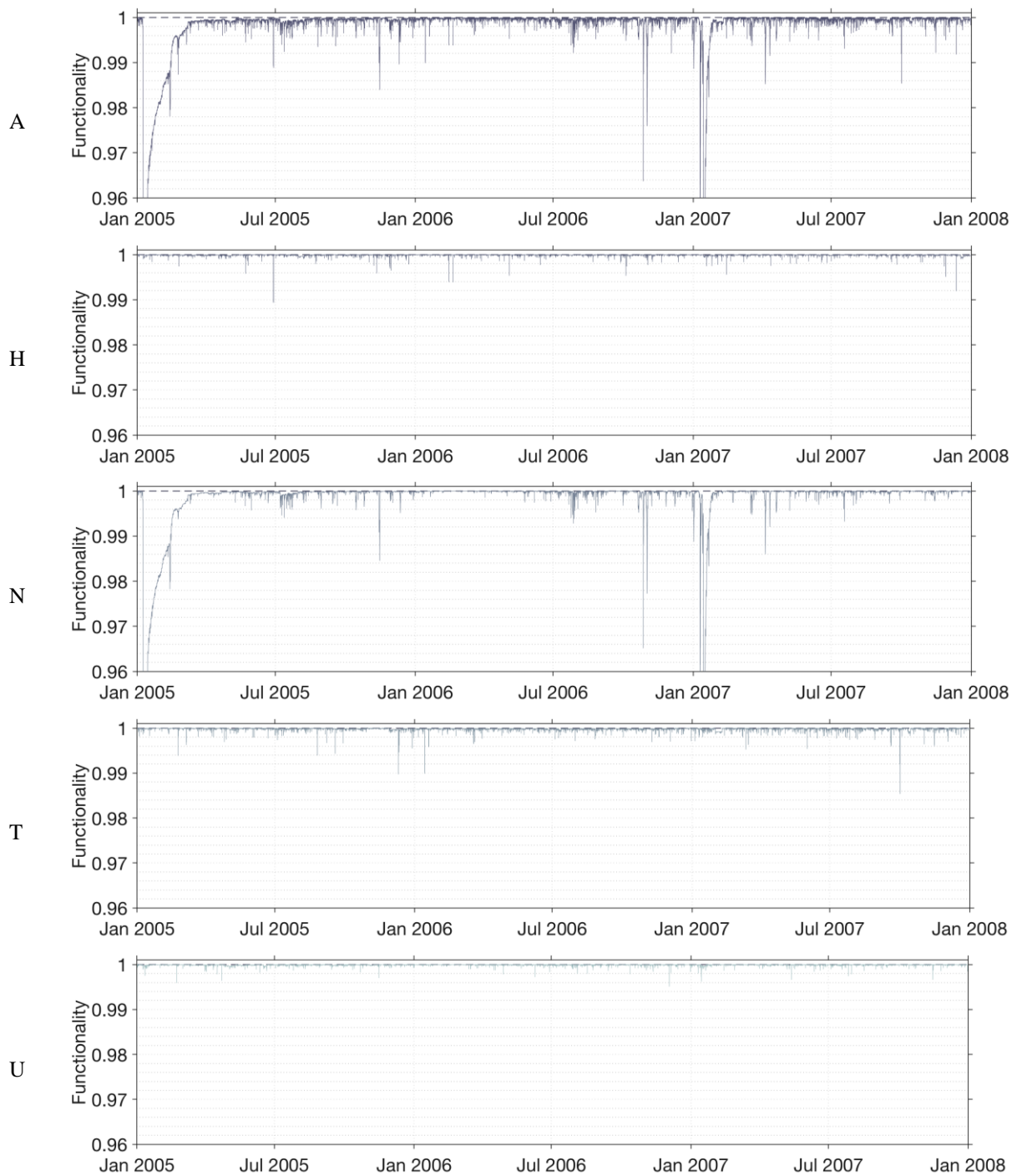
## 6.2 ELECTRICITY DISTRIBUTION

### 6.2.1 NATIONAL SYSTEM LEVEL RESILIENCE OF ELECTRICITY DISTRIBUTION

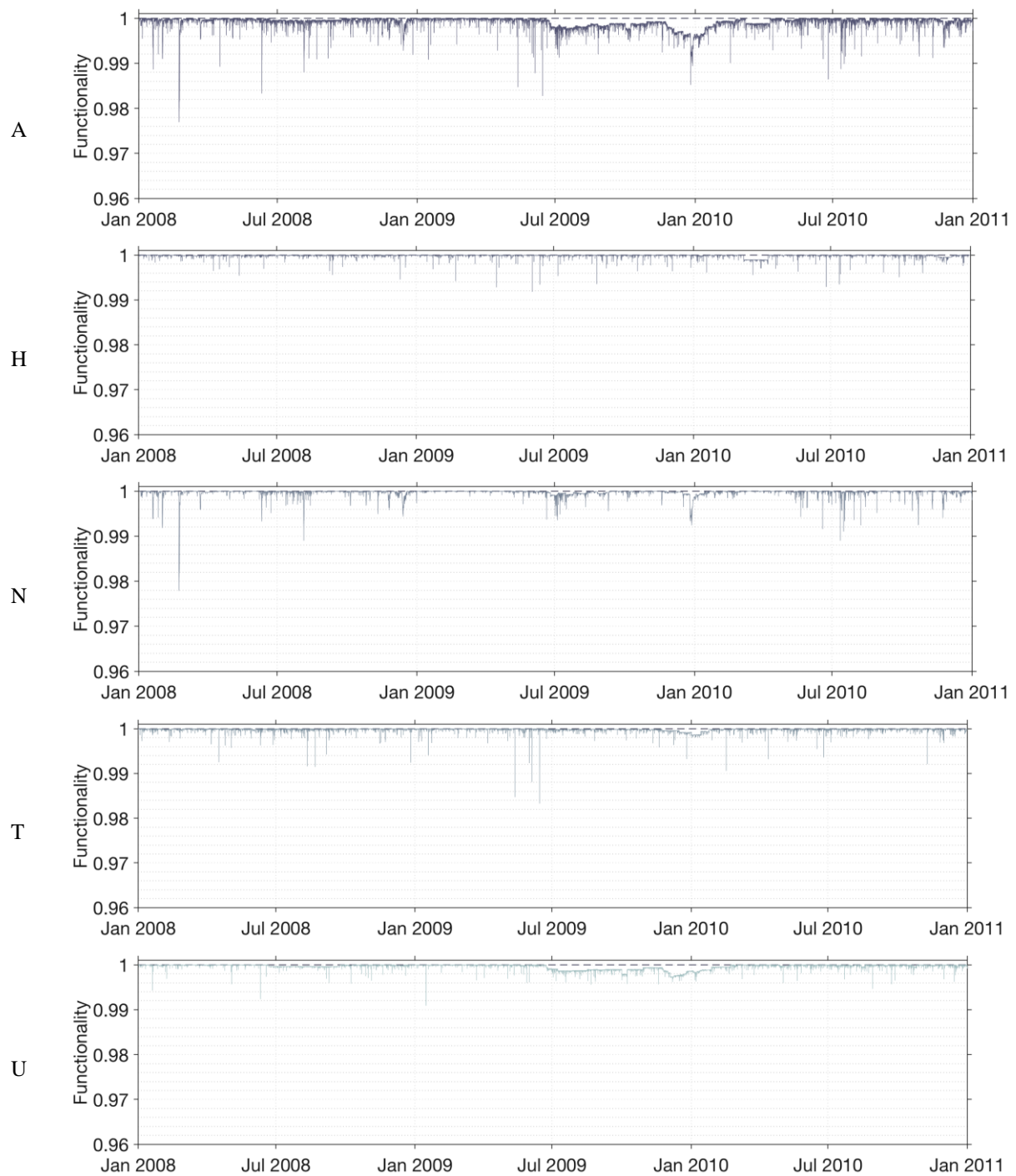
Figure 43 to Figure 46 demonstrates the functionality of the Electricity Distribution infrastructure at a national system level over the time period of the data and given the data availability. The findings demonstrate that the Electricity distribution infrastructure, seen from a national level perspective, is nearly continuously experiencing interruptions, some of which results in high functionality losses. The results show that these peaks in functionality loss occur generally during the late autumn/winter, where there is generally a strong correlation between the interruptions and natural failure causes.

Table 12, as complement to Figure 43 to Figure 46, gives an indication of which interruption causes that contribute most to the total losses of functionality level of the infrastructure. By far, natural related interruption causes have the most significant impact on the total functionality of the infrastructure. Natural interruption causes score the highest in all categories (Duration

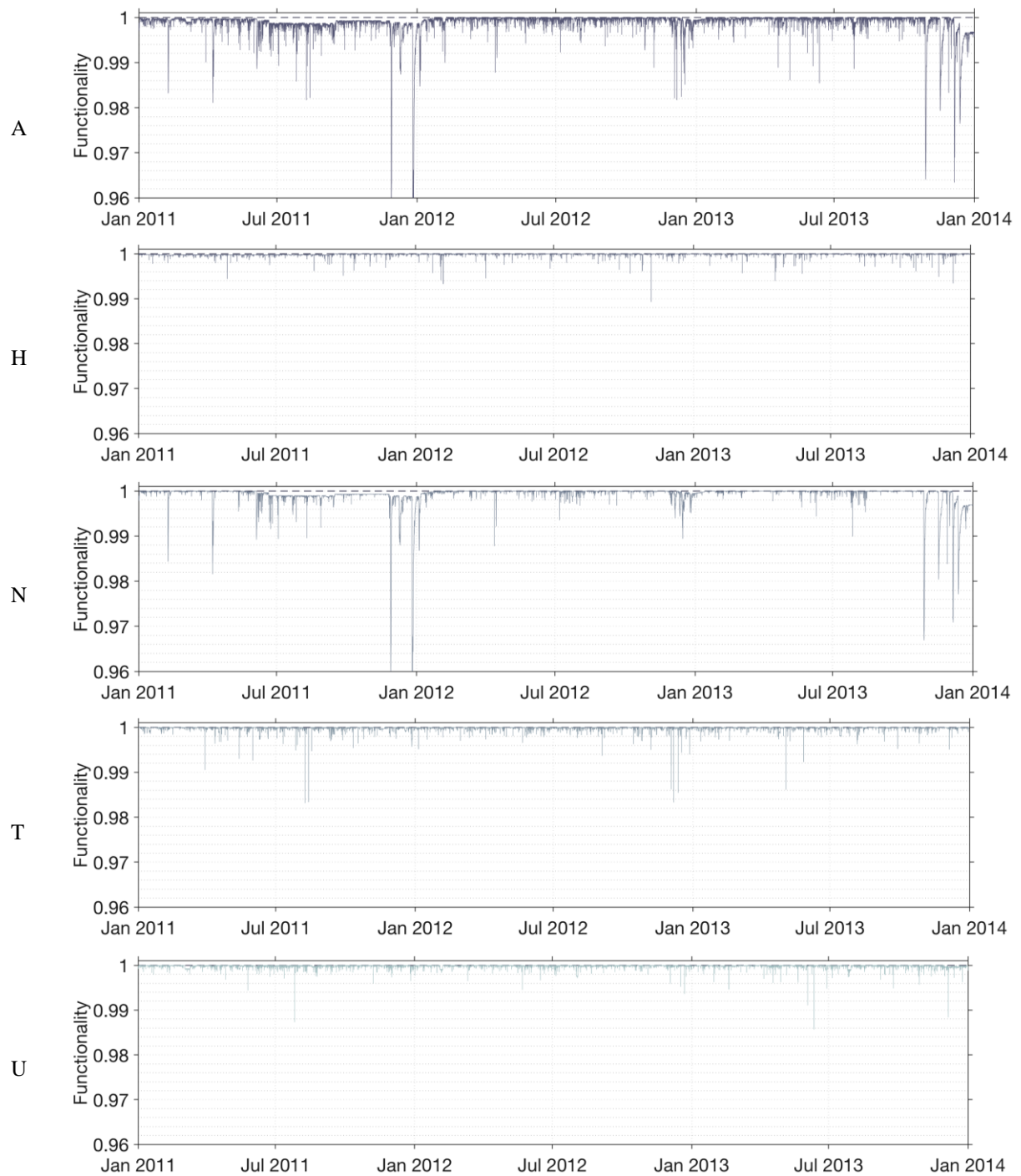
Mean, Functionality Loss Mean, Resilience Mean, Resilience Loss Mean). Technical related causes are the second most contributing factor to the total system functionality.



**Figure 43 Resilience curve for Electricity Distribution during the time period 2005-2007 – part 1/4. All values are first plotted as reference (A), then categorised according to the generic interruption causes: (H) human causes, (N) natural, (T) technical, (E) external and (U) unknown/missing data, here are no external causes. A dashed line is plotted as reference, displaying a fully functional system. The vertical axes are given a unified value of (0,96) for better resolution. Extreme values falling outside of the displayed bounds are presented for accounting purposes as [Year (maxFL)]: 2005(0,159) and 2007(0,105).**

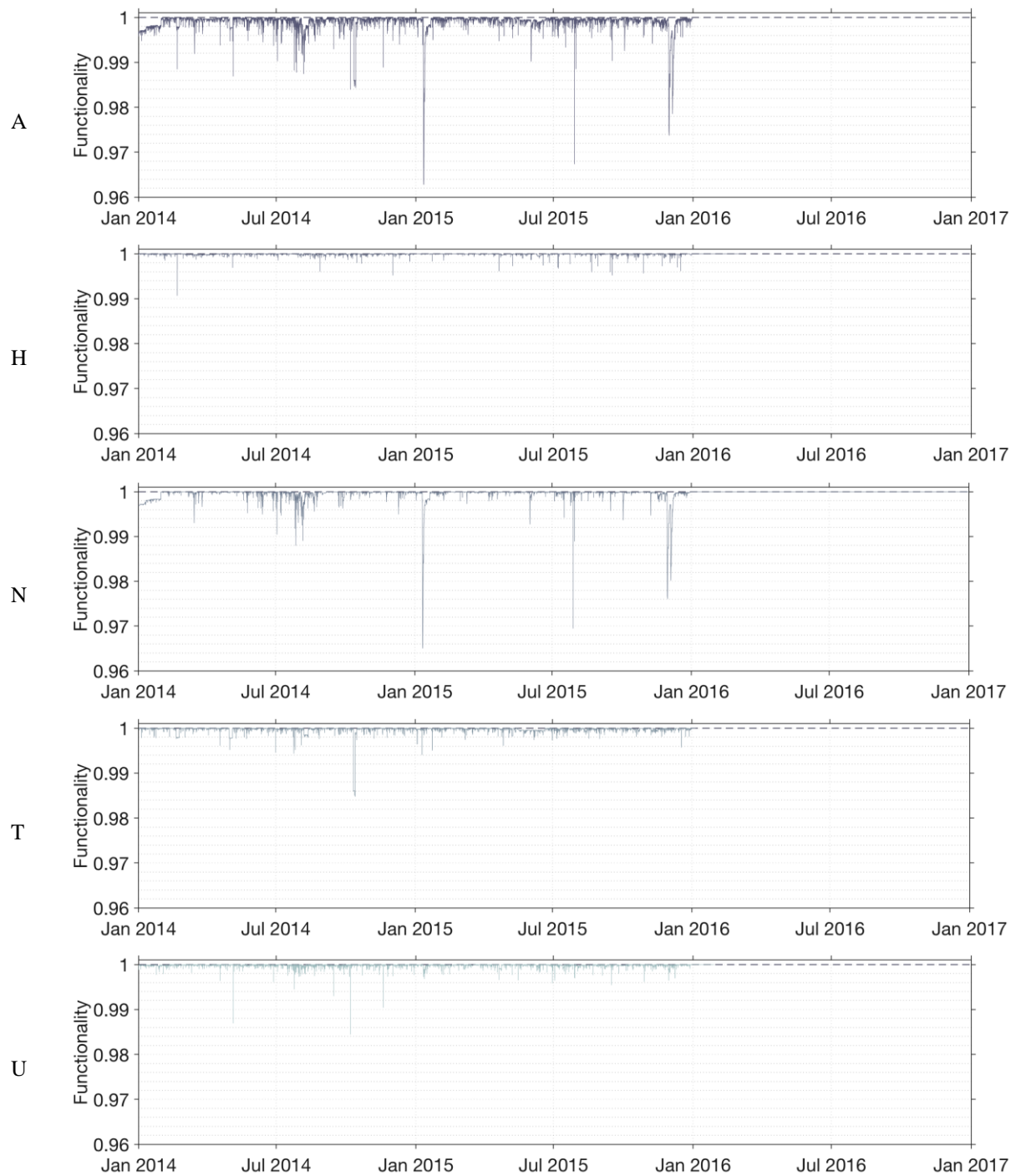


**Figure 44 Resilience curve for Electricity Distribution during the time period 2008-2010 – part 2/4. All values are first plotted as reference (A), then categorised according to the generic interruption causes: (H) human causes, (N) natural, (T) technical, (E) external and (U) unknown/missing data, here are no external causes. A dashed line is plotted as reference, displaying a fully functional system. The vertical axes are given a unified value of (0,96) for better resolution.**



**Figure 45 Resilience curve for Electricity Distribution during the time period 2011-2013 – part 3/4. All values are first plotted as reference (A), then categorised according to the generic interruption causes: (H) human causes, (N) natural, (T) technical, (E) external and (U) unknown/missing data, here are no external causes. A dashed line is plotted as reference, displaying a fully functional system. The vertical axes are given a unified value of (0,96) for better resolution. Extreme values falling outside of the displayed bounds are presented for accounting purposes as [Year (maxF<sub>L</sub>): 2011 (0.076)].**





**Figure 46 Resilience curve for Electricity Distribution during the time period 2014-2015. – part 4/4. All values are first plotted as reference (A), then categorised according to the generic interruption causes: (H) human causes, (N) natural, (T) technical, (E) external and (U) unknown/missing data, here are no external causes. A dashed line is plotted as reference, displaying a fully functional system. The vertical axes are given a unified value of (0,96) for better resolution.**

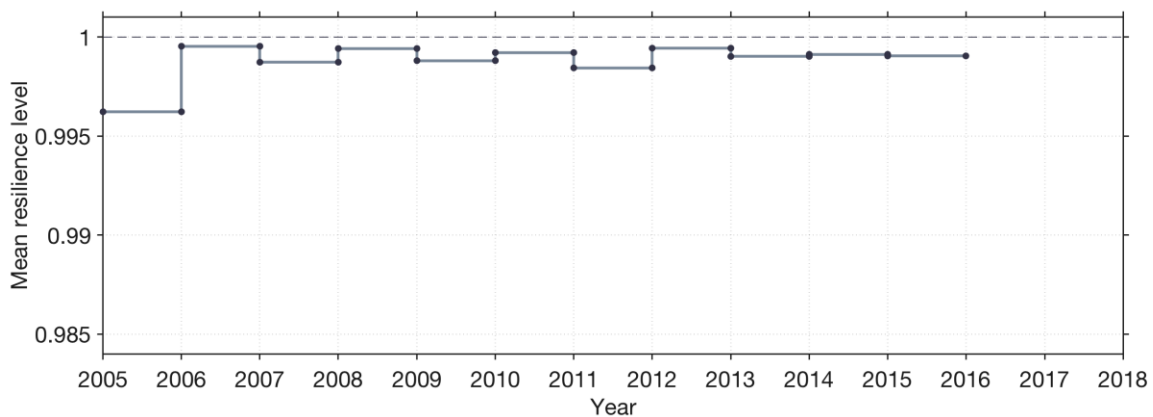
**Table 12 Overall resilience values of the generic interruption causes for Electricity Distribution. A: The total functionality of the system at a national system level. The generic interruption causes: H: human, N: natural, T: technical, E: external and U: unknown/missing data.**

Cause	Duration (h)		Max	F <sub>L</sub>		Max	Resilience Loss		Max	Resilience
	Mean	Var		Mean	Var		Mean	Var		
				(10 <sup>-3</sup> )	(10 <sup>-6</sup> )	(10 <sup>-3</sup> )	(10 <sup>-6</sup> )	(10 <sup>-6</sup> )		Mean
<b>A</b>	8.25	4210	8770	3.97	160	160	1180	20.2	0.16	0.99882
<b>H</b>	3.71	952	6130	0.134	0.0925	10.7	88.5	0.045	0.0107	0.99991
<b>N</b>	19.2	10010	8770	8.62	403	157	769	19.3	0.157	0.99923
<b>T</b>	3.49	1980	8770	0.222	0.294	16.8	169	0.245	0.0168	0.99983
<b>U</b>	2.75	1290	8040	0.232	0.211	15.6	153	0.137	0.0156	0.99985

## 6.2.2 THE ANNUAL RESILIENCE LEVELS OF ELECTRICITY DISTRIBUTION

In Figure 47 the calculated annual mean resilience level for the Electricity distribution system is given. In Table 13 detailed accounts of the annual resilience level, mean duration of the given year, along with mean Functionality Loss per year and mean resilience loss.

The results show that 2005 has the lowest resilience level, while 2006 has the highest resilience level. The mean resilience loss during 2005 is approximately eight times greater than the resilience loss during 2006. The results also show that the resilience level differs from year to year. During 2006 there is a significant increase in resilience level, from which the level fluctuates somewhat until 2013. From 2013 to 2015 the resilience level shown to have stabilised somewhat, compared to the years before 2013.



**Figure 47 Annual resilience level of Electricity distribution. The dotted horizontal line refers to fully functional system.**

**Table 13 Resilience values for Electricity Distribution per year**

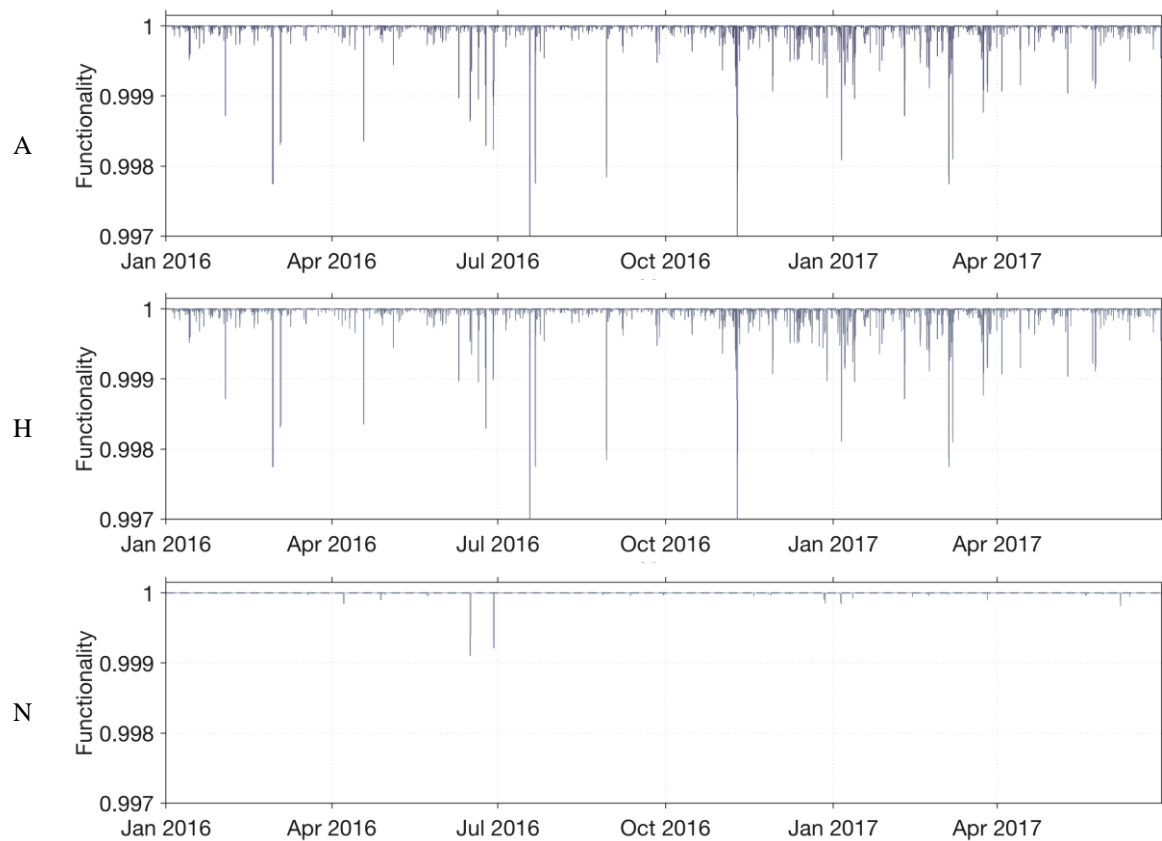
Year	Duration (h)			FL			Resilience Loss			Resilience
	Mean	Var	Max	Mean (10 <sup>-3</sup> )	Var (10 <sup>-6</sup> )	Max (10 <sup>-3</sup> )	Mean (10 <sup>-6</sup> )	Var (10 <sup>-6</sup> )	Max	Mean
<b>2005</b>	38.5	29700	8770	14.4	836	160	3770	137	0.160	0.99623
<b>2006</b>	3.21	1330	8040	1.19	9.07	36.3	462	1.16	0.0363	0.99954
<b>2007</b>	9.77	957	2210	7.92	373	106	1270	40.3	0.106	0.99873
<b>2008</b>	3.74	654	3670	1.36	6.79	23.1	578	1.40	0.0231	0.99942
<b>2009</b>	3.48	3280	6550	1.65	2.45	17.2	1190	1.69	0.0172	0.99881
<b>2010</b>	2.71	299	2530	1.12	1.49	13.6	784	0.959	0.0136	0.99922
<b>2011</b>	5.19	2260	8770	4.69	102	75.5	1560	14.9	0.0754	0.99844
<b>2012</b>	2.87	334	2710	1.09	4.32	18.3	561	1.21	0.0183	0.99944
<b>2013</b>	5.97	790	2730	3.12	43.0	36.7	979	7.57	0.0366	0.99902
<b>2014</b>	3.58	707	2750	1.32	2.99	16.1	872	2.20	0.0161	0.99913
<b>2015</b>	6.82	1060	3650	2.78	33.5	37.3	952	6.11	0.0373	0.99905
<b>All years</b>	8.25	4210	8770	3.97	160	160	1180	20.2	0.16	0.99882

## 6.3 TRANSPORT ROAD

### 6.3.1 THE NATIONAL SYSTEM LEVEL RESILIENCE OF TRANSPORT ROAD

Figure 48 shows the functionality of the Transport Road infrastructure at a national system level over the time period of the data and given data availability. The findings demonstrate that the infrastructure experiences interruptions with minor level functionality losses on somewhat regularly basis, while interruption of higher functionality losses occurs with longer time intervals.

Table 14, as complement to Figure 48, gives an indication of which interruption causes that contribute most to the total losses of functionality level of the infrastructure. The results are well correlated to human causes, as can be seen between (see Figure 48) interruption causes. The frequency of natural related interruptions is very low compared to human related causes.



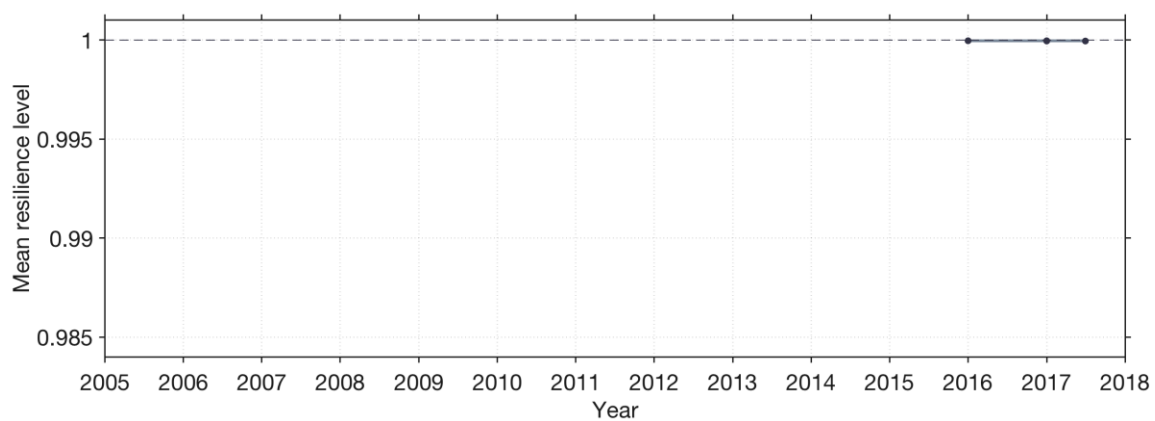
**Figure 48 Resilience curve for Transport Road during the time period 2016 to 2017-06-30. All values are first plotted as reference (A), then categorised according to the generic interruption causes: (H) human causes, (N) natural, (T) technical, (E) external and (U) unknown/missing data, here are only human and natural causes that affect the system. A dashed line is plotted as reference, displaying a fully functional system. The vertical axes are given a unified value of (0,997) for better resolution. Extreme values falling outside of the displayed bounds are presented for accounting purposes as [Year (maxFL)]: 2016 (0.1596).**

**Table 14 Overall resilience values of the generic interruption causes for Transport Road. A: The total functionality of the system at a national system level. The generic interruption causes: H: human, and N: natural.**

Cause	Duration (h)		FL	Resilience Loss			Resilience		
	Mean	Var		Mean	Var	Max	Mean	Var	Max
				(10 <sup>-3</sup> )	(10 <sup>-6</sup> )	(10 <sup>-3</sup> )	(10 <sup>-6</sup> )	(10 <sup>-6</sup> )	Mean
<b>A</b>	0.973	2.10	12.0	0.101	0.134	5.89	39.7	0.0387	0.00589
<b>H</b>	0.93	1.96	12.0	0.0964	0.134	5.89	37.5	0.0370	0.00589
<b>N</b>	1.86	4.20	12.0	0.0183	0.00515	0.895	2.18	0.0012	0.000895

### 6.3.2 THE ANNUAL RESILIENCE LEVELS OF TRANSPORT ROAD

In Figure 49 the calculated annual mean resilience level for the Transport Road infrastructure is given. In Table 15 detailed accounts of the annual mean resilience level, mean duration of the given year, along with mean functionality loss per year and mean resilience loss is given. It is demonstrated in Figure 49 that the mean resilience level is quite close to full resilience, where according to Table 15 the mean resilience level during 2016 is 0.9962. Tendencies are difficult to see with such a small statistical basis, but the first six months of 2017 the mean resilience level improved slightly compared to 2016. The mean resilience losses are approximately eight times greater during 2016 compared to the first six months of 2017.



**Figure 49 Annual resilience level of Transport Road**

**Table 15 Resilience values for Transport Road per year to 2017-06-30 ()**

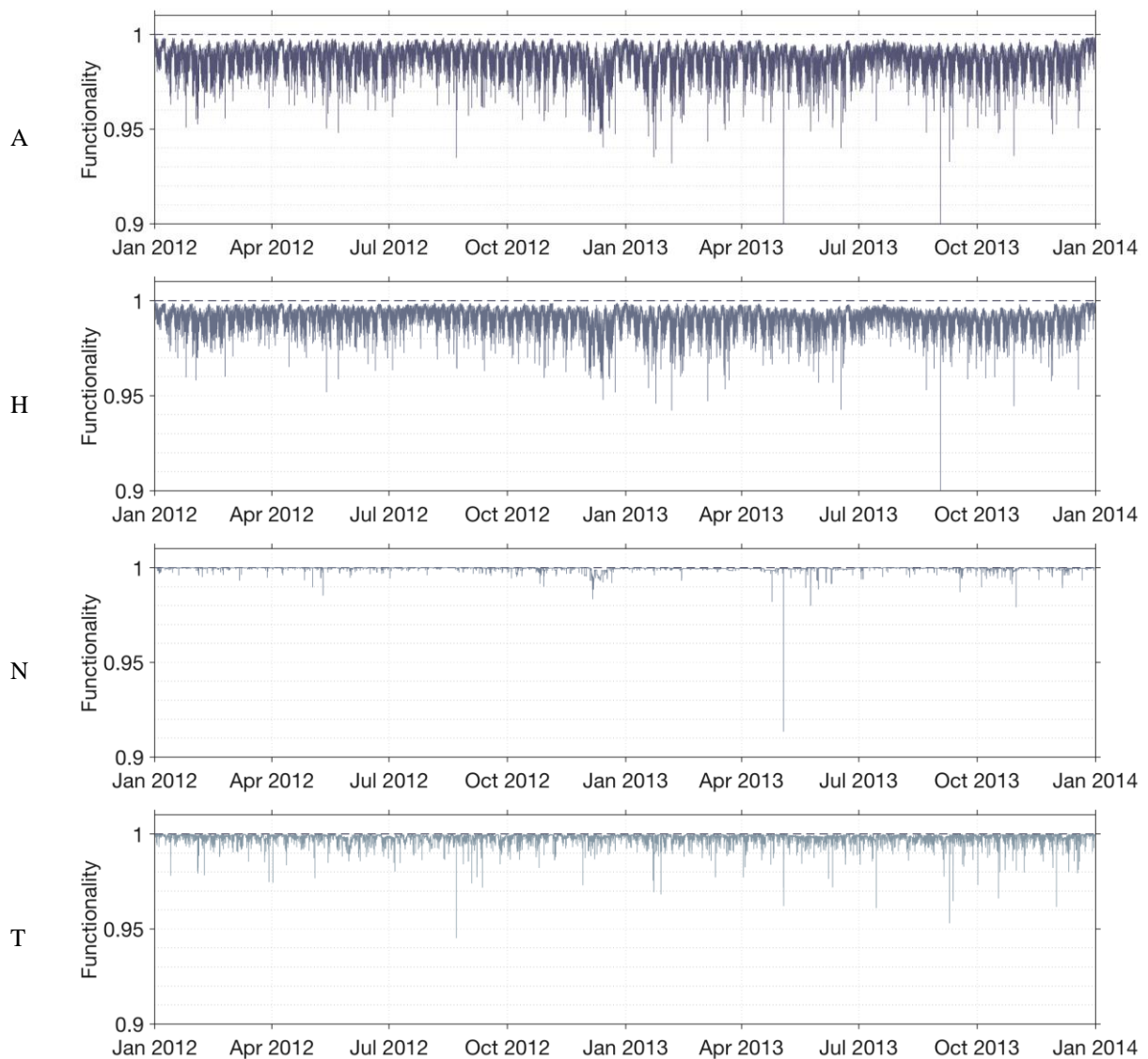
Year	Duration (h)			F <sub>L</sub>			Resilience Loss			Resilience
	Mean	Var	Max	Mean	Var	Max	Mean	Var	Max	
				(10 <sup>-3</sup> )	(10 <sup>-6</sup> )	(10 <sup>-3</sup> )	(10 <sup>-6</sup> )	(10 <sup>-6</sup> )		Mean
<b>2016</b>	0.937	1.63	12.0	0.0963	0.176	5.89	35.5	0.0431	0.00589	0.99996
<b>2017*</b>	1.03	2.84	12.0	0.109	0.0661	2.26	48.1	0.0295	0.00226	0.99995
<b>All years</b>	0.973	2.10	12.0	0.101	0.134	5.89	39.7	0.0387	0.00589	0.99996

## 6.4 TRANSPORT RAILWAY

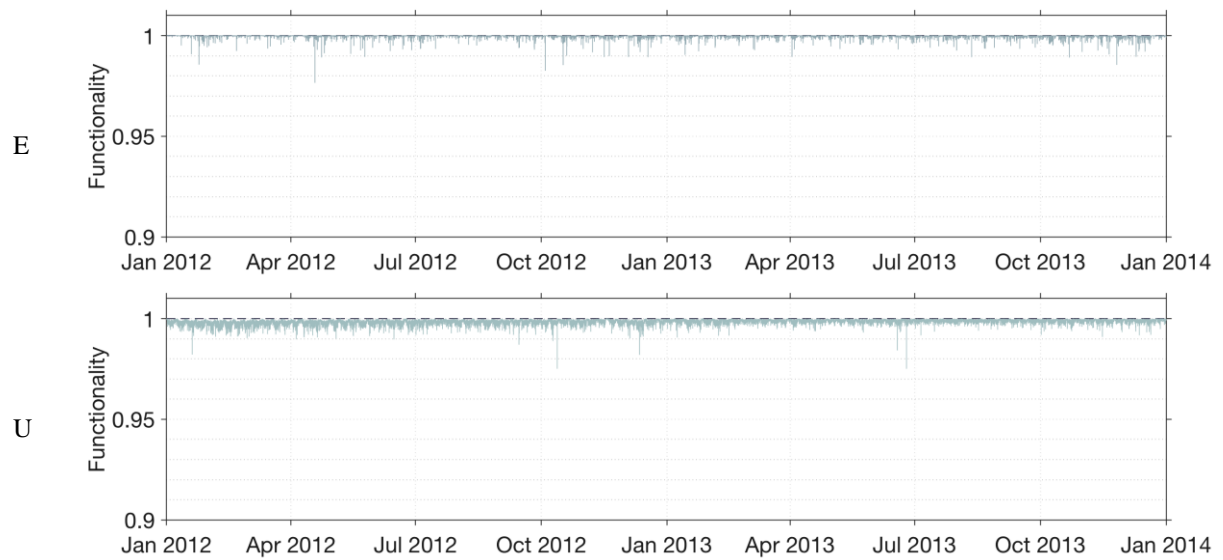
### 6.4.1 THE NATIONAL SYSTEM LEVEL RESILIENCE OF TRANSPORT RAILWAY

In Figure 50 to Figure 52 the Functionality Loss of the Transport Railway infrastructure at a national system level is given over the time period of the data and given data availability. The findings demonstrate that the infrastructure continuously experience interruptions, over all with quite high variation in Functionality Loss over time.

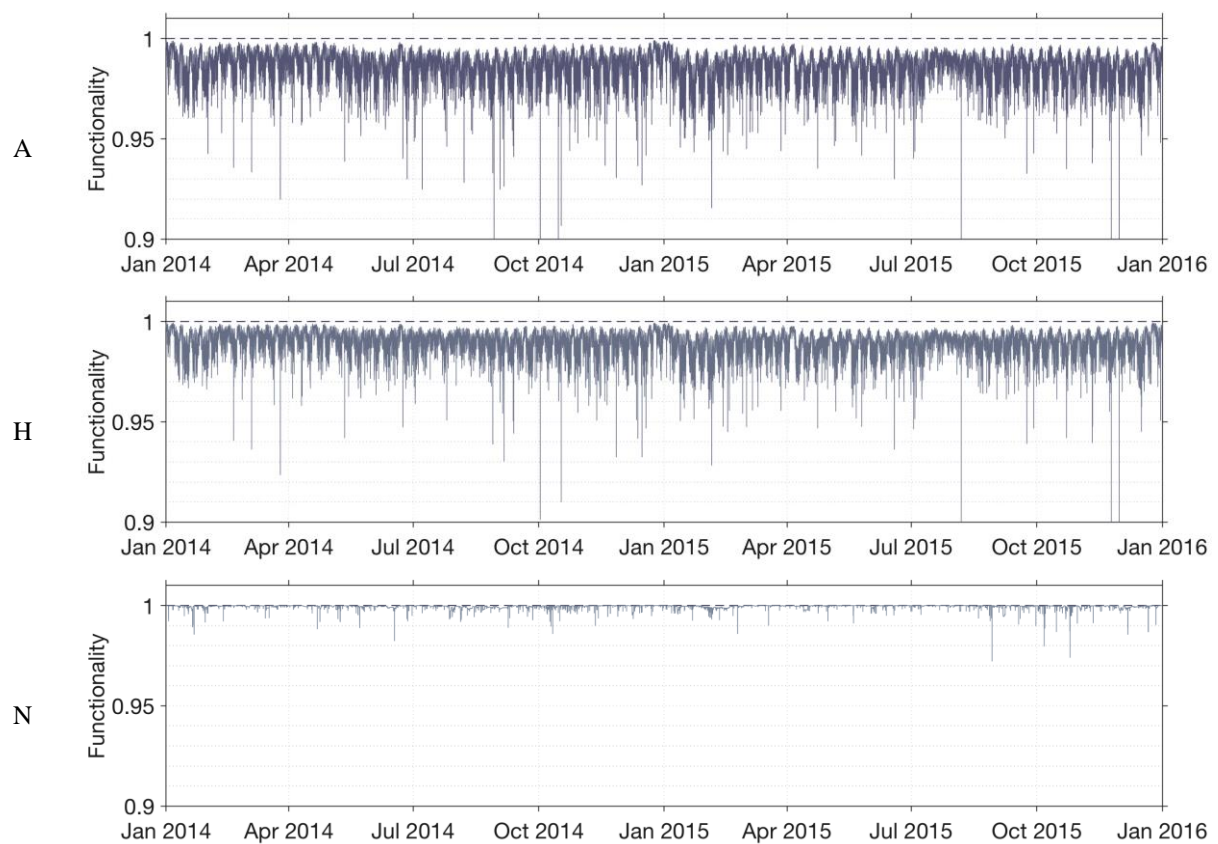
Table 16, as complement to Figure 50 to Figure 52, gives an indication of which interruption causes that contribute most to the total functionality level of the infrastructure. The biggest contributor to the total losses of functionality level of the infrastructure is related to interruptions due to human related causes, followed by technical interruption causes.



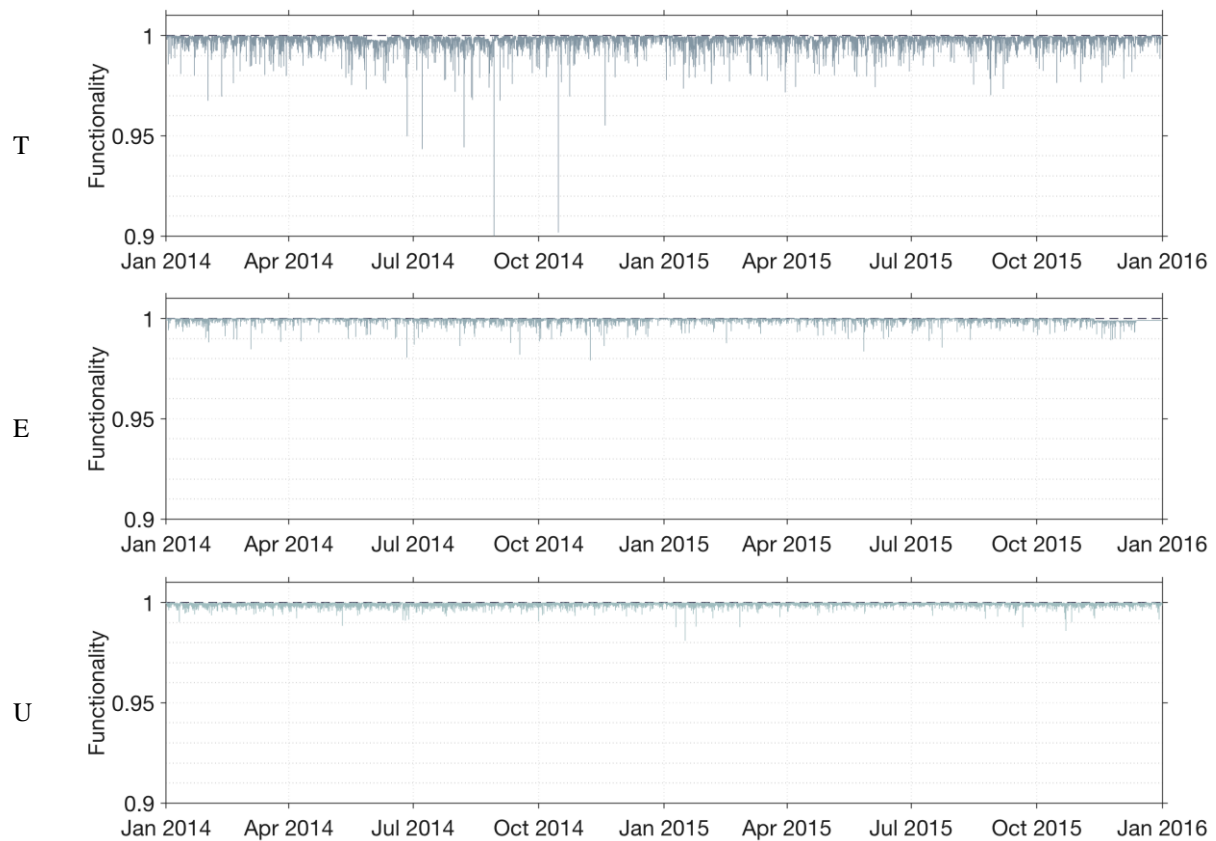
*Cont.*



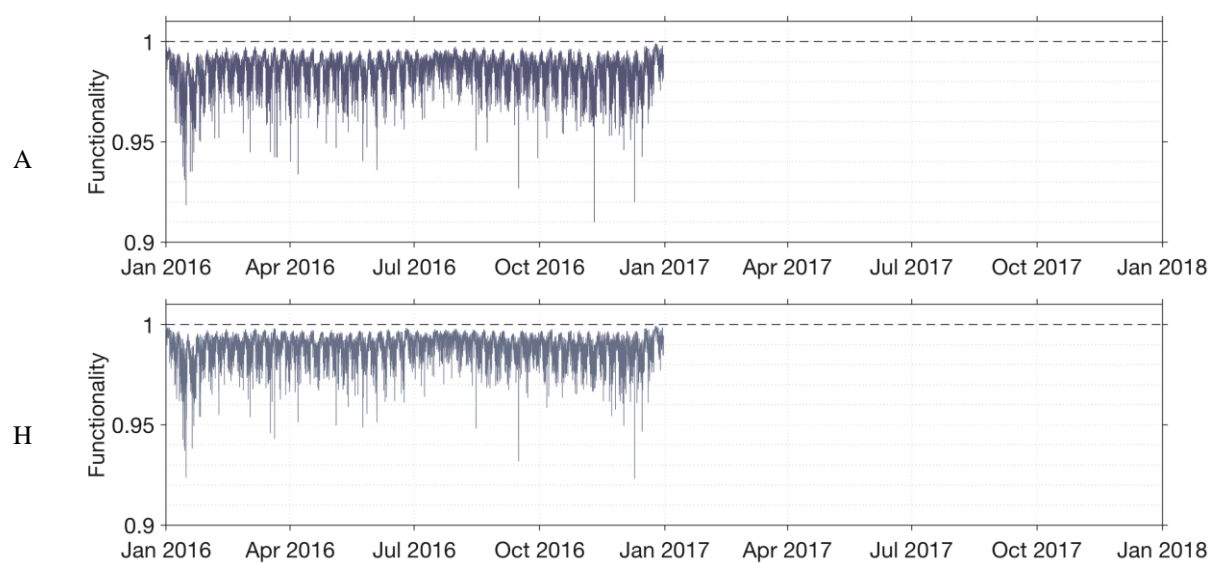
**Figure 50 Resilience curve for Transport Railway during the time period 2016 to 2017-06-30 – Part 1/3. All values are first plotted as reference (A), then categorised according to the generic interruption causes: (H) human causes, (N) natural, (T) technical, (E) external and (U) unknown/missing data. A dashed line is plotted as reference, displaying a fully functional system. The vertical axes are given a unified value of (0,9) for better resolution. Extreme values falling outside of the displayed bounds are presented for accounting purposes as [Year (maxFL)]: 2013 (0.1870).**



*Cont.*

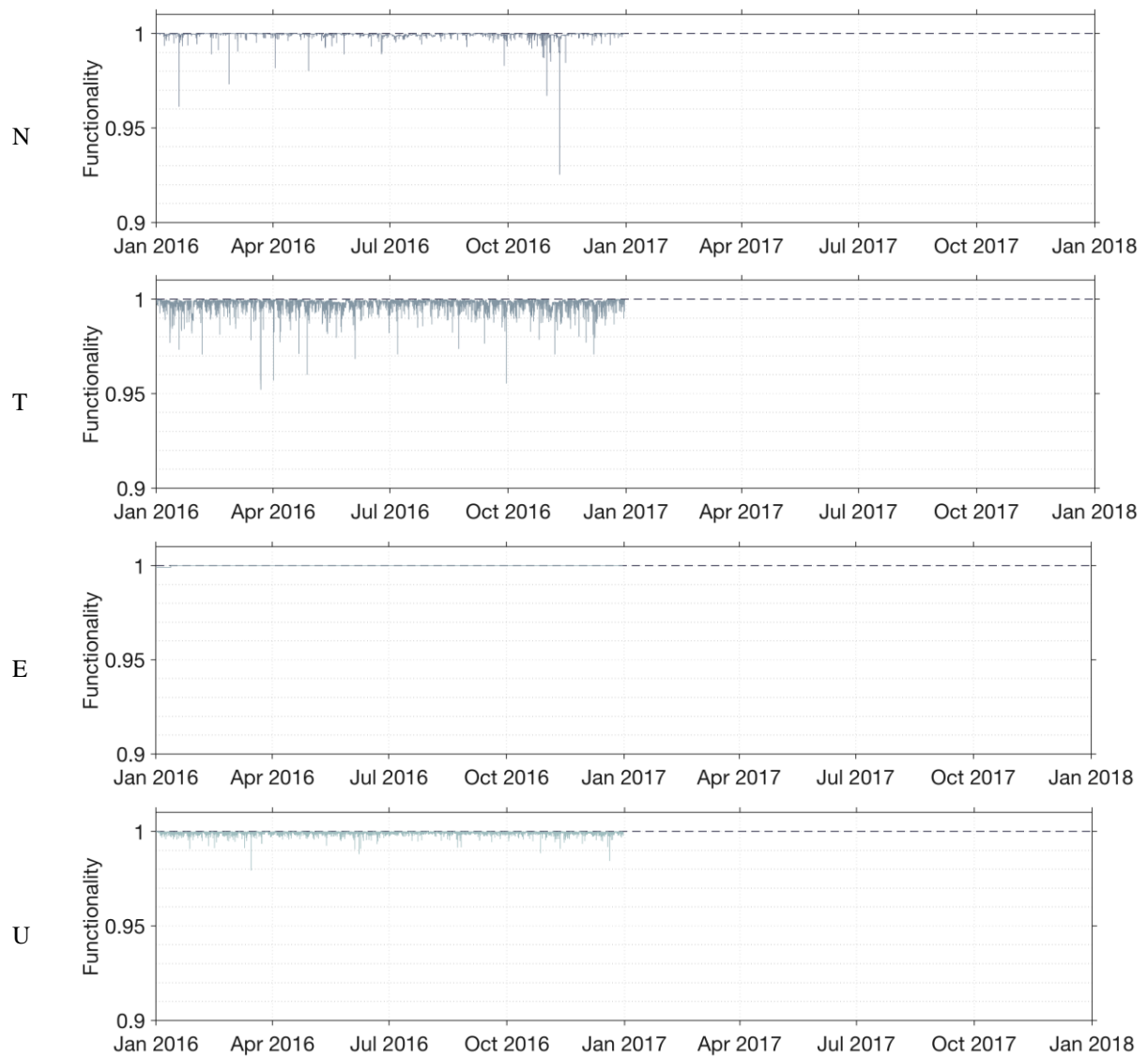


**Figure 51 Resilience curve for Transport Railway during the time period 2016 to 2017-06-30 – Part 2/3. All values are first plotted as reference (A), then categorised according to the generic interruption causes: (H) human causes, (N) natural, (T) technical, (E) external and (U) unknown/missing data. A dashed line is plotted as reference, displaying a fully functional system. The vertical axes are given a unified value of (0,9) for better resolution. Extreme values falling outside of the displayed bounds are presented for accounting purposes as [Year (maxFL)]: 2014 (0.2516) and 2015 (0.1484).**



*Cont.*





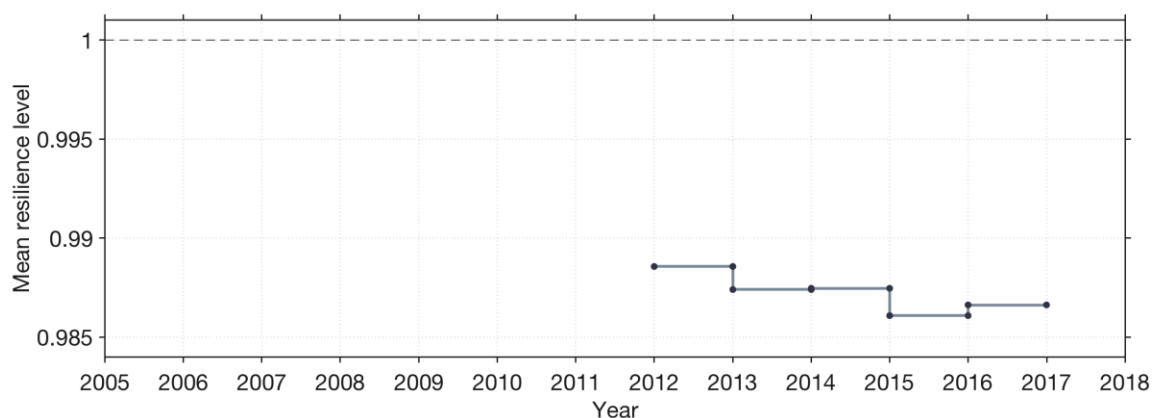
**Figure 52 Resilience curve for Transport Railway during the time period 2016 to 2017-06-30 – Part 3/3. All values are first plotted as reference (A), then categorised according to the generic interruption causes: (H) human causes, (N) natural, (T) technical, (E) external and (U) unknown/missing data. A dashed line is plotted as reference, displaying a fully functional system. The vertical axes are given a unified value of (0,9) for better resolution.**

**Table 16 Overall resilience values of the generic interruption causes for Transport Railway. A: The total functionality of the system at a national system level. The generic interruption causes: H: human, N: natural, T: technical, E: external and U: unknown/missing data.**

Cause	Duration (h)			FL			Resilience Loss			Resilience
	Mean	Var	Max	Mean (10 <sup>-3</sup> )	Var (10 <sup>-6</sup> )	Max (10 <sup>-3</sup> )	Mean (10 <sup>-6</sup> )	Var (10 <sup>-6</sup> )	Max	
<b>A</b>	18.0	73500	42700	15.3	48.7	252	12800	43.6	0.252	0.98723
<b>H</b>	13.8	46000	29200	11.6	31.3	183	9430	27.0	0.183	0.99057
<b>N</b>	107	291000	10300	1.06	4.13	86.6	440	0.999	0.0866	0.99956
<b>T</b>	99.6	607000	42700	2.36	9.10	238	1680	4.55	0.238	0.99832
<b>E</b>	5.98	2033	4000	0.734	1.21	23.4	288	0.352	0.0234	0.99971
<b>U</b>	3.86	373	2780	1.47	1.20	25.0	937	0.716	0.0249	0.99906

## 6.4.2 THE ANNUAL RESILIENCE LEVELS OF TRANSPORT RAILWAY

In Figure 53 the calculated annual mean resilience level for Transport Railway infrastructure of each given year of the time period of the data and given availability. In Table 17 detailed accounts of the annual mean resilience level, mean duration of the given year along with mean functionality loss and mean resilience loss per given year is given. The results show that the mean resilience level has been decreasing over the years with a slight increase during 2016 (of ~0,05% compared to 2015).



**Figure 53 Annual resilience level of Transport Railway**

**Table 17 Resilience values for Transport Railway per year**

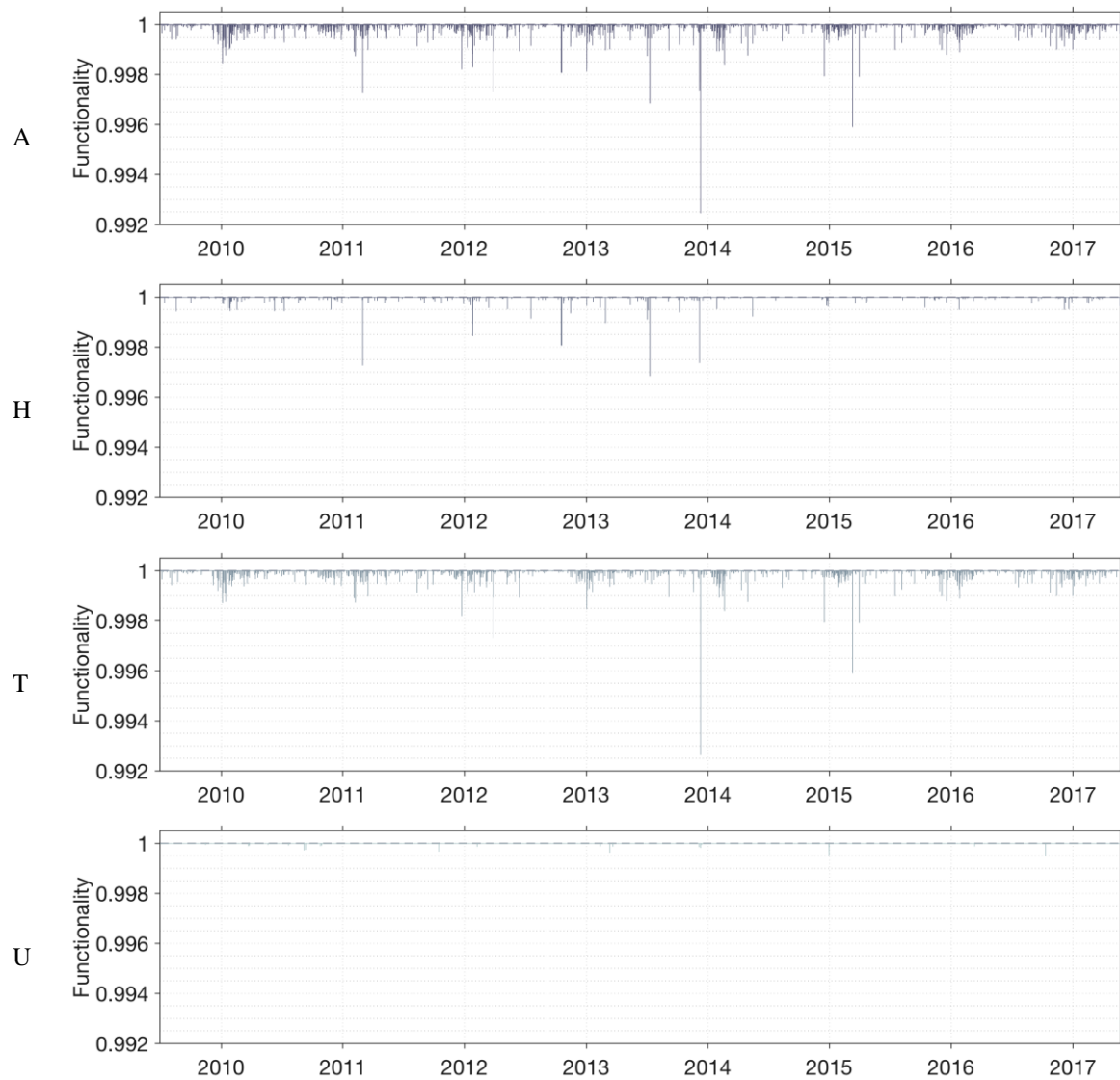
Year	Duration (h)			F <sub>L</sub>			Resilience Loss			Resilience
	Mean	Var	Max	Mean (10 <sup>-3</sup> )	Var (10 <sup>-6</sup> )	Max (10 <sup>-3</sup> )	Mean (10 <sup>-6</sup> )	Var (10 <sup>-6</sup> )	Max	Mean
<b>2012</b>	18.2	71400	31700	13.9	44.9	65.4	11400	37.2	0.0652	0.98856
<b>2013</b>	19.2	70100	16000	15.1	43.0	187	12600	39.7	0.187	0.98740
<b>2014</b>	18.5	126000	42700	15.1	51.1	252	12500	46.4	0.252	0.98746
<b>2015</b>	16.7	61800	22100	16.6	50.1	148	13900	45.9	0.147	0.98608
<b>2016</b>	17.5	37700	14300	16.0	50.1	90.7	13400	45.3	0.0902	0.98662
<b>All years</b>	18.0	73500	42700	15.3	48.7	252	12800	43.6	0.252	0.98723

## 6.5 WATER SUPPLY

### 6.5.1 THE NATIONAL SYSTEM LEVEL RESILIENCE OF WATER SUPPLY

Figure 54 demonstrates the functionality of the Water Supply infrastructure at a national system level over the time period of the data is given. The results show that the interruptions have tendencies to increase during the end of one year and in the beginning of the next (i.e. during the winter period).

Table 18, complement to Figure 54, gives an indication of which interruption cause contributes most to the total losses of functionality level of the infrastructure. Overall, Water Supply is most prone to be affected by technical interruption causes. Worth noticing is that no interruptions are registered with natural interruption cause, neither are any registered external.



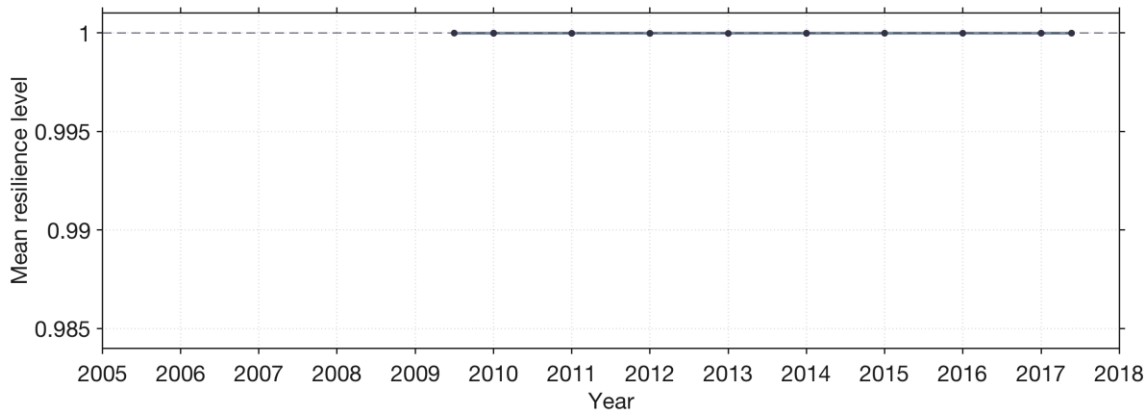
**Figure 54 Resilience curve for Water Supply during the time period 2005-2016. All values are first plotted as reference (A), then categorised according to the generic interruption causes: (H) human causes, (N) natural, (T) technical, (E) external and (U) unknown/missing data. Water Supply infrastructure has no interruptions related to natural and external causes. A dashed line is plotted as reference, displaying a fully functional system. The vertical axes are given a unified value of (0,9) for better resolution.**

**Table 18 Overall resilience values of the generic interruption causes for Water Supply. A: The total functionality of the system at a national system level. The generic interruption causes: H: human, T: technical, and U: unknown/missing data.**

Cause	Duration (h)			F <sub>L</sub>			Resilience Loss			Resilience	
	Mean	Var	Max	Mean (10 <sup>-3</sup> )	Var (10 <sup>-6</sup> )	Max (10 <sup>-3</sup> )	Mean (10 <sup>-6</sup> )	Var (10 <sup>-6</sup> )	Max	Mean	
<b>A</b>	4.76	130	350	0.165	0.155	7.55	17.8	0.0156	0.00755	0.99998	
<b>H</b>	4.94	10.8	45.0	0.0878	0.0641	3.16	5.02	0.00598	0.00316	0.99999	
<b>T</b>	4.76	162	350	0.144	0.118	7.37	12.5	0.00908	0.00737	0.99999	
<b>U</b>	3.54	9.07	19.0	0.0710	0.0107	0.505	0.251	0.0000679	0.000505	1.00000	

## 6.5.2 THE ANNUAL RESILIENCE LEVELS OF WATER SUPPLY

In Figure 55 the calculated annual mean resilience level of the Water supply infrastructure of each given year of the time period of the data and given availability. In Table 19 detailed accounts of the annual mean resilience level, mean duration of the given year, along with mean functionality loss per year and mean resilience loss is given. In Figure 55 it is hard to see any changes in the mean resilience level, as it the resilience level is close to one, nearly perfect. However, Table 19 reveals that there actually are some minor fluctuations.



**Figure 55 Annual resilience level of Water Supply**

**Table 19 Resilience values for Water Supply per year ( †from 2009-07-01, \* to 2017-05-23)**

Year	Durati on (h)			FL			Resilien ce Loss			Resilience	
	Mean	Var	Max	Mean (10 <sup>-3</sup> )	Var (10 <sup>-6</sup> )	Max (10 <sup>-3</sup> )	Mean (10 <sup>-6</sup> )	Var (10 <sup>-6</sup> )	Max	Mean	
<b>2009<sup>†</sup></b>	4.48	1.78	8.00	0.0927	0.0237	0.796	8.80	0.00315	0.000796	0.99999	
<b>2010</b>	4.60	5.45	20.0	0.173	0.0578	1.55	20.7	0.00853	0.00155	0.99998	
<b>2011</b>	4.31	7.26	24.0	0.163	0.110	2.75	18.1	0.0148	0.00275	0.99998	
<b>2012</b>	4.07	11.8	45.0	0.147	0.0748	2.68	25.3	0.0286	0.00268	0.99997	
<b>2013</b>	4.27	3.64	14.0	0.275	0.655	7.55	23.2	0.0382	0.00755	0.99998	
<b>2014</b>	5.28	137	150	0.170	0.0781	2.07	13.5	0.00914	0.00207	0.99999	
<b>2015</b>	4.11	4.16	24.0	0.160	0.167	4.10	15.6	0.0149	0.00410	0.99998	
<b>2016</b>	7.10	821	350	0.122	0.0349	1.12	15.0	0.00599	0.00112	0.99999	
<b>2017<sup>*</sup></b>	3.87	1.74	9.00	0.0859	0.0139	0.607	11.3	0.00270	0.000607	0.99999	
<b>All years</b>	4.76	130	350	0.165	0.155	7.55	17.8	0.0156	0.00755	0.99998	

## 6.6 TELECOMMUNICATION

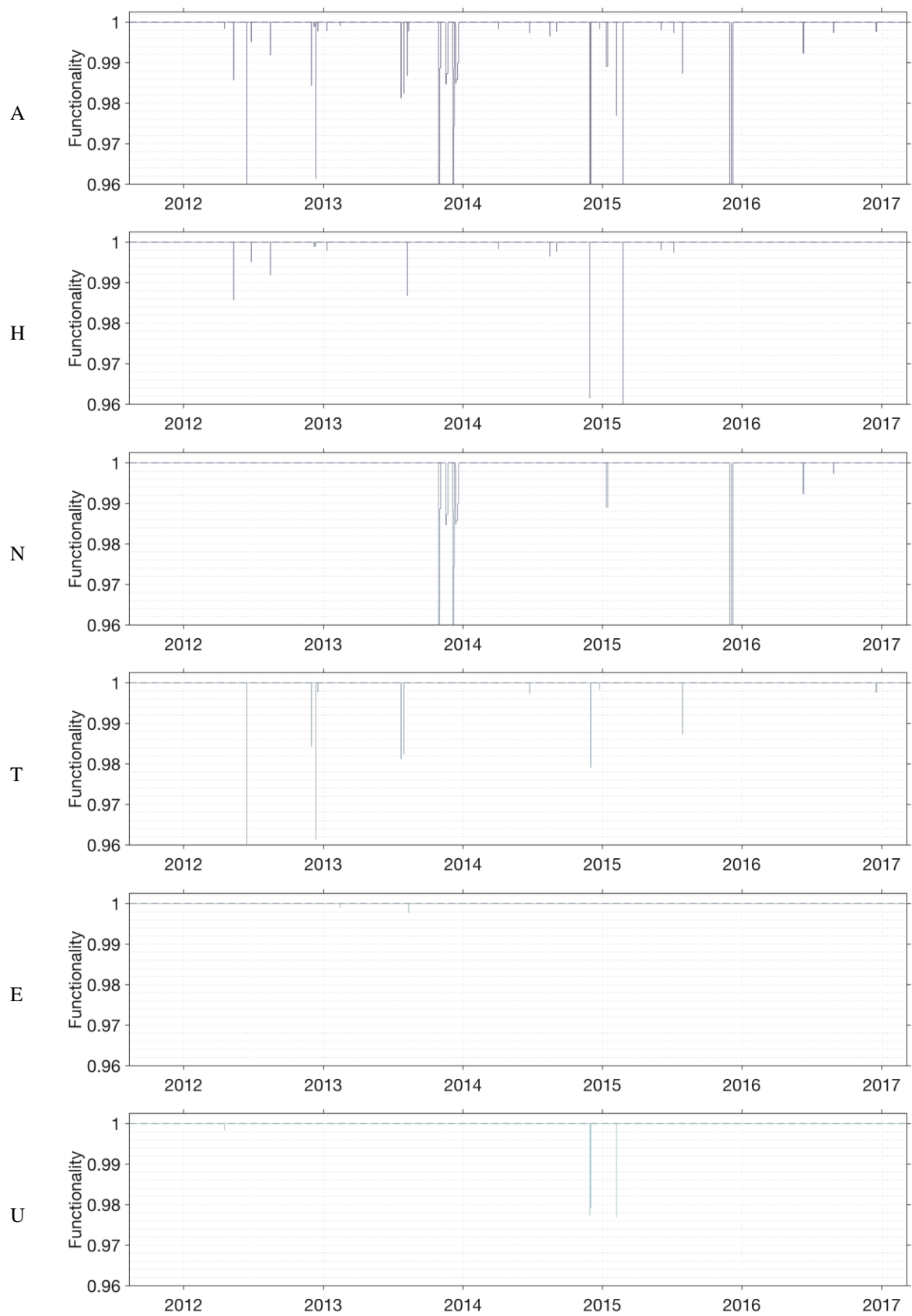
### 6.6.1 THE NATIONAL SYSTEM LEVEL RESILIENCE OF TELECOMMUNICATION

Over all, there is generally longer-time span between interruption in the Telecommunication sub-infrastructures (Mobile, Broadband Services and Fixed Telephony). That said, interruptions that does not fall under the mandatory reporting is not included, as it comes for regulatory authority.

#### TELECOMMUNICATION MOBILE

Figure 56 demonstrates the functionality of the Telecommunication Mobile at a national system level over the time period of the data and given data availability.

Table 20, as complement to Figure 56, gives an indication of what interruption causes that contributes most to the total losses of functionality level of the infrastructure. The results imply that it is the natural interruption causes that impacts the infrastructure the most, followed by technical interruption causes. Amongst the Telecommunication sub-infrastructures, Mobile is most prone to be affected by interruptions.



**Figure 56 Telecommunication Mobile.** Where the top figure (A) represent all interruptions during the time period August 2011- March 2017. The interruptions are then split in accordance of causes, where figure (H) represents human causes, (N) natural, (T) technical, and (U) unknown/missing. The horizontal line at

functionality 1 refers to fully functional system. Functionality loss exceeding 0,96 does not show in the figure. The vertical axes are given a unified value of (0,96) for better resolution. Extreme values falling outside of the displayed bounds are presented for accounting purposes as [Year (maxFL)]: 2012-06-14 (0,0855), 2013-10-28 (0.0634), 2013-10-30 (0.0499), 2013-12-05 (0.0576), 2014-11-28 (0.0615), 2014-12-01 (0.0419), 2105-02-23 (0.0805), 2015-11-29 (0.0458), 2015-11-29 (0.0637), 2014-12-01 (0.0419), 2015-02-23 (0.0805), 2015-11-29 (0.0458), 2015-11-29 (0.0637), 2015-11-29 (0.0754), 2015-12-03 (0.0637), 2015-12-04 (0.0458), 2015-12-04 (0.0503), 2015-12-04 (0.0611), 2015-12-07 (0.0566) and 2015-12-07 (0.0458).

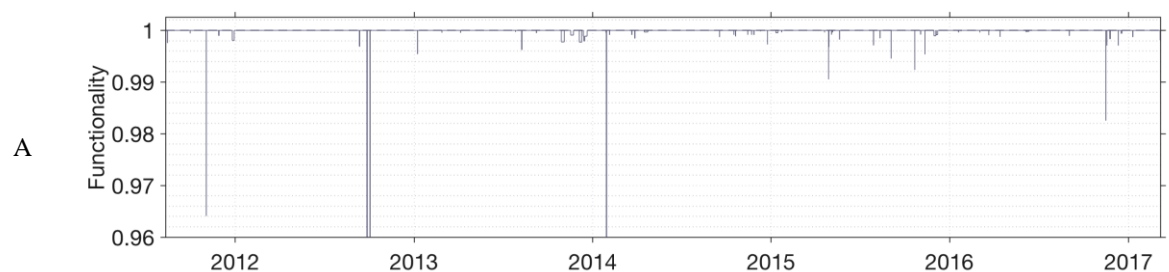
**Table 20 Overall resilience values of the generic interruption causes for Telecommunication Mobile. A:** The total functionality of the system at a national system level. The generic interruption causes: H: human, N: natural, T: technical, E: external and U: unknown/missing data.

Cause	Duration (h)			F <sub>L</sub>			Resilience Loss			Resilience
	Mean	Var	Max	Mean (10 <sup>-3</sup> )	Var (10 <sup>-6</sup> )	Max (10 <sup>-3</sup> )	Mean (10 <sup>-6</sup> )	Var (10 <sup>-6</sup> )	Max	Mean
<b>A</b>	39.3	2140	187	14.0	442	85.5	642	30.5	0.0855	0.99936
<b>H</b>	10.2	17.9	16.1	5.34	235	80.5	25.7	0.932	0.0805	0.99997
<b>N</b>	87.9	1680	187	21.6	546	75.4	577	28.3	0.0754	0.99942
<b>T</b>	10.0	94.3	36.4	8.10	283	85.5	29.9	0.855	0.0855	0.99997
<b>E</b>	5.19	12.0	7.75	0.408	0.667	2.26	0.488	0.000930	0.00226	1.00000
<b>U</b>	6.99	7.11	9.67	5.71	101	23.1	8.58	0.183	0.0231	0.99999

## TELECOMMUNICATION BROADBAND SERVICES

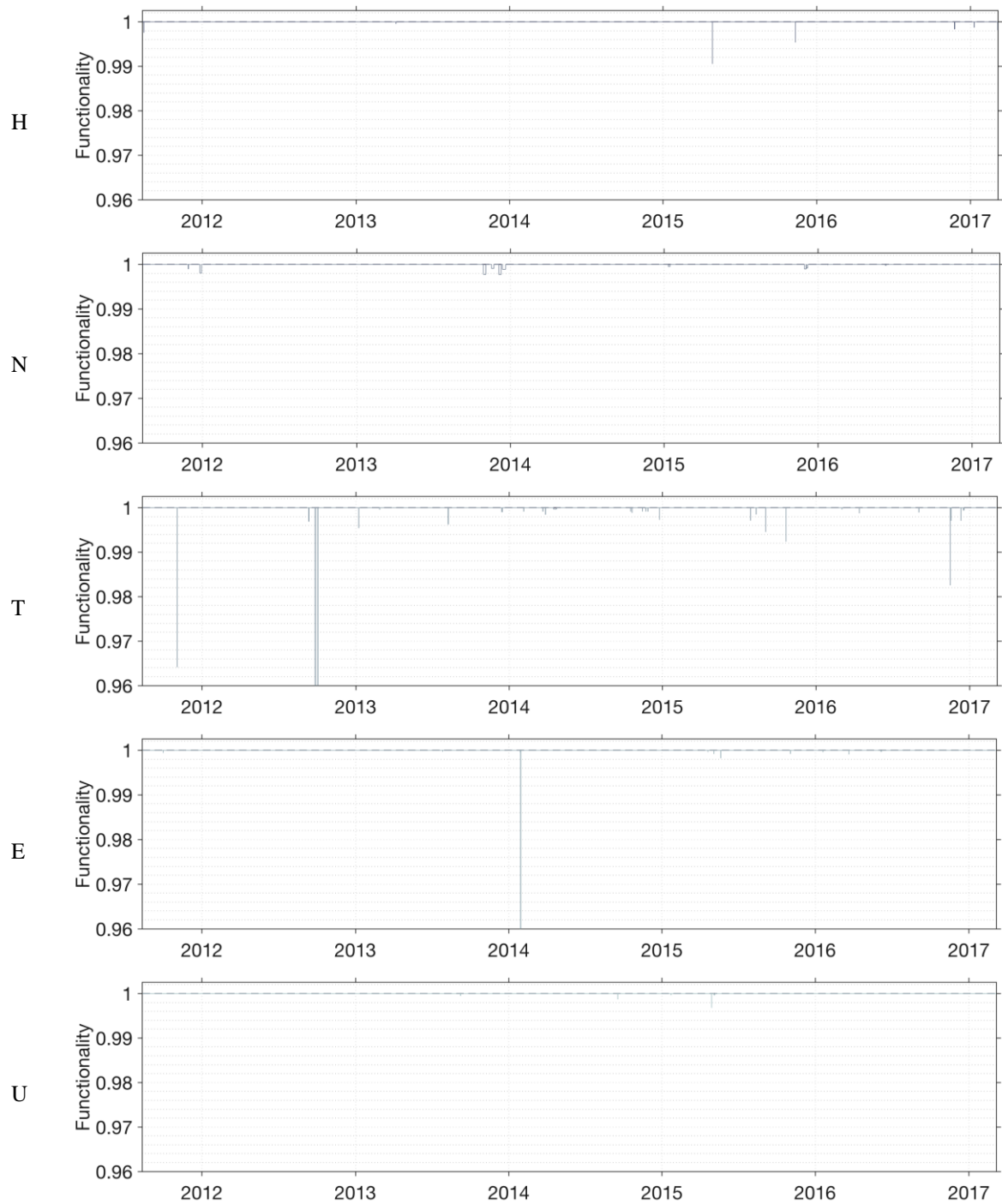
Figure 57 demonstrates the functionality of the Telecommunication Mobile at a national system level over the time period of the data and given data availability.

Table 21, as complement to Figure 57, gives an indication of what interruption causes that contributes most to the total loss of the functionality level of the infrastructure. The results imply that technical interruption causes have the most impact on the system.



*Cont.*





**Figure 57 Telecommunication Broadband Services.** Where the top figure (A) represent all interruptions during the time period August 2011- March 2017. The interruptions are then split in accordance of causes, where figure (H) represents human causes, (N) natural, (T) technical, and (U) unknown/missing. The horizontal line at functionality 1 refers to fully functional system. Functionality loss exceeding 0,96 does not show on figure. The vertical axes are given a unified value of (0,96) for better resolution. Extreme values falling outside of the displayed bounds are presented for accounting purposes as [Year (maxFL)]:2012-09-26 (0.0815), 2012-10-02 (0.0815), 2014-01-28 (0.1728), 2014-01-29 (0.1724).

**Table 21 Overall resilience values of the generic interruption causes for Telecommunication Broadband.**  
**A: The total functionality of the system at a national system level. The generic interruption causes: H: human, T: technical, and U: unknown/missing data.**

Cause	Duration (h)			F <sub>L</sub>			Resilience Loss			Resilience
	Mean	Var	Max	Mean	Var	Max	Mean	Var	Max	
				(10 <sup>-3</sup> )	(10 <sup>-6</sup> )	(10 <sup>-3</sup> )	(10 <sup>-6</sup> )	(10 <sup>-6</sup> )		Mean
<b>A</b>	25.8	1710	187	4.40	479	173	168	15.7	0.173	0.99983
<b>H</b>	9.19	103	32.0	0.660	3.35	9.46	2.66	0.0094	0.00946	1.00000
<b>N</b>	95.7	2480	187	0.452	0.525	2.27	27.9	0.0455	0.00227	0.99997
<b>T</b>	15.3	934	172	3.91	206	81.5	72.9	4.89	0.0815	0.99993
<b>E</b>	11.2	154	39.8	12.6	2040	173	63.5	10.8	0.173	0.99994
<b>U</b>	15.8	394	50.6	0.406	0.781	3.21	0.894	0.00116	0.00321	1.00000

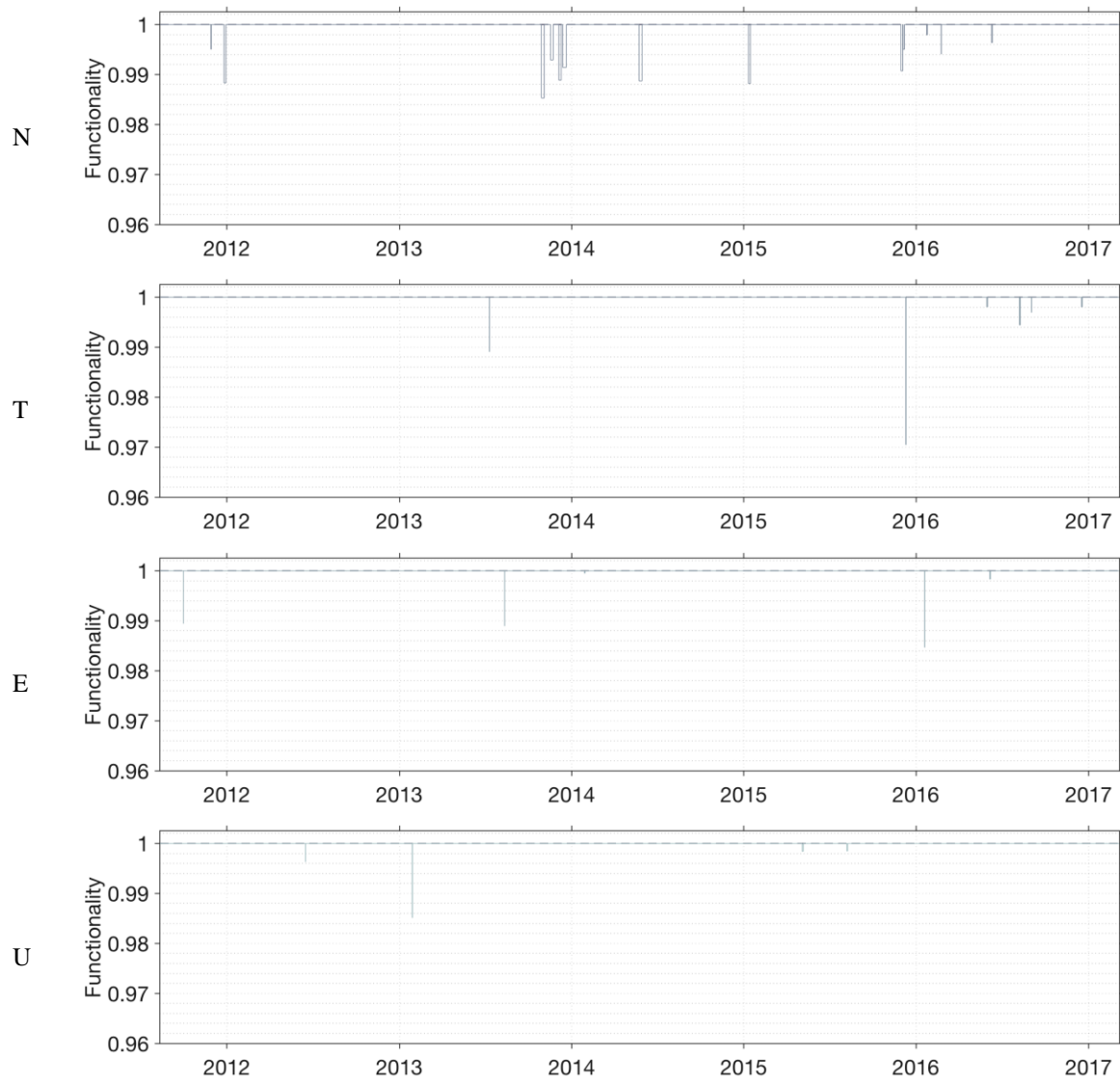
## TELECOMMUNICATION FIXED TELEPHONY

In Figure 58 demonstrates the functionality of the Telecommunication Fixed Telephony at a national system level over the time period of the data and given data availability.

Table 22, as complement to Figure 58, gives an indication of which interruption causes that contribute most to the total losses of the functionality level of the infrastructure. It is technical, followed by natural interruption causes that contribute most to the functionality loss in the system.



*Cont.*



**Figure 58 Telecommunication Fixed Telephony.** Where the top figure (A) represent all interruptions during the time period August 2011- March 2017. The interruptions are then split in accordance of causes, where figure (H) represents human causes, (N) natural, (T) technical, and (U) unknown/missing. The horizontal line at functionality 1 refers to fully functional system. Functionality loss exceeding 0,96 does not show on figure. The vertical axes are given a unified value of (0,96) for better resolution.

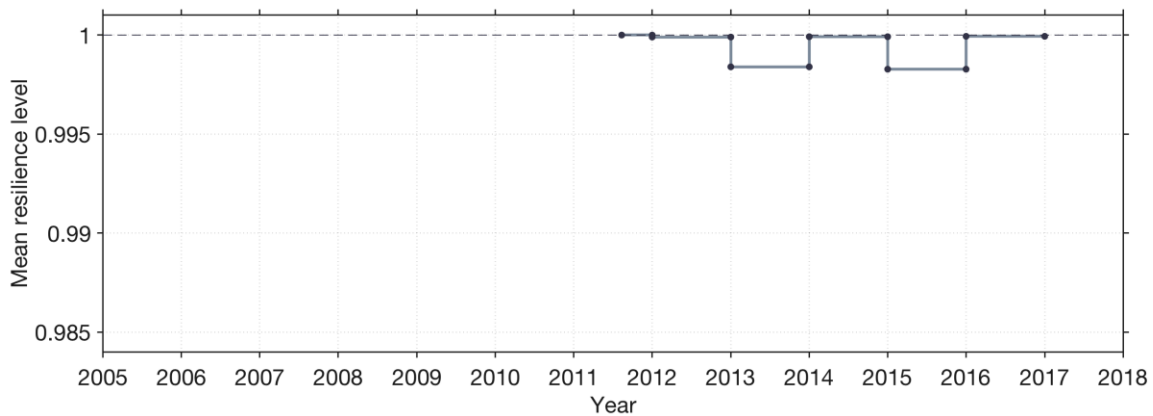
**Table 22 Overall resilience values of the generic interruption causes for Telecommunication Fixed Telephony. A: The total functionality of the system at a national system level. The generic interruption causes: H: human, T: technical, and U: unknown/missing data.**

Cause	Duration (h)			F <sub>L</sub>			Resilience Loss			Resilience
	Mean	Var	Max	Mean	Var	Max	Mean	Var	Max	
				(10 <sup>-3</sup> )	(10 <sup>-6</sup> )	(10 <sup>-3</sup> )	(10 <sup>-6</sup> )	(10 <sup>-6</sup> )		Mean
<b>A</b>	47.3	2440	187	3.25	29.2	29.5	281	3.01	0.0295	0.99972
<b>H</b>	13.1	74.3	32.0	1.53	10.2	12.9	6.93	0.0424	0.0129	0.99999
<b>N</b>	93.3	2900	187	3.35	22.5	14.7	238	2.48	0.0147	0.99976
<b>T</b>	26.4	234	45.5	3.31	57.5	29.5	21.3	0.358	0.0295	0.99998
<b>E</b>	17.5	234	39.8	2.61	26.4	15.3	7.24	0.0771	0.0153	0.99999
<b>U</b>	26.3	390	50.6	1.81	18.2	14.9	7.87	0.076	0.0149	0.99999

## 6.6.2 THE ANNUAL RESILIENCE LEVELS OF TELECOMMUNICATION

### TELECOMMUNICATION MOBILE

Figure 59 displays the calculated yearly mean resilience level for Telecommunication Mobile sub-infrastructure of each given year of the time period of the data and given availability. In Table 23 detailed accounts of the annual mean resilience level, mean duration of the given year, along with mean functionality loss per year and man resilience loss is given. Figure 59 demonstrates a system functionality that varies between years.



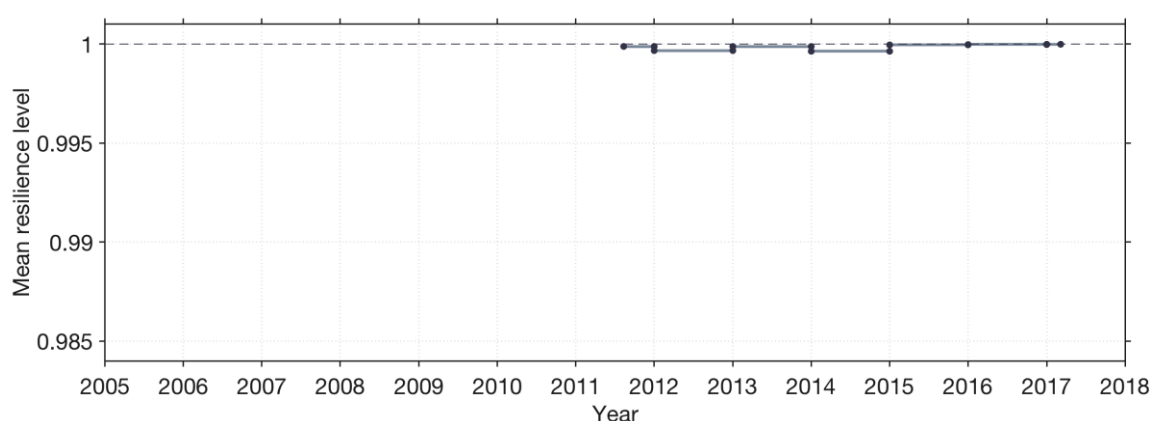
**Figure 59 Annual resilience level of Telecommunication Mobile**

**Table 23 Resilience values for Telecommunication Mobile per year (†from 2011-08-12, \* to 2017-03-07). The Telecommunication data spans from 2011 – 2017, that said there are no interruptions that occur for the Telecommunication Mobile sub-infrastructure during 2011 and 2017 (marked with ‘-’ in table).**

Year	Duration (h)			FL			Resilience Loss			Resilience
	Mean	Var	Max	Mean	Var	Max	Mean	Var	Max	
				(10 <sup>-3</sup> )	(10 <sup>-6</sup> )	(10 <sup>-3</sup> )	(10 <sup>-6</sup> )	(10 <sup>-6</sup> )		Mean
<b>2011</b> <sup>†</sup>	-	-	-	-	-	-	-	-	-	-
<b>2012</b>	9.54	20.3	14.8	8.26	396	85.5	100	3.34	0.0855	0.99990
<b>2013</b>	60.3	3180	187	13.3	259	63.4	1600	53.7	0.0634	0.99840
<b>2014</b>	7.96	21.1	16.1	12.3	362	61.5	83.1	3.46	0.0615	0.99992
<b>2015</b>	51.8	2130	106	24.3	809	80.5	1720	106	0.0805	0.99828
<b>2016</b>	38.4	144	51.3	1.8	7.99	7.63	62.6	0.381	0.00763	0.99994
<b>2017</b> <sup>*</sup>	-	-	-	-	-	-	-	-	-	-
<b>All years</b>	39,3	2140	187	14	442	85,5	0,999	642	30,5	0,08550

## TELECOMMUNICATION BROADBAND SERVICES

Figure 60 displays the calculated yearly mean resilience level for Telecommunication Mobile sub-infrastructure of each given year of the time period of the data and given availability. In Table 24 detailed accounts of the annual mean resilience level, mean duration of the given year, along with mean Functionality Loss per year and man resilience loss is given. Figure 60 demonstrates a highly resilient tCI, where the system functionality varies a bit from 2012 to 2014. And 2015 to 2016 there is a more stable resilience level, though with minor variations.



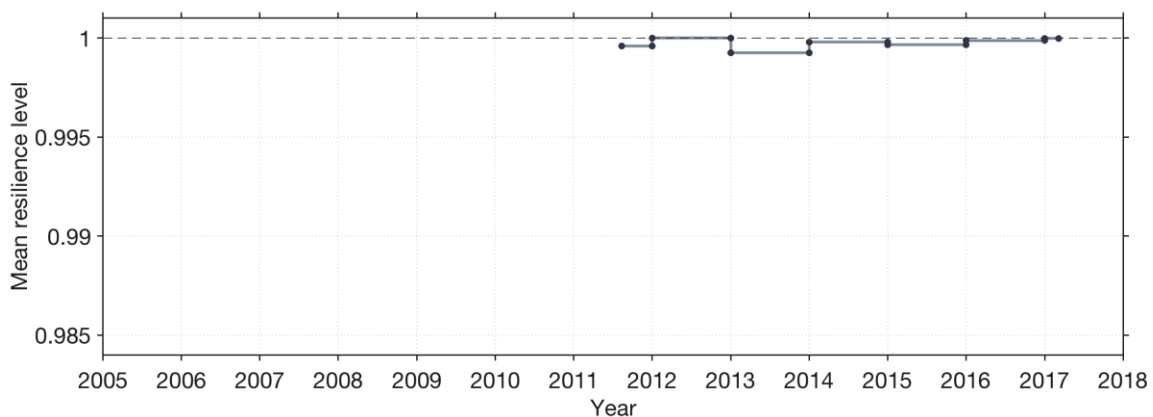
**Figure 60 Annual resilience level of Telecommunication Broadband Services**

**Table 24 Resilience values for Telecommunication Broadband Services per year (†from 2011-08-12, \* to 2017-03-07)**

Year	Duration (h)			F <sub>L</sub>			Resilience Loss			Resilience
	Mean	Var	Max	Mean (10 <sup>-3</sup> )	Var (10 <sup>-6</sup> )	Max (10 <sup>-3</sup> )	Mean (10 <sup>-6</sup> )	Var (10 <sup>-6</sup> )	Max	Mean
<b>2011</b> <sup>†</sup>	27.5	1260	96.0	3.00	90.2	35.9	120	2.00	0.0359	0.99988
<b>2012</b>	18.8	14.6	21.8	23.7	1560	81.5	329	26.1	0.0815	0.99967
<b>2013</b>	53.5	4530	187	0.737	1.50	4.58	125	0.242	0.00458	0.99988
<b>2014</b>	19.9	1810	172	11.6	1850	173	365	60.0	0.173	0.99964
<b>2015</b>	21.9	1110	95.5	1.27	5.26	9.46	42.0	0.0971	0.00946	0.99996
<b>2016</b>	16.0	269	51.3	0.919	9.40	17.4	24.7	0.174	0.0174	0.99998
<b>2017</b> <sup>*</sup>	6.67	59.6	12.1	0.792	0.899	1.89	11.4	0.0153	0.00189	0.99999
<b>All years</b>	25.8	1710	187	4.40	479	173	168	15.7	0.173	0.99983

## TELECOMMUNICATION FIXED TELEPHONY

Figure 61 displays the calculated yearly mean resilience level for Telecommunication Fixed Telephony sub-infrastructure of each given year of the time period of the data and given availability. In Table 25 detailed accounts of the annual mean resilience level, mean duration of the given year, along with mean functionality loss per year and man resilience loss is given. Figure 61 demonstrates that the system functionality varies slightly between the years, where 2013 is more affected by interruptions. Overall, the Telecommunication Fixed Telephony displays a constant and high level of resilience.



**Figure 61 Annual resilience level of Telecommunication Fixed Telephony**

**Table 25 Resilience values for Telecommunication Fixed Telephony per year (†from 2011-08-12 \* to 2017-03-07)**

Year	Duration (h)			F <sub>L</sub>			Resilience Loss			Resilience	
	Mean	Var	Max	Mean (10 <sup>-3</sup> )	Var (10 <sup>-6</sup> )	Max (10 <sup>-3</sup> )	Mean (10 <sup>-6</sup> )	Var (10 <sup>-6</sup> )	Max	Mean	
<b>2011</b> <sup>†</sup>	38.6	1610	96	3.04	21.2	11.7	402	4.05	0.0117	0.99960	
<b>2012</b>	6.00	0	6.00	1.24	4.60	3.71	2.54	0.00942	0.00371	1.00000	
<b>2013</b>	65.3	5250	187	3.95	30.4	14.9	745	7.72	0.0149	0.99926	
<b>2014</b>	60.9	5900	149	3.53	34.7	12.9	204	2.26	0.0129	0.99980	
<b>2015</b>	60.1	1040	95.5	4.51	71.8	29.5	338	4.19	0.0295	0.99966	
<b>2016</b>	28.7	266	51.3	2.23	13.3	15.3	117	0.643	0.0153	0.99988	
<b>2017</b> <sup>*</sup>	12.1	0	12.1	1.32	3.46	2.63	20.5	0.0535	0.00263	0.99998	
<b>All years</b>	47.3	2440	187	3.25	29.2	29.5	281	3.01	0.0295	0.99972	



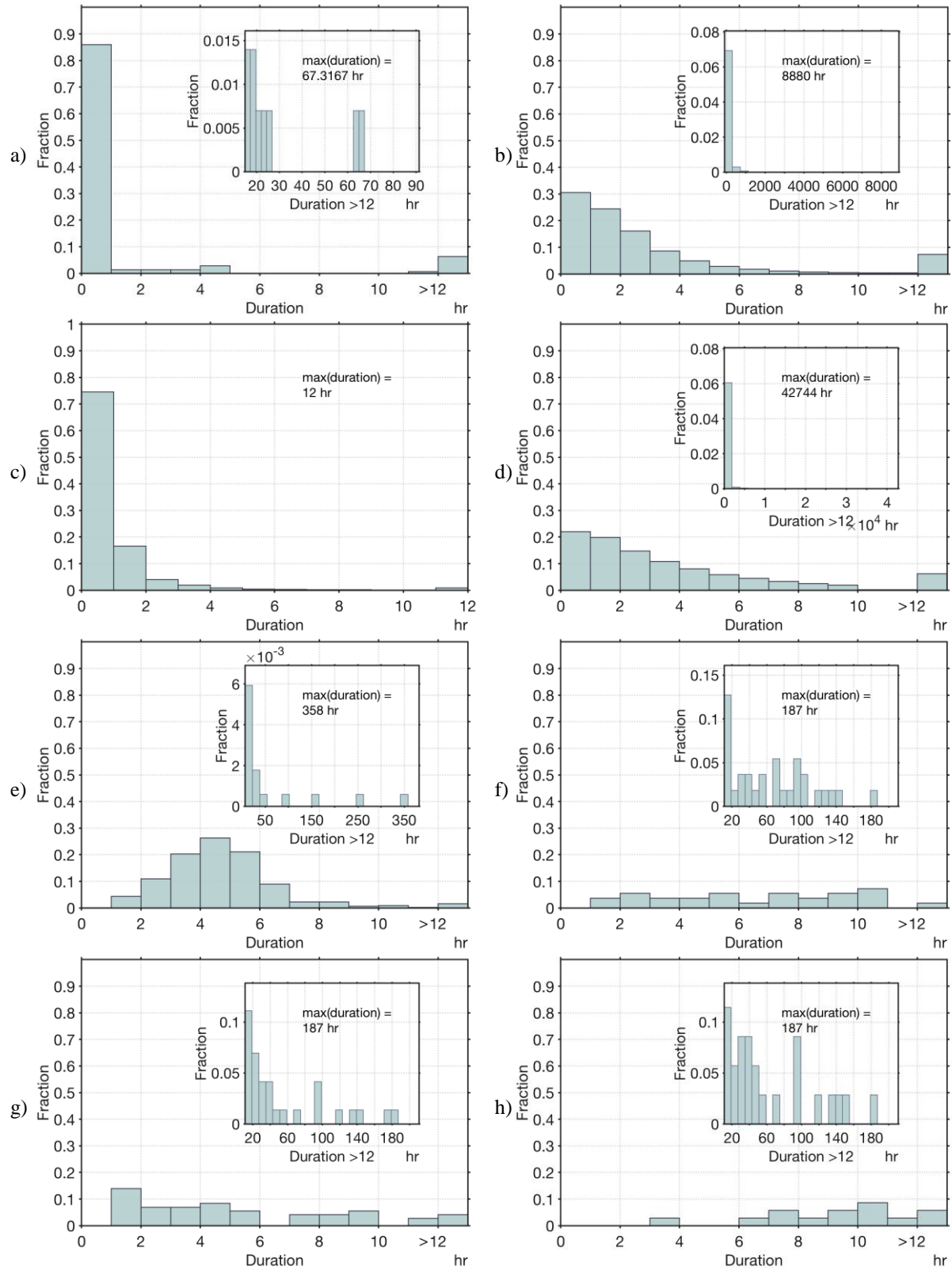


# 7 RESILIENCE COMPARISON OF CRITICAL INFRASTRUCTURES

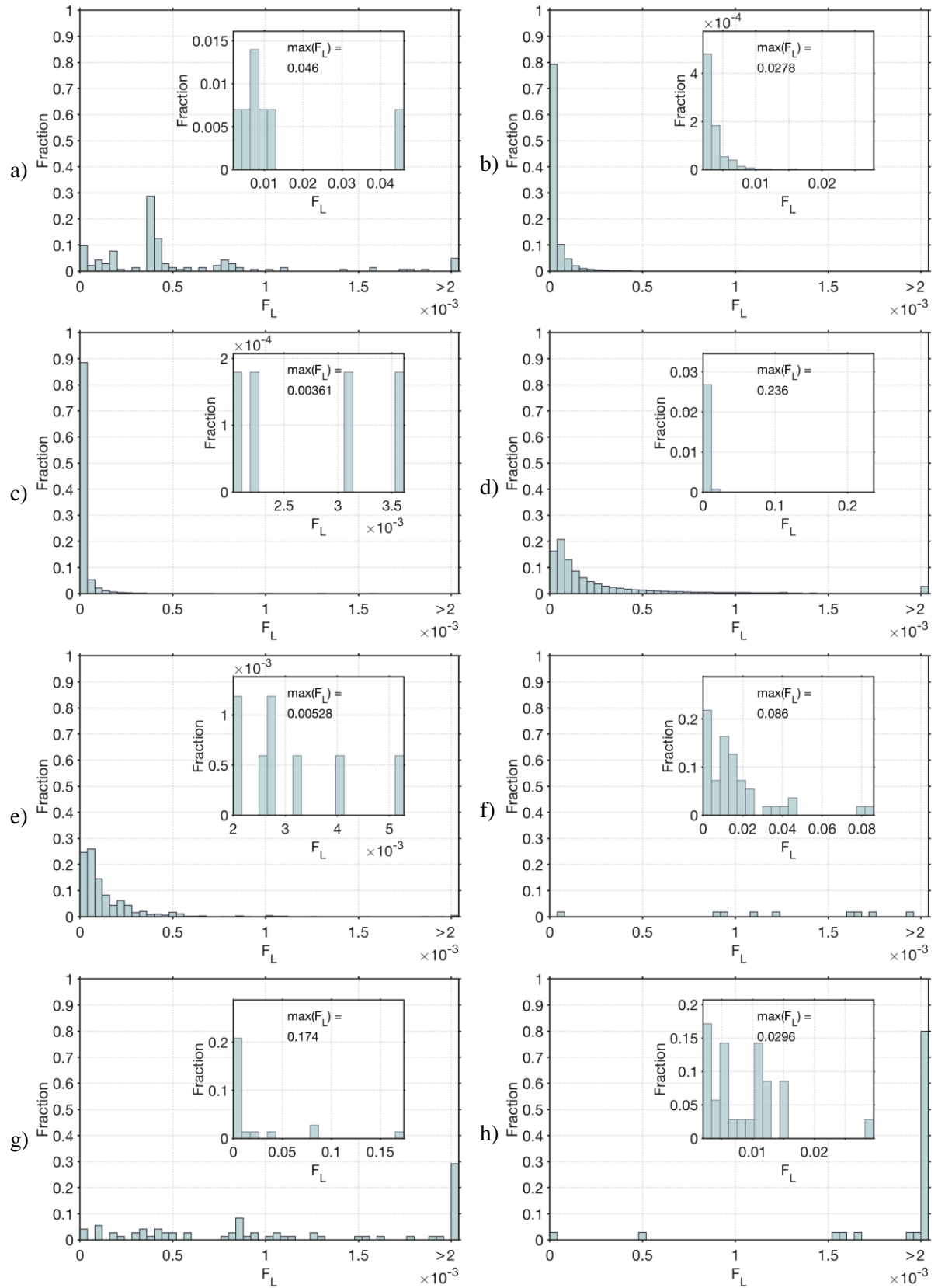
In this chapter a comparison of the studied CIs is presented. The first comparison (section 7.1) involves comparing the duration of the single interruptions that meet the criteria of the RAA in terms of duration and consequences (functionality loss). The second comparison (section 7.2) involves comparing the resilience level of the studied infrastructure from an annual perspective. The last comparison (section 7.3) entails comparing the national system level resilience curves. This chapter concludes by putting forth suggestion of practical usage of the RAA, specifically so in terms of RMP and spatial planning (see section 7.4).

## 7.1 COMPARISON OF DURATIONS AND CONSEQUENCES

In Figure 62 the histograms that are presented displays how the durations of the interruptions for each of the CIs are distributed, respectively in Figure 63 histograms are presented in terms of Functionality Losses. All data that meets the fundamental requirements of the RAA (in accordance see section 3.3 and Chapter 4 - 5) is included. The great variations of the durations and Functionality Losses makes it difficult to compare the results in single histograms, so each data set is equally presented with primary histogram. The interruptions that exceed the duration of 12 hours and Functionality Loss of 0.002 are all summarised in the last bin of the unified histogram. They are then accounted for in a secondary histogram as an insert-figure to document how the larger values are distributed. Note that the histograms presented here are based on the single interruptions, and not the aggregated data used for the resilience plots and calculations.



**Figure 62** Histograms of duration for: a) Electricity Transmission, b) Electricity Distribution, c) Transport Road, d) Transport Railway, e) Water Supply, f) Telecommunication Mobile, g) Telecommunication Broadband Services, and h) Telecommunication Fixed Telephony. For clarification, interruptions exceeding 12-hour duration have binned sparsely within its respective figure.



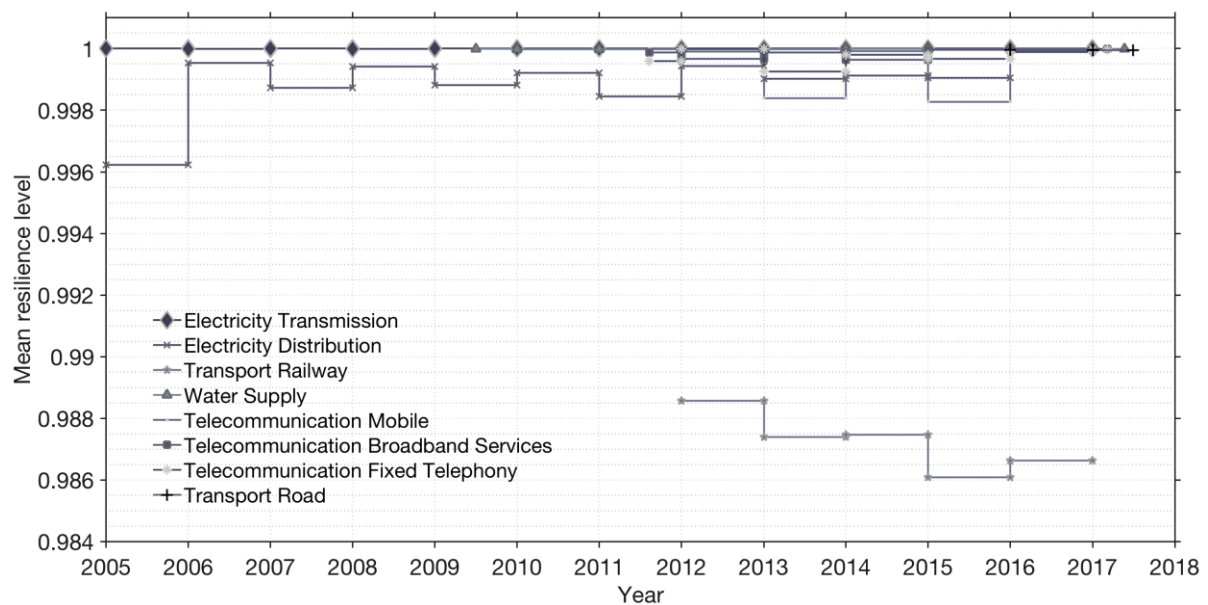
**Figure 63** Histograms of Functionality Loss,  $F_L$ , for: a) Electricity Transmission, b) Electricity Distribution, c) Transport Road, d) Transport Railway, e) Water Supply, f) Telecommunication Mobile, g) Telecommunication Broadband Services, and h) Telecommunication Fixed Telephony. For clarification, interruptions exceeding Functionality Loss of 0,002 have binned sparsely within its respective figure.

Comparing the durations (see Figure 62), the Electricity Transmission, Electricity Distribution, Transport Road and Transport Railway typically have an interruption last from 0-1 hours, while interruptions in Water Supply usually last from 4-5 hours and 12-20 hours within the three Telecommunication sub-infrastructures (Mobile, Broadband Services, and Fixed Telephony). The probable reason for the typical interruption duration in the Telecommunication infrastructure is that the regulatory authority, from whom the underlying data was collected, have a threshold reporting criterion of equal or longer then 1h for interruptions (see section 4.6). Hence interruptions including the shorter everyday events are not included in the data.

Comparing the Functionality Loss in Figure 63 gives that generally the Functionality Loss is very small for the different infrastructures, ranging maximum from 0.4% to 3%. However, some infrastructures have experienced interruptions of greater magnitude: Telecommunication Mobile of up to 9%, Telecommunication Broadband Services of up to 17%, and Transport Railway of up to 24%.

## 7.2 COMPARISON OF RESILIENCE LEVEL

The resilience level of different types of CIs are presented in Figure 64 and complemented with Table 26. The yearly mean resilience level has been calculated depending the accessibility of data. It is evident that the resilience levels vary quite a lot when comparing the different infrastructures. The results show that the Electricity Transmission is the best performing infrastructure and Transport Railway is the worst performing infrastructure.



**Figure 64 Annual resilience level of studied infrastructures**

In Table 26 the overall mean and variance of resilience level for the different types of CI is presented, along with mean and variance of duration, functionality loss, resilience loss (respectively). The results show that the Electricity Transmission scores the best, followed quite closely by Water Supply and Transport Road. Not only do these three infrastructures have in common that they demonstrate quite high overall mean resilience level, but they also have in common that the resilience level is quite stable over the years with only minor differences over the years. After follows the Telecommunication sub-infrastructure, out of which the Telecommunication Broadband Services best, followed by Telecommunication Fixed Telephony and then Telecommunication Mobile. The Telecommunication Broadband Services infrastructure fluctuates slightly between 20012 and 2014, but somewhat steady resilience level from 2015 and onward. The Telecommunication Fixed Telephony infrastructure has slightly more fluctuation over the years, but their resilience level seems to have improved over the years. The Telecommunication Mobile infrastructure demonstrates slightly different behaviour as the variation between years are quite big compared to the others sub-Telecommunication infrastructures. The Electricity distribution infrastructure scores to have the second worst resilience level overall. The resilience level varies quite a lot until 2013, from 2013 and onward the resilience level between the are demonstrating more steady resilience level. As mention previously, the lowest scoring infrastructure is Transport Railway, this is the only infrastructure that demonstrates degrading resilience levels over the longer period of time (from 2012 to 2015), from where the mean resilience level has increased slightly.

**Table 26 Resilience values for: Electricity Transmission (ETr), Electricity Distribution (EDi), Trasport Road (TRo), Transport Railway (TRa), Water Supply (Wat), Telecommunication Mobile (TeM), Telecommunication Broadband Service (TeB), and Telecommunication Fixed Telephony (TeF).**

Inf.	Duration (h)			FL			Resilience Loss			Resilience
	Mean	Var	Max	Mean	Var	Max	Mean	Var	Max	Mean
				(10 <sup>-3</sup> )	(10 <sup>-6</sup> )	(10 <sup>-3</sup> )	(10 <sup>-6</sup> )	(10 <sup>-6</sup> )		
<b>ETr</b>	2.23	76.5	67.3	0.512	8.05	44.5	0.216	0.000963	0.0445	1.00000
<b>EDi</b>	8.25	4210	8770	3.97	160	160	1180	20.2	0.160	0.99882
<b>TRo</b>	0.973	2.10	12.0	0.101	0.134	5.89	39.7	0.0387	0.00589	0.99996
<b>TRa</b>	18.0	73500	42700	15.3	48.7	252	12800	43.6	0.252	0.98723
<b>Wat</b>	4.76	130	350	0.165	0.155	7.55	17.8	0.0156	0.00755	0.99998
<b>TeM</b>	39.3	2140	187	14.0	442	85.5	642	30.5	0.0855	0.99936
<b>TeB</b>	25.8	1710	187	4.40	479	173	168	15.7	0.173	0.99983
<b>TeF</b>	47.3	2440	187	3.25	29.2	29.5	281	3.01	0.0295	0.99972

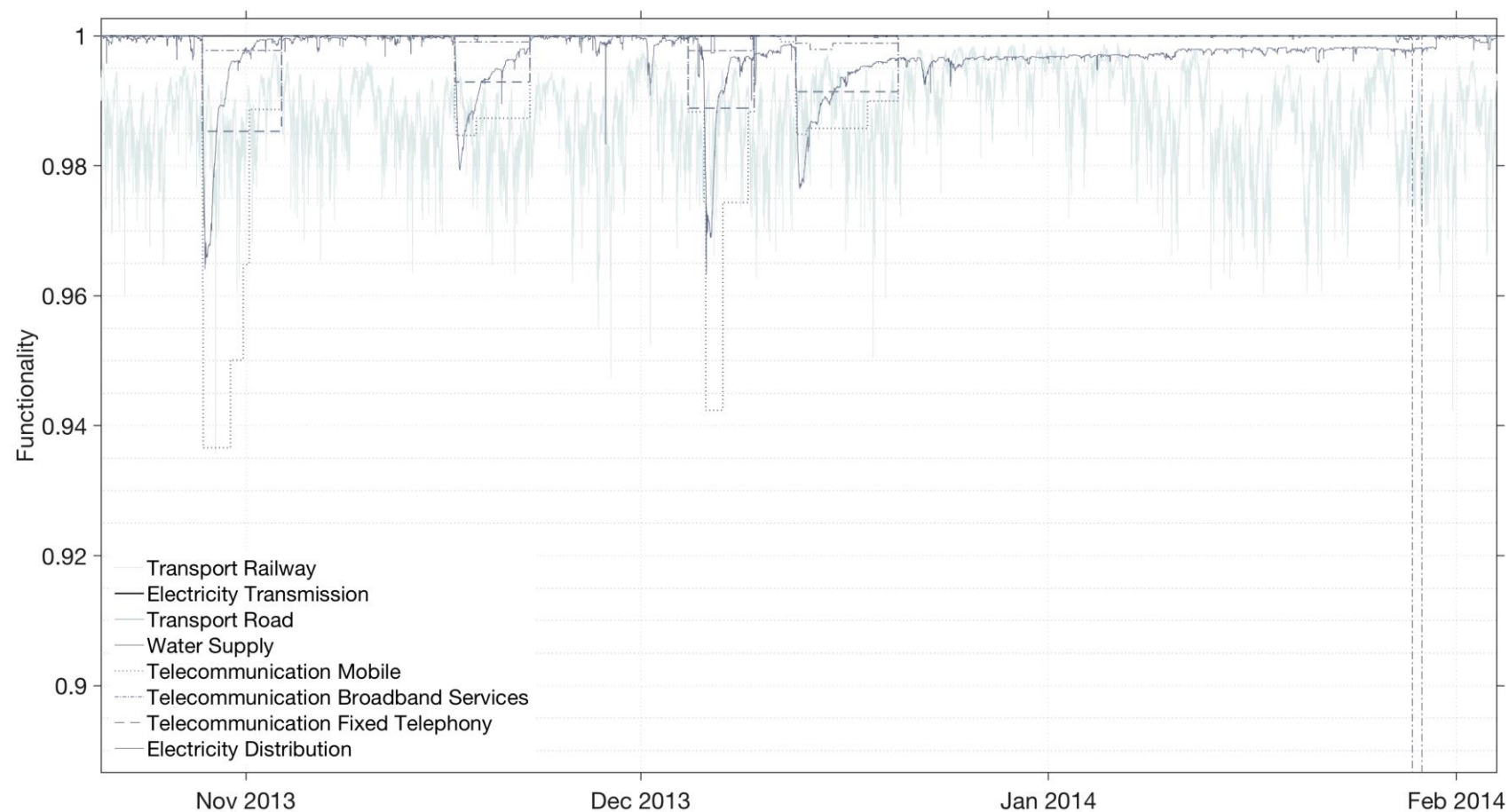
Table 27 shows the ranking from the best to worst performing infrastructure, furthermore a comparison is made where the overall mean resilience losses of the different infrastructures are compared to the best performing infrastructure (Electricity Transmission). These results demonstrate that the worst performing infrastructure (Transport Railway) which has 59 101 times higher resilience loss than Electricity Transmission infrastructure.

**Table 27 Ranking of CI based on and compared to the best performing infrastructure (ETr). Comparison based on mean Resilience Loss.**

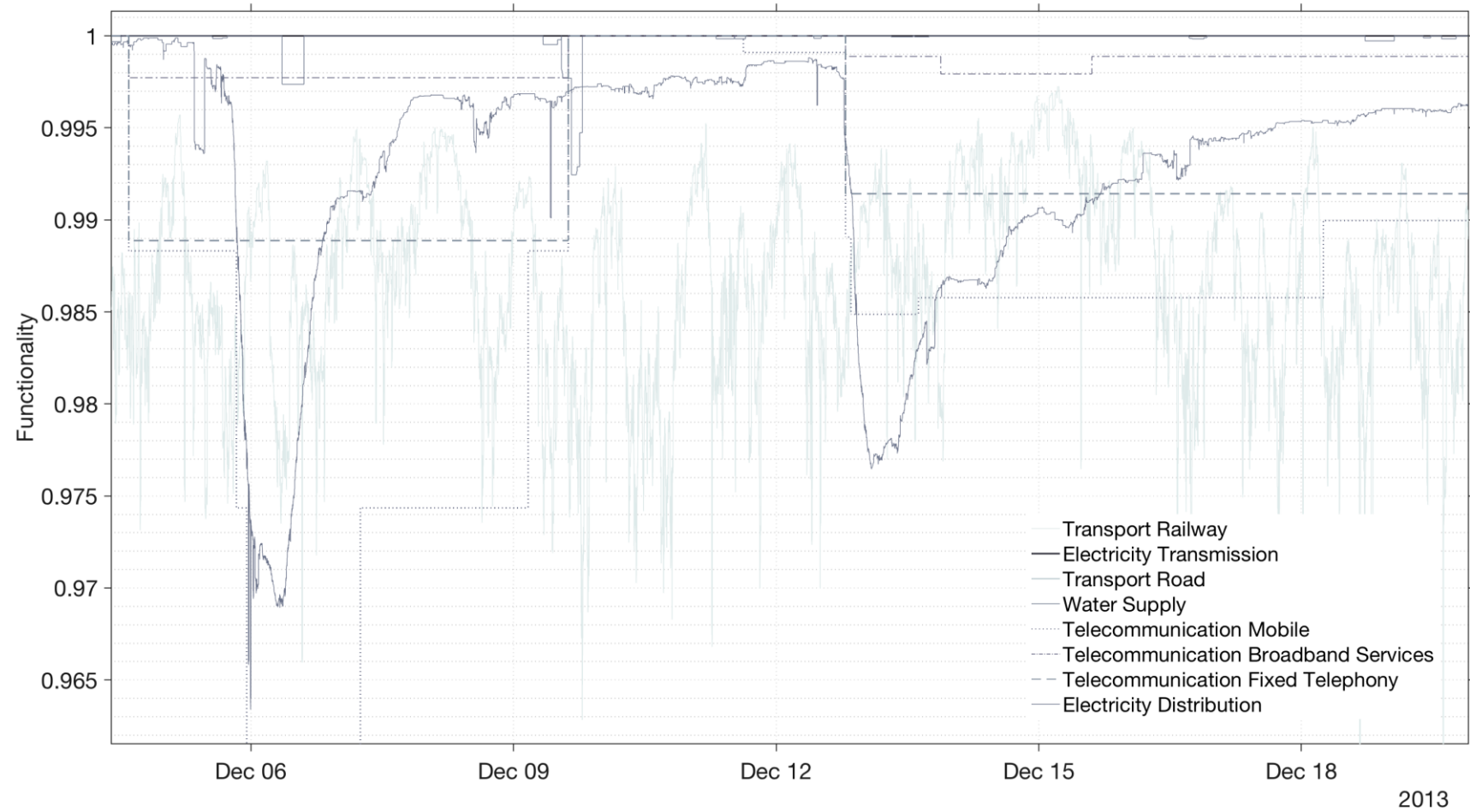
Infrastructure	Ranking	Mean Resilience Loss ( $10^{-6}$ )	Comparison of mean Resilience Loss to ETr
Electricity Transmission (ETr)	1	0.216	–
Water Supply (Wat)	2	17.8	82
Transport Road (TRo)	3	39.7	184
Telecommunication Broadband (TeB)	4	168	776
Telecommunication Fixed Telephony (TeF)	5	281	1302
Telecommunication Mobile (TeM)	6	642	2969
Electricity Distribution (EDi)	7	1180	5459
Transport Railway (TRa)	8	12800	59101

## 7.3 NATIONAL SYSTEM LEVEL WITH SEVERAL TYPES OF CRITICAL INFRASTRUCTURES

By plotting the national system level resilience curves on top of each other, as displayed in Figure 65 and Figure 66 (where Figure 66 is a close-up of the section around November and December 2013 in Figure 65) it is possible to analyse if there seems to be any correlation between the interruptions in different infrastructures. If correlations exist, it could be an indication of interdependencies between the infrastructures, where interruptions in one infrastructure leads to interruptions in another. A typical example is the Telecommunication Mobile infrastructure which is highly dependent on electricity supply, such as when the Electricity Distribution infrastructure experiences functionality losses in its system, it sometimes results in functionality losses also for the Telecommunication Mobile infrastructure. It is possible to see this kind of behaviour in Figure 66, the event between Oct 26<sup>th</sup> and Nov 9<sup>th</sup>. An event, in this case a storm, creates a dip in functionality for the Electricity Distribution infrastructure, and the Telecommunication Mobile system is heavily impacted as well, and it is also noticeable that the other two Telecommunication sub-infrastructure are affected to some degree.

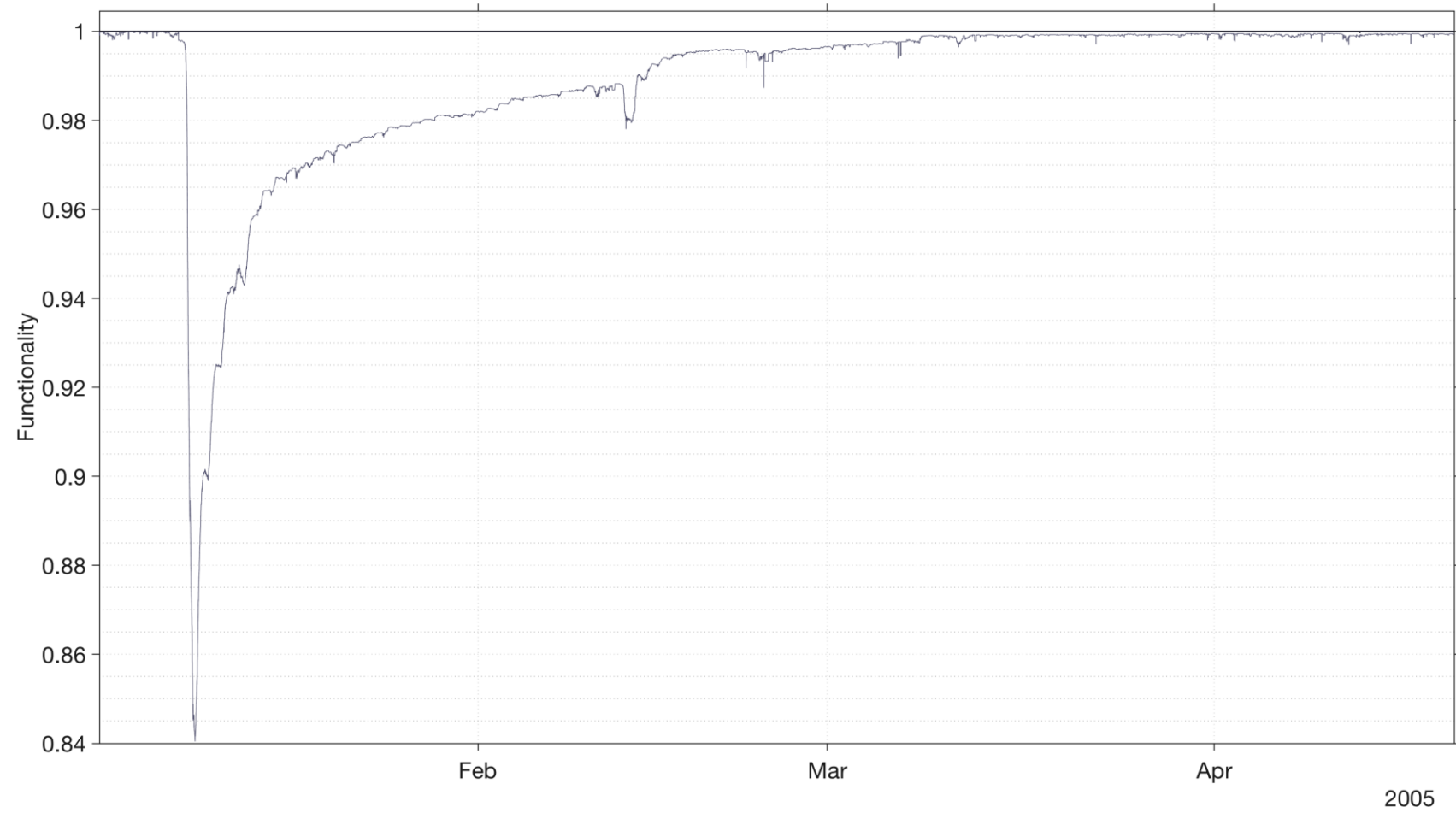


**Figure 65 National system level resilience curve for several types of CIs. Overview during the storms Simone (2013-10-28), Hilde (2013-11-16), Sven (2013-12-05) and Ivar (2013-12-12) in Sweden.**



**Figure 66 National system level resilience curve for several types of CIs. Overview during the storms Sven (2013-12-05) and Ivar (2013-12-12) in Sweden.**





**Figure 67 National system level resilience curve for Electricity Transmission and Electricity Distribution, during the storm Gudrun in Sweden (2005-01-08).**

## 7.4 APPLYING THE RAA, PRACTICAL USAGES

In this section, our proposals of practical usages of the RAA will be discussed in relation to the RMP and spatial planning. This discussion is largely based on our beliefs, opinions and knowledge, consequently also biased accordingly. Furthermore, we do not want to limit the discussion to cover only the data and the results as they have been presented in the thesis, but to also keep an open discussion of the possible further potential usages of the RAA and how its usages can possibly be developed. One of the main ideas of dividing the interruptions into generic failure causes was to display how easy it is to adapt the data to certain needs, to categorise the interruptions and how that can be used to draw more in-depth conclusions of the data. Some of the discussed ideas in this section would require changes in current data gathering processes and hence only be possible if some proposed parameters are successfully gathered, which are presented and clarified in section 7.4.2.

### 7.4.1 SOCIETAL SAFETY

Using the RAA to measure, contrast and compare resilience of different tCIs is something that could possibly fit in processes related to increasing societal safety, e.g. in contingency plans or national risk and capability assessments. As the RAA enables objective comparisons, the differences between the tCIs can then be critically discussed and for example open up for critical infrastructure owners to learn from each other of ways to achieve resilience. Such discussions could be on the basis of the actual differences in the measured resilience, connecting the results with known factors e.g. risk cultures, level of funding or legislative regulations. Or they can be on the basis of how and why the achievements of similar incentives or decisions differ. Strategic decisions about where to put efforts and investments can also be backed up with results of the RAA. Such results could be used both as an informative basis, before taking a decision that is expected to increase resilience; then the RAA also can be used to evaluate such decisions. Those analyses might improve the efficiency and accuracy of future decisions, by learning from both success and mistakes.

### SYSTEM FUNCTIONALITY

By breaking down the factors that correlates with an increased level of resilience in the RAA, we find that less severe and shorter interruptions in the measured system correlates with increased resilience. Hence, we argue that the RAA, by enabling analyses and quantification of resilience for different types of tCIs, can be used to increase functionality in the studied tCIs. The RAA regards each studied tCI as a system, with the purpose of continuously delivering a service. It uses interruptions in this delivered service as indicator of functionality to measure and analyse resilience. This means that resilience is adopted as a function of interruptions' magnitude and duration, i.e. an increased level of resilience in the RAA correlates with overall

less impacts for the end users. This is why we believe that any successful initiative made by regulatory bodies or decision makers to increase the resilience according to the RAA, should decrease the interruptions' overall magnitudes and durations, therefore also have a positive effect on the overall functionality in the measured tCIs.

#### 7.4.2 SUCCESSFUL DATA GATHERING, SUGGESTIONS

When analysing large-scale data on a national level from very different sources, it has come to our attention that the raw data we received in all cases came with some kind of failure cause description or categorisation. These descriptions varied between each data-set, to only include a few failure causes in some cases, while in others including many dozens of failure causes. In some of the data sets the failure causes were also given with sub-categorisation of the failure causes. When evaluating these, a couple of things came to our attention. Firstly, we realised how easily the data can be separated by different categorisations, adding to some potential uses. Secondly, analyses of the data indicate that the interruptions can spread through and between the tCI's. This is something we believe is crucial to study further in order to better understand the vulnerabilities in the system, and why we believe there should be better descriptions/categorisations of the difference between an interruption's internal *cause* and its external *source*. The cause for a telecommunication interruption could be an offline/down server, while the interruption source might be a power outage. The responsible power supply actor might say their outage was due to excavation, making a construction site the actual root cause. However, when the interruption source is internal, it does not make much sense to separate it from its cause.

We suggest that the following additional parameters should be gathered.

1. Interruption source – enabling evaluations of single large-scale widespread events, affecting many infrastructures simultaneously or the spreading of effects between infrastructures.
2. Interruption locality – the source's position or area, to enable spatial analysis (e.g. GIS-data or coordinates)

We believe that if such data would be successfully gathered, algorithms could be developed to find connections between the interruptions with separate sources in order to see how an interruption spreads within or between tCIs and over geographical areas.

#### 7.4.3 THE RISK MANAGEMENT PROCESS

Results derived from an executed RAA is argued to have potential of being useful in assisting the work carried out in various risk management processes and could fit in several steps of the RMP. Figures 1 – 3 (see Chapter 2) displays some exemplifying models and flowcharts of the

RMP. With those in mind, the following sections address some ideas of where in the RMP the results from applying the RAA can be a useful input. Obviously, all of the suggestions can be made similarly in the different tCIs, to enable comparisons and evaluations according to given discussion in section 7.4.1.

The following discussion presupposes a successfully performed RAA, based on accurate data that fits the scope and delimitations of the supposed RMP. Meaning that any performed RAA does not necessarily enable all of the suggested applications below, but each of the suggested example is argued to be achievable with the RAA when based on data that produces adequate results.

## **RISK IDENTIFICATION**

This is an essential part of any risk analysis. It is likely that unidentified risks can potentially poses a great threat. The RAA could be used to analyse interruptions in a given tCIs, for example their failure causes, system spread (by suggested parameter 1 in section 7.4.2) or unanticipated functionality drops. Such information could be used to identify previously unknown risks and hazards (see section 8.3 below for further discussions on interruption causes). This knowledge can be used to learn more about the differences or similarities of the tCIs, why and how the risks look different.

## **RISK ANALYSIS AND ESTIMATIONS**

To begin with, the RAA displays a quantitative method for assessing system resilience of different tCIs, a process that can be used to quantify and assess risks in a unified manner; a key procedure in any risk management processes. With quite small means one can quantify risks in terms of the classic risk definition of probabilities and consequences; by setting a threshold value of a given consequence level (Functionality Loss), the probability for a tCI to be affected by an interruption of that given magnitude can be derived. This makes it possible to adapt the approach to more traditional risk quantifications and comparisons with methods that already are in place.

## **VULNERABILITIES**

As with risk identification, we see possibilities with analysing the data for unanticipated functionality drops from given interruptions or failure causes. What type of interruption causes generates highest resilience loss within a given tCI? If the interruption causes are categorised in a desired way, the approach could be used to identify vulnerabilities amongst those interruption causes.

In the UNDP supported research by Pelling et al. (2004), the need of gathering better data on a local-scale resolution is addressed. They mention this in a perspective of mapping interdependencies between different hazards, to enable deeper analysis of vulnerabilities. Doing so by

arguing that it is of importance to find and develop methods for measuring vulnerabilities, that ultimately can be used to assess and mitigate risks. Even if our thesis is written from a Swedish perspective, a country that faces totally different challenges than the nations addressed by UNDP's programme, the methodology of the presented RAA can similarly be applied to infrastructures in societies with different vulnerabilities. When the resilience curves for different infrastructures are plotted on top each other as in Figure 65 and Figure 66, interdependencies between the infrastructures can be identified, opening for ways of both analysing and quantifying infrastructure interdependencies. In this particular case, by looking in the cause section (when available and the information was unmasked) of the incident reports that were used as the basis for the Telecommunication data, we could read that many of those interruptions were actually due to power outages and hence determine some degree of proof for the theory; that the Telecommunication infrastructures are dependent on Electricity Distribution. However, given more complex data where the interdependencies are not so clear-cut or easy to identify, we believe that data through analysis, e.g. through algorithms, might be able to reveal previously unknown system vulnerabilities, as results of interdependencies.

If the interruption data would be categorised by the interruption locality in a desired way, the RAA could be used to identify vulnerabilities amongst these interruption localities. This could perhaps be used to reveal which roads, tracks or specific areas that are most prone to be affected by certain interruptions. Such data could possibly be adapted to a GIS-layer as a tool for assessing and highlight vulnerable areas and perhaps even to illuminate multi-hazard correlations and interdependencies, how interruptions in one tCI correlates with interruptions in one or several other tCIs. As with all types of failures, the RAA displays possibilities to evaluate how any measured parameter behave over time, e.g. trends of improvements or if there are certain times of the year when a system is more vulnerable, as if the consequences tend to be worse.

More discussions about vulnerabilities is found in the discussion chapter, section 8.2.1 Metrics.

## **CAPABILITY ASSESSMENT**

There are probably several ways of estimating capabilities from the given RAA, but one way that could portray capability with small adjustments, is to measure different strains that are putting loading on the system and assess how the system copes (i.e. what is the system's capability of coping with certain levels of strain). Examples of load or strain-factors that are expected to affect certain tCIs could be e.g. wind speed, temperature, rainfall, snowfall or earthquake magnitude levels.

Another way to measure system strain could perhaps be by logging disruptive events that does not lead to any interruptions in the measured system. Such zero-values, where parts of the system are failing but no interruption occurs, could be found in most data sets, but mainly in the data from Electricity Transmission. We believe such zero-values should be carefully

logged, perhaps defined by the failing part and how long it takes to restore. The load can then be derived from expected interruption times from similar failures/failing components, as part of the capability assessment.

Here we want to display the usability of data containing logged zero-values in regard to consequences, meaning interruptions that does not result in any consequences in terms of non-delivered service, but still comes with clear consequences in terms of damaged or disconnected parts of the engineering system (meaning the physical structure). Examples of such data was especially found in the Electricity Transmission data, where detailed information was given about events with failing components or system parts, where no consequences (PNS) were measured. If it is possible to log such information in a unified way, can it be used to display and quantify stress that is absorbed by the system? Can such information be used as another dimension in resilience quantification? We believe that the answer would be yes to both questions.

If the analysed interruption data is logged adequately so that single events can be withdrawn and analysed, the response system (i.e. the system involved in recovering the infrastructure from strains and stresses) can also be evaluated. Looking at Figure 67, the recovery phase in relation to the initial drop reveals some information about the response systems' capabilities (see more in section 7.4.4).

## **RISK EVALUATION AND MONITORING**

The chosen time frame for a conducted RAA can be fitted to evaluate a performed RMP or specific risk mitigation decision/s, as it allows measurements of resilience over time. Effects of mitigation decisions and different structural changes can be evaluated through comparisons of the measured system before and after a decision has come into force, by simply adapting the RAA to such time frames. Evaluations can also possibly be made by comparing other parts of the evaluated system that was not affected by the decision (by adapting the analysed data according to suggested parameter 1), or even another similar system, to evaluate if given changes had the anticipated effect.

### **7.4.4 SPATIAL PLANNING**

We want to highlight the difficulty of approaching such a comprehensive and slightly fuzzy concept as the spatial planning process in relation to the RAA. The wide scope of spatial planning makes it difficult to structure and delimit potential usages. Compared to the spatial planning process, the RMP is much more clear cut. While the RMP is addressed and well defined in scientific literature, no clear definition of spatial planning has been made to our knowledge, much less is there a well-defined idea about the 'spatial planning process'. As of this, the discussion will start by addressing the main objectives of spatial planning, as presented by the

European Spatial Development Perspective (ESDP, 1999). From these main objectives, the ideas of how the RAA could contribute with improvements to the spatial planning process will be addressed as clearly as possible.

ESDP (1999) presents the objectives of spatial planning as: achieving *social, economic and environmental* goals in the process of “Balanced and Sustainable Spatial Development” (p. 10). To enable such environmentally, socially and economically sustainable development, we believe that on a general level practically any society could benefit from analysis with the RAA with the goal to achieve more resilient tCIs. That the RAA could contribute positively on spatial planning processes without specifically addressing them. E.g. theoretically a successfully performed RAA could contribute to a more resilient Transport Railway infrastructure, which in turn could result in more users choosing railway over other modes of transportation and perhaps even lower the prices due to increased efficiency, adhering to both environmental and social goals of spatial planning. Further, increased usage of Transport Railway could for example decrease the usage of Transport Road, hence also increase the capacities of Transport Road infrastructures and in turn contribute with increased level of resilience in such (by possibly increasing absorptive capability). Similarly, increased resilience of the Electricity Transmission, Electricity Distribution and Water Supply infrastructures could possibly lead to a decrease of temporary solutions that are less environmentally sustainable, e.g. bottled water or gasoline generators, and by doing so it could also aid the environmental goals. With that initial discussion we want to display how spatial planning processes might already gain from the RAA, even without specifically addressing it.

The following discussion will be based on the ten items given by UNECE (2008), previously presented in section 2.1.4, suggesting a summary of Spatial Planning goals. Our way of addressing the ‘spatial planning process’, is basically by trying to find processes which aims to achieve those goals (and off course doing so from a spatial planning perspective) and suggest how the RAA could aid such processes. The following headings represent three of the suggested UNECE items, where each section will present short suggestions of how the RAA could be applied to the given item.

### **ENCOURAGE DEVELOPMENT GENERATED BY URBAN FUNCTIONS AND IMPROVE THE RELATIONSHIP BETWEEN THE TOWN AND COUNTRYSIDE**

We believe that a successfully applied RAA could develop urban functions, in sequence also encourage development. Suggested parameter 2, interruption locality, can be used to narrow down the spatial scope of the RAA to a given area that connects ‘the town and the country side’ in order to increase resilience of tCIs by specifically addressing that given area. By analysing the failure causes in such area, further incentives can be gained of where recourses are most wisely put to use.

## **PROMOTE MORE BALANCED ACCESSIBILITY**

By using similar methods as suggested in the last paragraph under *Vulnerabilities* in section 7.4.3 above, by categorizing the interruptions by their location, the RAA could be used to identify how resilient different tCIs are in different areas. With such methods in mind, we believe that the RAA could be used to promote more balanced accessibility, especially considering that any tCI's level of resilience according to the RAA, is derived from the actual 'access' to that specific tCI; meaning that a more accessible tCI is exactly the same as a more resilient tCI. With only the tCIs studied in this thesis in mind, accessibility then comes from access to

- Electricity (Electricity Transmission and Electricity Distribution)
- Areas via road transports (Transport Road)
- Areas via railway (Transport Railway)
- Water supplies (Water Supply)
- Mobile networks services (Telecommunication Mobile)
- Broadband services (Telecommunication Broadband Services)
- Fixed telephone services (Telecommunication Fixed Telephone)

Some ideas of a refined RAA, with the intention of promoting a more balanced accessibility, and how it can be performed are presented below.

### *IDENTIFY MORE OR LESS ACCESSIBLE INFRASTRUCTURES*

By performing the RAA we believe that one could identify more or less accessible (resilient) tCIs. Decision makers could then use information from such results as a basis, by better knowing where to put efforts in the process of promoting accessibilities that are more balanced between the tCIs.

### *IDENTIFY MORE OR LESS ACCESSIBLE AREAS*

By focusing on specific areas of accessibility, the RAA could be used to identify such areas which are more or less accessible due to resilience variations in the different tCIs. The results can be used separately by looking at one tCI at a time, to see which areas are more or less accessible in relation to that specific tCI. The results can also be used as the weighted sum of several tCIs, to map out areas that are overall more exposed to interruptions in the different tCIs. Such results could possibly be used to match with other properties in the given area, e.g. social factors, access to other non-technical infrastructures or emergency services' response times to find correlations between such properties and differences in accessibility.



### *IDENTIFY SOURCES FOR ACCESSIBILITY VARIATIONS*

We believe that information gained from the RAA could come to use as basis for decision makers in the process of deciding where financial incentives might be best put to use. By analysing e.g. failure causes, one might get some useful information about whether or not such investments should be put to strengthen the actual tCI, or if they are more wisely put to locate and/or mitigate the source of the interruptions. Further, by combining the RAA with other data such as average income or population densities in the studied areas, further analyses could be made to reveal other dimensions and reasons for resilience (accessibility) variations.

### **LIMIT THE IMPACT OF NATURAL DISASTERS**

Applying the RAA on data from large scale events and natural disasters could enable some additional information on how and why different tCIs are affected differently. E.g. the shape of the recovery phase of the storm Gudrun for the Electricity Distribution infrastructure (see Figure 67) does clearly have a shape representing the recovery behaviour that G. Cimellaro et al. (2009) defines as ‘Exponential recovery’ (also see Figure 5 in section 2.2.1). The theories, presented by G. Cimellaro et al. (2009), is one example of plenty where researchers applies theory of algebraic geometry of ‘curve-shapes’ (as in Figure 5), to quantify resilience-attributes by analysing the resilience curves’ recovery behaviour. In this way, by fitting parts of the resilience curves to certain mathematical functions, it could be possible to derive new parameters. This suggests possibilities to adapt the RAA to more disaster related, single event resilience assessments, so that new metrics can be defined, in addition to the approach as it is presented in this thesis. Theories have been found that quantifies different measurements e.g. of rapidity, robustness and responsiveness, by applying similar theories of fitting and analysing the resilience curve’s responsive behaviour, that we believe would be possible to incorporate to the RAA (Nan & Sansavini, 2017; Panteli et al., 2017; G. P. Cimellaro et al., 2010).

Supposing that such new metrics can be derived, measurements achieved by analysing single events in the RAA, to quantify different properties of disaster resilience that are given by the recovery behaviour of the different tCIs’ resilience curves. Such metrics could then be used to quantify disaster resilience, making it possible identify and compare how resilient different infrastructures are to different types of natural disasters. In the long run, combined with suggested parameters 1 and 2, it seems as this could possibly enlighten some underlying causes for differences in disaster resilience; both in relation to different types of disasters, but also in relation to other tCIs, and finally also in relation to different localities and failure causes. Given that such comparisons can be made, that such underlying causes can be identified and that the spatial dimension can be studied, we believe those comparisons can be used to limit the impact of future natural disasters as an input to the spatial planning process. In doing so, one can learn from different disasters and how they give rise to different risks depending on what preventive

measures that have been but to place, initiating more in-depth discussions on such underlying differences.

# 8 DISCUSSION

Here we discuss the results of this thesis and the limitations of the RAA in relation to the gathered data, how and why that might have influenced our attained results. We will also present some of our ideas and visions of the RAA's strengths and possibilities; how usable the approach is and how can it be applied? What could have been done if the data was better adjusted to our needs and how could such adjustments look like? The chapter is ended with discussions about possible future work, that which we believe is of importance but could not fit in the thesis.

## 8.1 DATA

### 8.1.1 DATA GATHERING PROCESS

The data gathering process became a much greater part of the work than initially anticipated. In the early phase of the work it was uncertain even if it would be possible to retrieve adequate interruption data for multiple tCI to allow for the resilience comparison, which lead to broader search of data straight from the start. This search made interruption data available to us form a broad selection of Swedish tCI, but at such an early stage the intended usage was not known in detail which in turn limited us. E.g., initially the data was referred to as 'Failure data', which limited us to solely ask for failures. While retrieving data we were occasionally asked if we also wanted data from planned interruptions as well, however we declined the offer, arguing that planned interruptions were not to be considered failures. It is probable that that we could obtain data for planned interruptions at least for Transport Road, Electricity Transmission and Electricity Distribution. That would have been a beneficial contribution, not least as some of

the interruption data turned out to include planned interruptions in the end, such as the interruption data for Transport Railway, where interruptions due to planned reconstructions were logged. And the Water Supply interruption data, where more or less every single interruption is due to intended maintenance of the water piping; planned interruptions does put a stress on the system no matter what, stress that very much relates to and affects the system's resilience.

As the mentioned example above displays how much the choice of wording matters while interpreting and working with such complex concepts; a planned outage was not considered a 'failure', but when the failures instead was addressed as an interruption, all planned outages suddenly became a natural part of the interruptions. So, the process of developing and changing the approach obviously changed the way data was interpreted, which naturally reformed the prerequisites for the data along the way. The biggest change was made when the interruptions of all tCI were aggregated to create the *resilience curves*, displaying the total system functionality. Before adopting the resilience curves, the interruptions were interpreted as single individual and independent events. As independent events, an interruption is the sum of all consequences resulting from that event or root cause, which initially made us very focused on a 'cause and effect' kind of perspective. With this in mind, we deemed it difficult to make use of data that was not logging clear consequences of the interruptions; our minimum requirements during the gathering process was that the interruption data included Start DT, End DT and a 'consequence parameter'. This point of view was used as argumentation when we dismissed some data that possibly have been of great interest, e.g. data of cancelled trains. As we were told that the cancelled trains were logged separately without possibility to register the total consequence of a given interruption, we could not see how those cancelled trains would fit our 'resilience approach' when it lacked Start DT, End DT and a 'consequence' parameter. But such data could possibly have been put to great use when creating resilience curves, as the resilience curves adopts a system's engineering perspective where all interruptions that affects a system (tCI) are added together and considered dependent of each other and to put a strain on the measured system. With this knowledge, the data of cancelled trains could probably have been adjusted to suit the model. Instead of estimating the numbers of delayed trains in the system as a measurement of functionality, the estimated number of cancelled trains in the system would probably have been more accurate.

### 8.1.2 DATA QUALITY

The gathered data varies much in terms both quality, scope and format. We consider that one possible reason behind that is possibly related to why the data is gathered and for what purpose. Some actors are obliged by law to gather interruption data like in terms of the Electricity Transmission, Electricity Distribution and Telecommunication infrastructures, while other actors

collected it for internal usages like in the Water Supply infrastructure. Transport Railway infrastructure is somewhere in between and utilises their data for regulating fees and tracking disturbances. Consequently, to mark differences in quality and usability of the interruption data is thus not unexpected.

The results of the RAA, as it is conducted in this thesis, are as valid as the underlying data used, and limited by the achieved data as it was made available for us. This does not relate to the validity of the approach per se, merely the results of the approach as it is conducted in our thesis with the interruption data that we received. Though, even if all the collected data did not come with equally high quality, and that the collected data in many cases was limited in different ways for confidentiality reasons, it is of our belief that the overall assumptions and conclusions have been made so that the end-results gives a good estimate of the resilience levels of the different infrastructures under study.

The following addresses some of the observed limiting factors of the collected interruption data and its possible implications.

#### **UNKNOWN DISRUPTIVE AND RECOVERY PHASE**

One observed uncertainty related to the limitations discussed above, inherent within the data's resolution, is the unknown behaviour of a single interruption during its progress, meaning that the behaviour during the disruptive and recovery phase is uncertain. As a result, overall, we are expecting to slightly overestimate the measured losses in the system.

#### **TELECOMMUNICATION – THRESHOLD FOR REPORTING INTERRUPTIONS**

The interruption data received for the Telecommunication infrastructure is biased in accordance to the given thresholds for reporting (see Table 7), therefore we are missing the interruptions that telecommunication actors are not required to report. Taking this into consideration the ratio of the collected interruption data is unknown in relation to the factual interruptions in the system; on one hand it could be that nearly all interruptions are missing, and on the other hand it could also be that most interruptions are available.

#### **TRANSPORT RAILWAY – CONSEQUENCE PARAMETER**

Choosing consequence parameter and corresponding baseline for the Transport Railway data came with some rough estimations. As discussed in 8.1.1 above, cancelled trains were not used, delayed trains were used instead. Hence, this data might not display interruptions very well, but it does show a congested system with a constant and large part of disrupted trains. As all tCIs, Transport Railway is an important network, but seem to be working on the limits of its full capacity. We do not have full insight of the data that Trafikverket collects, and it is possible that there is other data available that was not thought of in our communication. Though, according to the informative and investigative communication we had with the responsible parts,

including hours of phone calls with professionals that are expected to be very familiar with the system, we got surprised when told that no data is stored that connects cause and effect of a given interruption or disruptive event; cancelled trains or blocked train tracks are nowhere logged as consequences of interruptions. E.g., if a tree tears down a contact wire, we have been informed that there is no gathered data that can be applied to sum up the consequences, such as the affected trains that are delayed or cancelled due to a given event of interruption. Again, there are perhaps other parameters and data stored in the system, which we are unaware of, that is used to measure consequences of disruptive events in risk assessments. However, based on our knowledge and the data we received, Transport Railway is the only tCI that does not collect interruption data that easily fits the consequence metric we have used (Functionality Loss). According to our view on risks and risk management, approaching risks without clear-cut consequences is not making it easy. However, the data we used does contain a field to log the causing train number, a suggestion could be a similar field for a more open and situation-specific description of a root failure cause. We believe this could be handy when there is no train responsible for causing the interruption, and particularly useful in case of natural incidents, e.g. great storms or floods, or other major situations.

## **TRANSPORT ROAD - BASELINE AND DATA GATHERING**

All the CIs interruption data sets have different qualities, and different reasons for their data gathering, which in almost all cases has been well described for us, making it much easier to understand their strengths and weaknesses. This helped in the process of adapting the data to the RAA, in most cases choosing consequence measures and finding baselines to correspond to these was clear cut. In some cases, however, this was not as straight forward. Choosing baseline for the consequences of Transport Road was difficult, the average number of vehicles in the system, that is all Sweden, is not a number that could be found estimated anywhere. The estimation we used came from the total sum of vehicle distance travelled (see Eq. 15) divided by the total road length. This gives the average number of vehicles needed to cover this distance and is true if on average: a) all vehicles drive equally long, and b) the whole system is used equally much (cars are equally spread out on all roads). We hope and believe that the uneven spread of cars on all the roads will cover the uneven spread of how much each car is used.

Secondly the consequences in this data set are computed by algorithms, meaning there is no equipment that counts the actual number of cars in any of the incidents that are affected by the TTS, they are instead estimated by statistical averages. Due to this, the consequences (the number of affected vehicles, *Palpability*) are roughly approximated and there is expected to be an unknown number of TTS that are not registered by the system, given by the traffic interruptions that are either resolved without external help or communication with emergency response systems.

## **FAR STRETCHING DATA SETS**

The last comment we have on the data quality is an obvious matter for any data stretching over such long time; due to developments and changes. Working with data that stretches for years, there is a probability that the methods and prerequisites for gathering will change and develop over time, possibly resulting in partly biased data. In some cases, such changes were easily spotted and obvious, whilst in others such changes were subtler and only visible over several years. Only in one case, the Water Supply data, the data quality of some parts varied so much from the rest that it was considered unusable. We were warned about this and it was easily detected in this case.

## **8.2 THE RESILIENCE ASSESSMENT APPROACH**

### **8.2.1 METRICS**

The metrics used in the RAA is each interruptions duration (given by the Start DT and End DT) and Functionality Loss and if available, also the given failure causes. Any given data set of interruptions with metrics that fulfils these requirements can utilise the RAA. That said, the RAA is still applicable with interruption data of higher resolution, where the disruptive phase and recovery phase of the data is known. The purpose of adopting the failure cause is not only to show how these different causes affect the tCI, but also to display how simple categorisations can be used to classify the interruptions for further analyse of the data.

One complication regarding the metrics which we did not have to apply on our data, but we want to bring up in this discussion, is consequences that cannot easily fit the binary approach of consequences used in this thesis. With binary, we mean the nature of the consequences from an interruption to either deliver the service or not. In our data, the measured system either delivered the expected service (power, water, telecommunication etc.) or it did not. We did come across some issues where the consequence measures were not so clear cut, just touching upon it in the interruption data but clearly identified the issue as highly probable for other data. The examples found in our data comes from the Telecommunication data, where many consequences were described in terms such as ‘almost half of the attempted calls to numbers outside of Sweden were not connected’ or ‘phones connected to the 3G experienced data traffic problems in area X, but fully functioning call services’. The Functionality Loss to be drawn from someone affected by a total outage of mobile connectivity services, it is probably not fair to equate with someone that has issues to connect an international call. Another rather common issue we have seen examples of this, but never received any data of, is contaminated water. Our example of Water Supply data (SVOA) did not contribute with such quality related interruptions, simply because they have not been affected by issues resulting in undrinkable water for the measured period. Such an event of contaminated water would create an interruptive

event with very big consequences if all the affected customers with water that needs boiling would be counted equally as e.g. customers without power supply. Another Swedish water distribution actor that we were in contact with was, VA SYD (see section 4.7.2), whom have had issues with water quality (water contamination) that has been officially declared as non-drinkable. That water was still considered drinkable if boiled, so it can be discussed how fair it would be to log such incident and value it the same way as total outage, as if they had no running water at all. If everyone affected by such an event would all be counted equal to customers without water, VA SYD would probably have scored poorly in this RAA, and the Resilience Loss from that event would probably be equal to or greater than a severe storm, which might not be fair assessment from a societal safety point of view. Nevertheless, given a situation of polluted drinking water in need of boiling; as much as that would not substantially interfere with every-day living conditions for many, it does make parts of the society more vulnerable. Other CIs, e.g. a hospital, are highly dependent on that drinking water and might be much more vulnerable to such incidents. Suppose that it happens in combination with a power outage, and all of a sudden close to no one have access to clean drinking water, the situation can quickly change and display new consequences that would not be expected normally.

## 8.2.2 STRENGTHS AND WEAKNESSES

The RAA developed in this thesis allows for resilience comparison of different tCI as well as measuring changes in resilience level over time. It is an approach where interruption data from different types of infrastructures, with completely different scopes, can be gathered and contrasted, where it with other means would be quite hard to do a resilience comparison. With the data received from a variety of Swedish tCI, we managed to do a cross-infrastructure comparison in a unified manner.

It is of our sincere belief the RAA has potential to become a useful input in resilience analyses of all sorts of interruption data of tCIs. One of the strengths of this RAA is that any type of interruption data can be used to produce the given results, to create *Resilience Curves* and other resilience-based conclusions. Since the RAA most likely can be applied to interruption data of any engineered system, it could possibly contribute with useful information as a basis for any decision-maker in, at any level; to compare and contrast the differences in resilience levels of the studied systems. Though, one should though keep in mind that the approach is solely a retrospective study, and that we are only utilising data of past events. Thus, the approach is limited when it comes to predicting resilience of future and unknown stresses that have not yet been experienced by the system, which leads us to some of its limits.

One of the main limitations of the RAA, is its inability to measure the actual strain put on the system. Two systems with equal Resilience Loss will score similar, no matter if the underlying



stresses might have been very different. By analysing the results and studying the Resilience Curves, one should get hints of differences in such underlying stresses. That is, two systems with similar average resilience levels, but different system strains, should be fairly easy to separate if their resilience curves are compared and studied. We do present some initiating ideas on how such underlying strains could be measured and incorporated to the RAA in section 7.4.3, under heading *Capability assessment*.

The discussion initiated under section 8.2.1, about consequences that are more complicated to value and quantify, leads to further discussions about how such consequences can fit the concept of engineered systems and Functionality Loss. Thus, one of the limitations of the RAA is its inability to clearly define the interruptions from such less clear-cut consequences, e.g. contaminated drinking water or some specific mobile network errors such as inability to call abroad. Some ideas of how to deal with this is presented under section 8.4 Future work.

### 8.2.3 VALIDITY

The developed RAA has been tested and verified by applying it on empirical interruption data from several tCI. There are however a few question marks that we have found being too common along the way, which we believe are in need of further discussion to clarify and validate our work.

#### **IS IT REALLY RESILIENCE WE ARE MEASURING?**

Yes, we believe we do. This is one way of interpreting resilience; one angle, perspective or idea of engineered system resilience in the context of tCIs. The RAA enables both discussions and conclusions on the concept of system resilience and it also allows for quantifications of such. These quantifications could be seen as ‘broad’ and overarching averages that might not fit the typical research on system resilience; our approach lacks specific quantification of single event’s functionality development that is often seen in this field of research, e.g. the disruption and recovery phase. However, if one would manipulate/change any of the analysed data to display somewhat ‘better resilience’ in terms of more efficient disruptive or recovery phase, it would also result in somewhat ‘better resilience’ in the RAA as executed in the paper, meaning that our RAA correlates with such ideas of increased system resilience.

#### **IS THIS APPROACH AN ATTEMPT TO DEFINE RESILIENCE?**

Most certainly not. Our intentions with the RAA is not to complete the field of infrastructure resilience, but merely to develop an approach that enables cross-infrastructural quantifications, thus also comparisons. In this matter we believed the RAA is successful.

## **IS IT NOT RELIABILITY WE ARE MEASURING?**

Yes, that is also true, as reliability is a subset of resilience. We do believe however, that the RAA display results that lies closer to the concept of resilience. Nonetheless, suppose the RAA describes both resilience and reliability equally well, or even describing reliability better. We then argue that wording both needs to be correct, but also beneficial. So if not for any other reason, we believe that to simply receive attention from a word that is a trendy topic could be a good enough reason its own.

## **INDEPENDENT OR DEPENDENT INTERRUPTIONS**

We believe that one of the main limitations of the approach is that some parts of the RAA use single events (interruptions) as they are logged in the given data (e.g. Figure 62 and Figure 63 in section 7.1), whilst other parts aggregate the data and approaches each infrastructure as one system (e.g. Figure 65, Figure 66 and Figure 67 in section 7.3). This means that the parts of the RAA that adopts the data as single interruptions are highly dependent on the way the data is logged, or ultimately the resolution of the data. This is why the histograms that presents all logged interruptions (see Figure 62 and Figure 63) will look very different if a given incident (e.g. a great storm) is logged as thousands of data points (e.g. Electricity Distribution) or a handful of data points (e.g. Telecommunication). A higher resolution will contribute to more but shorter events with less consequences. Vice versa, a lower resolution would contribute to fewer but longer events with higher consequences, which ultimately will reconfigure such histograms, even if reality stays unchanged. To better validate such histograms, the data needs to be carefully logged and all interruptions that comes as a result of a united root cause, should preferably be easily identifiable, further suggestions are made under *Risk management and Spatial Planning* in section 8.2.4.

### **8.2.4 USABILITY**

To begin with, executing any approach similar to this, empirical interruption data is needed. All data was made available to us without any requirements or cost associated with it. This suggests good possibilities of retrieving data for a regulative public sector, where not only all data can be made available through regulatory incentives, but new data gathering processes can be initiated to adapt to the needs of the assessment and not the other way around. Meaning that this approach is much easier applicable for businesses, organisations and governmental or public bodies, even better so in counties with more centralised power, where some of the data that would be interesting to gather might already belong to the public sector. For policy makers (in such countries), it can be worth looking into the processes of the actors that are gathering the data/information that might be usable as interruption data. Perhaps some data can be retrieved by simple means, for example if a data gathering process could be adjusted so that its collected the required data that fits our approach. It might be likely that many of them probably already

gathers data that is similar to what is searched for, via incident reports or similar systems. It seems like most of the data sources from which we have received inadequate data that does not exactly fit this approach, do in most cases log big parts of the data we wanted and then just needs some adjustments to fulfil the requirements. They don't need to hire consultant firms to evaluate, install, educate and implement, they just need to put an End DT in the same database they are already using, by the same person who would already put in all the other parameters, according to the same routines that everyone already is familiar with. We did receive a very extensive data set from Göteborg Kretslopp och Vatten (see section 4.7.1) that unfortunately did not contain the data we needed. It would probably not be associated with much extra work to introduce a couple of new parameters which are relevant to the approach. Not long after receiving this data, we learned that the Swedish municipalities have established a trade association called Svenskt Vatten<sup>14</sup>. They run a research and development project called "Swedish Waters Development"<sup>15</sup>, that has given out a handbook in development and planning of water supply systems. A chapter in this handbook addresses the needs and importance of interruption data gathering. Unfortunately, when they discuss the parameters one should gather for such data, mostly parameters related to water quality and technical specifications are mentioned, but nothing related to the consequences and durations of interruption that we are looking for. This is a kind of actor that would probably be easy to work with and that is likely to adapt the ideas presented here.

The data's intended usage is quite narrow, but its properties was diverse; the quality and accuracy vary both in terms of feasibility and validity. The utilised data was not always perfect, but it could be adapted to suit the RAA and its intended purposes. This implies some promising possibilities of adaptation, which we argue is of essence when analysing different and complex systems. In section 7.4 we have put forth ideas for usability of the approach. As mentioned in the that section, we did not want to limit the discussion to only to the results presented in this thesis, but instead keep and open discussion of the full potential of the usage of the approach where we then narrowed the focus toward risk management and spatial planning processes.

## **RISK MANAGEMENT AND SPATIAL PLANNING**

To further elaborate the discussion of the results in section 7.4, we present some concrete suggestions to improve the results of the RAA to aid *the risk management* and *spatial planning* process.

1. One authority responsible for centralised data gathering and communication for all tCIs.

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<sup>14</sup> In English: The Swedish Water & Wastewater Association (SWWA)

<sup>15</sup> In Swedish: Svenskt Vatten Utveckling (English Translation Disclaimer)

2. Clear and unified procedures for data gathering, including definitions of interruptions and threshold values for each tCI. Instead of complicated incident reports, this procedure should be simple and only ask for relevant information/parameters and can probably be easily incorporated into existing procedures or in best case even automated. Such data is simple, light-weight and can easily be logged online and should be easy to protect, as it is not very sensitive on its own. Only when many pieces are put together it can create a picture that can become a threat for national safety.
3. Responsible authority administrates smart, unified and simple categorisations of the data, e.g. internal failure cause, root failure cause, responsible part and locality of the incident. Request possibilities for new failure causes can highlight the needs of ad-hoc additions of specific root failure causes, e.g. storms, floods or other specific or local incidents. If well administrated, such data gathering procedures could enable almost real-time vulnerability analyses and become valuable asset for Spatial Planning procedures and perhaps even national safety.
4. The data gathering should be confidential and separated from procedures that might bias the data, such as economic/juridical reprisals or punishments (as seen in rules for the Transport Railway, Telecommunication and Electricity data).
5. To enable analysis of system strain, the responsible authority administrates how gathering of zero values should be incorporated; i.e., which types of incidents that must be reported even if no interruption occurs for the end-users.

## 8.3 RESULTS OF THE RESILIENCE COMPARISON

In this section, the focus is put on discussing the factual results of the comparison. There are many aspects that can possibly explain the differences in resilience level of the studied tCI. Whilst trying to enlighten some of those differences, we will also address our ideas on the excluded research question D, as there are some obvious facts to enlighten regarding the results, starting with Electricity Transmission, the most resilient of the studied tCIs.

We regard Electricity Transmission as the backbone of the electricity infrastructure. Being the main source of all consumed power in the country and managed by a centralised authority, it does make sense for this tCI to stand out in terms of greater resilience. Worth saying for Electricity Transmission, is that nearly all their interruptions are due to thunder, a risk that one might think should be easier to manage in such a highly developed society as Sweden. For Electricity Distribution on the other hand, the proportion of interruptions due to thunder is much less, instead a set of new risks are introduced that relates to its physical structures, as some of its most common interruptions are due to falling trees and excavation. No cases of falling trees that results in any resilience loss are found in the Electricity Transmission data, whilst

falling trees is one of the overall top interruption causes in the Electricity Distribution data and accounted for nearly all resilience loss in the storm Gudrun (Figure 67). We assume it simply originates from the Electricity Transmission's taller power grid lines, reaching higher above the terrain and the trees. Regarding differences of risks due to excavation, perhaps they might be of administrative nature. Maybe Electricity Transmission does a better job with communicating where their underground grids are located, whilst administrations in the Electricity Distribution infrastructure might have more troubles with such communication. Perhaps the location plans of underground power cables are misread, alternatively disregarded by the actor responsible, or the information about positioning is simply faulty. Such mistakes should be more likely in Electricity Distribution than Electricity Transmission, as there are many actors involved and to our belief the power grid networks are finer and more complex. Additionally, the risk at stake in the Electricity Distribution network should be less as the possible outcome of interruptions are much less than the consequences of interruptions in the Electricity Transmission network. Similar issues are found within the Telecommunication infrastructure, where different types of excavation-damaged signal cables seem to count for a substantial part of the interruptions.

The measured results of the Water Supply infrastructure show a highly resilient tCI, results that also can be related to its physical structures. The water distribution piping is pressurised which means that broken pipes and leakages in most cases will not affect the end customer in terms of availability, but only increase the water consumption in the system which creates a sort of built in redundancy in the system (see section 4.5.2). This redundancy is enhanced further by the meshed water distribution network, where a given mass of water often can take several ways to reach a final user, there are parts in the system where cutting the flow of water will not necessarily mean that anyone is affected. Similar redundancy is found in the meshed network of IP-data traffic, where data packages finds their way to the destination even if some might be lost on the way; and in the meshed power grid, where the electricity can find multiple ways to reach its end user (ENTSOE, 2017; Lindberg, 2009). The Swedish data that we have received is luckily not affected by issues related to ground movements, as interruptions due to ground movements has the potential of affecting all the studied tCIs, e.g. broken water piping, damaged power cables or IP-cables (possibly affecting all Telecommunication infrastructures) or roads and railway sections that are either damaged or unusable due to fallen debris.

## 8.4 FUTURE WORK

During the progress of thesis, it became clear how much work could possibly be done on this topic. Some of the ideas could not be studied in greater detail, ideas that are beyond the scope of this thesis but still worth looking into. In this section such ideas are presented.

## **DATA OF SEPARATE EVENTS**

As discussed in section 8.1.1, we changed the way we interpreted the data. Initially, we found it too difficult to determine and sum which interruptions are dependent on each other as consequences to a given root cause. With this in mind, we only made inquiries of interruption data with the minimum parameters of given Start DT and End DT and a measure of the gathered consequences for each interruption. With knowledge about the final RAA, less focus on requirements of gathered consequences should have been made. If anything, we would have preferred data without a united source of interruption, where each interruption rather is separated by all its included consequences. Data that displays separated consequences would have given a higher resolution than data displaying the sum of each interruption. It might be that our mind-set made some actors dismiss data that could possibly have been of use. Looking at an engineering system as whole, we believe that instead of only asking for interruption or failure data, one could rather sit down and think about what retrievable information could represent an outage in the delivered service of the studied infrastructure. Instead of asking for interruptions in the train traffic, one should perhaps have asked for individual cancelled trains, or even information about closed train tracks. Instead of asking for interruptions in the flight traffic of airports, one could have asked for cancelled flights. By asking for such information without the prerequisite that a common interruption source is needed for each event, we believe that new and interesting functionality curves potentially could have been made.

## **PLANNED EVENTS**

In section 8.1.1, we also discuss the fact that planned interruptions were dismissed. We believe that any future work on the topic should strive for including all types of interruptions, planned or not, as they all put a stress on the measured system.

## **INTERDEPENDENCIES**

If adequate interruption data can be found that displays several infrastructures affected by a single large-scale event (similar to Figure 65), possible interdependencies can be studied. Interesting fields we have been thinking about is primarily which infrastructures that are dependent on another and if the dependency is mutual or one sided. Can the dependencies be quantified? What are the underlying reasons for potential interdependencies and could such information be used to mitigate the effects of interdependencies?

## **DISRUPTIVE EVENTS WITHOUT INTERRUPTION**

Here we want to display the usability of logged interruptions with no consequences in terms of interruption of the delivered service, but with clear consequences in terms of damaged or disconnected parts of the engineering system. Such data was especially found in the Electricity Transmission data, where detailed information was given about events with failing components

or system parts, where no consequences (PNS) were measured. If it is possible to log such information in a unified way, can it be used to display and quantify stress that is absorbed by the system? Can such information be used as another dimension in resilience quantification?

## **REASONS FOR RESILIENCE DIFFERENCES**

Our initial intent was to look into what the plausible explanations for the differences and similarities of the resilience levels for the different CIs, however due to reasons mentioned in Chapter 1 it was excluded. In the discussion above we do however put forth some speculation regarding the issue. That said, investigating whether the differences and similarities of the tCI could be traced to e.g. technical aspects, safety cultural aspects, legislative or regulatory aspects, could potentially give a deeper understand what the underlying factors are behind the resilience levels of the RAA. Furthermore, understanding why gives an opportunity for learning, both for a tCI owner and/or regulatory authority to learn the reasons behind their resilience level, as well as it has the potential for cross-infrastructural learning which consequently has the potential of facilitate changes which may result in increased level of resilience.





# 9 CONCLUSIONS

## **HOW CAN THE RESILIENCE OF DIFFERENT CRITICAL INFRASTRUCTURE BE MEASURED THROUGH EMPIRICAL INTERRUPTION DATA AND COMPARED IN A UNIFIED MANNER?**

This thesis suggests a resilience assessment approach (RAA) that uses empirical interruption data to measure, analyse and compare resilience level of several different technical critical infrastructures (tCIs), and has successfully been applied to five different Swedish tCIs. The approach is based on a resilience curve, measuring the given tCIs' functionality as a function of time, and is derived from each interruption's Functionality Loss and calendar duration. The suggested RAA is performed in two parts: 1) each separate tCI's state of resilience is analysed, 2) all the tCIs' resilience results are brought together to be compared and contrasted. The first part is given by a) tables of key values, b) a yearly mean resilience plot and c) a plotted "national system level" resilience curve. The second part is made to aggregate the results of the individual tCIs to further illustrate and clarify the comparison.

Given adequate and valid data, and if executed accordingly, it is of our belief that the results achieved by applying the RAA result will give relevant information for policymakers or professionals to compare and contrast tCIs' level of resilience in a unified manner.

## **HOW RESILIENT ARE THE DIFFERENT TYPES OF CRITICAL INFRASTRUCTURES?**

From the conclusions drawn by applying the developed RAA for several Swedish technical infrastructures, it can be concluded that: Electricity Transmission is the most resilient, with extremely few interruptions that results in any consequences in terms of disrupted service. The least resilient tCI is Transport Railway, where many disruptive events constantly stress and affects the system's measured level of functionality. Of the remaining tCIs, that is Transport Road, Water Supply, Telecommunication Mobile, Telecommunication Broadband Services and Telecommunication Fixed Telephony, it is shown that their resilience is on similar levels. However, out of these five the validity of the Water Supply data is better, hence the result more

accurate. Due to the uncertainties in the underlying data for the other four infrastructures, their assessed resilience levels are likely less accurate.

### **HOW CAN SUCH RESULTS BE USED AS INPUT TO RISK MANAGEMENT AND SPATIAL PLANNING PROCESSES?**

A successfully performed RAA enables simple, objective and comparable results that are believed to be useful as inputs in different parts of risk management processes (RMPs) and spatial planning processes. Examples are given on how the RAA can be used to give additional information whilst performing a RMP for *Risk identification*, *Risk analysis and estimations*, analysis of *Vulnerabilities* and *Capability assessments* and *Risk evaluation and monitoring*. Suggestions are also given on how the RAA can be used to improve the spatial planning process, by using its goals as guideline.

To reach closer to the RAA's full potential, we suggest that critical infrastructures should be either legally obliged or encouraged by official instances to gather interruption data. If possible, one single centralised authority could be in charge of deciding what specific data required of each individual tCI, given with unified parameters and thresholds (Some ideas of how such data could look like is presented in section 7.4 Applying the RAA, practical usages).

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# APPENDIX, MATLAB-CODE

The appendix is made to present examples of the written Matlab-code used for all data analysis and data visualisation i.e. plots and tables. The code will be presented in a chronological order in relation to what order the code is used in the paper. The headings will be given according to the chapter where the presented code was used.

## A 1. EXTRACT THE DATA FROM SOURCE (EXCEL) ELECTRICITY DISTRIBUTION AS EXAMPLE

Excel is given as an example in the heading, as this has been the data format we received all data in,

```
%% LOAD DATA AND PUT IT IN MATLAB FILES
clear;clc;close all;
%% GOOD INFO!!!
% SYNTAX                                WHAT IT DOES
% categories('tablename.columnname')    gives the categories (if categorical)
% summary(tablename)                   gives cool summary of the table
% writetable(tablename, 'newfilename.xlsx') creates new .xlsx file from table

% opts = detectImportOptions(filename)   Create import options based on file content
% for help on this one see, https://se.mathworks.com/help/matlab/ref/spreadsheetimportoptions.html

%% EXCEL IMPORT OPTIONS
FilePath      = 'FILEPATH/EnergifV@retagen, lV*gspv$nnng/For Analyse, edited/All edited names/Alla oplanerade ';
FileType      = '.xlsx';
DatetimeType  = 'exceldatetime';
TimeFormat    = 'HH:mm';
DateFormat    = 'yyyy-MM-dd';
DateInputFormat = 'yyyy/MM/dd';
FillValueCategorical = 'Missing data';
ImportOptionsYear = '2005';

% If the exeldocument uses excel-datetime data, it is important that the
% 'DatetimeType' is 'exceldatetime'. Otherwise the dates will show as wierd
% numbers/code. But if the exeldocument has written dates, saved as text
% or numbers, use different 'DatetimeTypes', for more help see:
% https://se.mathworks.com/help/matlab/ref/detectimportoptions.html#namevaluepairarguments
ExcelImportOptions = detectImportOptions([FilePath ImportOptionsYear FileType], 'DatetimeType', 'exceldatetime');

% 1) Type ExcelImportOptions.VariableNames in the command window
% 2) copy and change the info and change it to your new variableNames
ExcelImportOptions.VariableNames = {...
    'InterruptionType',...
    'StartDate',...
    'StartTime',...
    'EndDate',...
    'EndTime',...
    'InterruptionTime',...
    'Hspab',...
    'Lspab',...
    'DisconnectingSite',...
    'FailureSite',...
    'Network',...
    'InstallationComponent',...
    'FailureCause'};

% copy and change the info in ExcelImportOptions.VariableTypes to the
% 1) Type ExcelImportOptions.VariableTypes in the command window
% 2) change the variable types that you want to change
ExcelImportOptions.VariableTypes(1) = {...
    'categorical'};
```

```

ExcelImportOptions.VariableTypes(9:13) = {...
    'categorical'};
ExcelImportOptions.VariableTypes(2) = {...
    'datetime'};
ExcelImportOptions.VariableTypes(4) = {...
    'datetime'};

% Check in ExcelImportOptions.VariableOptions which variables that are datetime and
% give them the following properties
ExcelImportOptions.VariableOptions(2).InputFormat = DateInputFormat;% startdatetime
ExcelImportOptions.VariableOptions(4).InputFormat = DateInputFormat;% enddatetime

ExcelImportOptions.VariableOptions(2).DatetimeFormat = DateFormat;
ExcelImportOptions.VariableOptions(4).DatetimeFormat = DateFormat;

% Check in ExcelImportVariableOptions which variables that are categorical and
% give them the following properties
ExcelImportOptions.VariableOptions(1).FillValue = FillValueCategorical;
ExcelImportOptions.VariableOptions(9).FillValue = FillValueCategorical;
ExcelImportOptions.VariableOptions(10).FillValue = FillValueCategorical;
ExcelImportOptions.VariableOptions(11).FillValue = FillValueCategorical;
ExcelImportOptions.VariableOptions(12).FillValue = FillValueCategorical;
ExcelImportOptions.VariableOptions(13).FillValue = FillValueCategorical;

% Create tables
PowerDist.Data = table;
YearNumber = table;

YearNumber.RowNrStart(1,1) = 1;
YearNumber.RowNrStart(2:11,1) = NaN; % allocate space
%% EXCEL READ-IN

YEAR = {'2005', '2006', '2007', '2008', '2009', '2010', '2011', '2012', '2013', '2014', '2015'};

for k = 1:11 % Choose right r i YEAR skall vara k = 1:11
    disp(YEAR(k))

    Y = YEAR(k); % ex. Y = '2012'
    % ExcelImportOptions.Sheet = YEAR(k); if sheets are used
    TEMPYEARTABLE = readtable([FilePath Y FileType], ExcelImportOptions);

    % SORT THE ROWS PROPERLY BY DATETIME
    % To start with, we sort the tables by time
    TEMPYEARTABLE = sortrows(TEMPYEARTABLE, {'StartTime'}, {'ascend'});
    % Then we sort the tables by date
    TEMPYEARTABLE = sortrows(TEMPYEARTABLE, {'StartDate'}, {'ascend'});

    StartTimeHour = floor(TEMPYEARTABLE.StartTime); % HH
    StartTimeMin = round((TEMPYEARTABLE.StartTime-StartTimeHour)*100); % MM
    StartTimeNull = zeros(size(StartTimeHour,1),1); % create zeros for the time matrix seconds
    TEMPYEARTABLE.StartTime = datetime([StartTimeNull,StartTimeMin,StartTimeNull,... zeros where we dont want input
        StartTimeHour,StartTimeMin,StartTimeNull],... we only want the time
        'format',TimeFormat);

    EndTimeHour = floor(TEMPYEARTABLE.EndTime); % HH
    EndTimeMin = round((TEMPYEARTABLE.EndTime-EndTimeHour)*100); % MM
    EndTimeNull = zeros(size(EndTimeHour,1),1);
    TEMPYEARTABLE.EndTime = datetime([EndTimeNull,EndTimeMin,EndTimeNull,... zeros where we dont want input
        EndTimeHour,EndTimeMin,EndTimeNull],...
        'format',TimeFormat); % given at EXCEL IMPORT OPTIONS above

    InterruptionTimeHour = floor(TEMPYEARTABLE.InterruptionTime); % hours setparate
    InterruptionTimeMinSec = abs(TEMPYEARTABLE.InterruptionTime-InterruptionTimeHour); % 0.MMX (MinMin.Min)
    InterruptionTimeMin = abs(round(InterruptionTimeMinSec*100)); % MM.M
    InterruptionTimeSec = abs(round((InterruptionTimeMinSec-...
        InterruptionTimeMin/100)*1000)*6);

    TEMPYEARTABLE.InterruptionTime...
        = duration(InterruptionTimeHour,...
            InterruptionTimeMin,...
            InterruptionTimeSec);

    % ONE TABLE TO RULE THEM ALL
    PowerDist.Data = vertcat(PowerDist.Data, TEMPYEARTABLE);

end
[NrRows,~] = size(PowerDist.Data);
PowerDist.Data.Nr(:,1) = 1:NrRows;

%% DATE AND TIME
PowerDist.Data.Start_DT= datetime(...
    year(PowerDist.Data.StartDate),...
    month(PowerDist.Data.StartDate),...
    day(PowerDist.Data.StartDate),...
    hour(PowerDist.Data.StartDate),...
    minute(PowerDist.Data.StartTime),...
    zeros(NrRows,1), ...
    'Format','yyyy-MM-dd HH:mm');
PowerDist.Data.End_DT= datetime(...
    year(PowerDist.Data.EndDate),...
    month(PowerDist.Data.EndDate),...
    day(PowerDist.Data.EndDate),...
    hour(PowerDist.Data.EndTime),...
    minute(PowerDist.Data.EndTime),...
    zeros(NrRows,1), ...
    'Format','yyyy-MM-dd HH:mm');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
DATA TREATMENT
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
DATA TREATMENT
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
DATA TREATMENT
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
DATA TREATMENT
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
DATA TREATMENT
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
DataSize = size(PowerDist.Data,1);
DataTreatment.DataToTreat = table;
DataTreatment.DataToTreat.Start_DT = PowerDist.Data.Start_DT;
DataTreatment.DataToTreat.End_DT = PowerDist.Data.End_DT;
DataTreatment.DataToTreat.DurationT = DataTreatment.DataToTreat.End_DT - DataTreatment.DataToTreat.Start_DT;
DataTreatment.DataToTreat.Duration = hours(DataTreatment.DataToTreat.DurationT);
DataTreatment.DataToTreat.Consequences = PowerDist.Data.Hspab + PowerDist.Data.Lspab;

```

```

DataTreatment.DataToTreat.InterruptionNr(:) = (1:DataSize);
% PRE-DATA TREATMENT
DataTreatment.PreDataTreatment = table;
DataTreatment.PreDataTreatment.MissingDuration...
    = isnan(DataTreatment.DataToTreat.DurationT);
DataTreatment.PreDataTreatment.MissingConsequences ...
    = isnan(DataTreatment.DataToTreat.Consequences);
DataTreatment.PreDataTreatment.ZeroDuration ...
    = DataTreatment.DataToTreat.DurationT==0;
DataTreatment.PreDataTreatment.ZeroConsequences ...
    = DataTreatment.DataToTreat.Consequences==0;
DataTreatment.PreDataTreatment.UnrealDuration ...
    = DataTreatment.DataToTreat.DurationT<0 | ...
    year(DataTreatment.DataToTreat.End_DT)>=2017 |...
    DataTreatment.DataToTreat.InterruptionNr == 677062|...
    DataTreatment.DataToTreat.InterruptionNr == 623183|...
    DataTreatment.DataToTreat.InterruptionNr == 4218|...
    DataTreatment.DataToTreat.InterruptionNr == 4137|...
    DataTreatment.DataToTreat.InterruptionNr == 4163|...
    DataTreatment.DataToTreat.InterruptionNr == 4466|...
    DataTreatment.DataToTreat.InterruptionNr == 441693|...
    DataTreatment.DataToTreat.InterruptionNr == 1768|...
    DataTreatment.DataToTreat.InterruptionNr == 66276; %
    negative time
    end time after the data set was recieved
    unreal dur
    unreal dur
    unreal dur
    unreal dur
    unreal dur
    unreal dur
    unreal dur
    unreal dur
    unreal dur
    unreal dur

DataTreatment.PreDataTreatment.UnrealConsequences(:) ...
    = false;

%% TREAT DATA prep

DataTreatment.MissreadEndDates = DataTreatment.DataToTreat.Start_DT>(DataTreatment.DataToTreat.End_DT +minutes(1));
DataTreatment.MissreadEndDatesYear = [623183;677062];

%% DATA TREATMENT
DataTreatment.TreatedData = DataTreatment.DataToTreat;
% add one day to the end dates that are 24h early
DataTreatment.TreatedData.End_DT(DataTreatment.MissreadEndDates)...
    = DataTreatment.DataToTreat.End_DT(DataTreatment.MissreadEndDates) + days(1);
% set the year right for those two little rats
DataTreatment.TreatedData.End_DT(DataTreatment.MissreadEndDatesYear).Year...
    = year(DataTreatment.TreatedData.Start_DT(DataTreatment.MissreadEndDatesYear));
DataTreatment.TreatedData.Duration...
    = hours(DataTreatment.TreatedData.DurationT);
DataTreatment.TreatedData.Consequences(DataTreatment.PreDataTreatment.ZeroConsequences==0) ...
    = DataTreatment.DataToTreat.Consequences(DataTreatment.PreDataTreatment.ZeroConsequences==0);
DataTreatment.TreatedData.InterruptionNr...
    = DataTreatment.DataToTreat.InterruptionNr;

DataTreatment.PostDataTreatment = table;
DataTreatment.PostDataTreatment.MissingDuration...
    = isnan(DataTreatment.TreatedData.DurationT);
DataTreatment.PostDataTreatment.MissingConsequences ...
    = isnan(DataTreatment.TreatedData.Consequences);
DataTreatment.PostDataTreatment.ZeroDuration ...
    = DataTreatment.TreatedData.DurationT==0;
DataTreatment.PostDataTreatment.ZeroConsequences ...
    = DataTreatment.TreatedData.Consequences==0;
DataTreatment.PostDataTreatment.UnrealDurationT ...
    = DataTreatment.TreatedData.DurationT<0|...
    isnan(DataTreatment.TreatedData.DurationT);
DataTreatment.PostDataTreatment.UnrealDuration(:) ...
    = false;
DataTreatment.PostDataTreatment.UnrealConsequences(:) ...
    = false;
DataTreatment.PostDataTreatment.UntreatableData...
    = any(DataTreatment.PostDataTreatment(:,1:6),2);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% RESILIENCE METRICS! %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% CREATE RESILIENCE METRICS
NrInterruptions = size(DataTreatment);

BaselineFilePath = 'FILEPATH\Energif\0retagen, l\*gsp\5nning\Baseline\Number of costumers.xlsx';
BaselineImportOptions = detectImportOptions(BaselineFilePath);
BaselineImportOptions.VariableNames = {'TotNoCustomers'};
BaselineImportOptions.DataRange = 'B2:B12';
BaselineImportOptions.RowNamesRange = 'A2:A12';
Baseline = readtable(BaselineFilePath, BaselineImportOptions);

ToUse = DataTreatment.PostDataTreatment.UntreatableData==0;
Metrics = table;
Metrics.BaseLine = Baseline.TotNoCustomers(year(DataTreatment.TreatedData.Start_DT(ToUse))-2004);

Metrics.InterruptionNr = DataTreatment.TreatedData.InterruptionNr(ToUse);
Metrics.Start_DT = DataTreatment.TreatedData.Start_DT(ToUse);
Metrics.End_DT = DataTreatment.TreatedData.End_DT(ToUse);
Metrics.DurationT = Metrics.End_DT - Metrics.Start_DT;
Metrics.Duration = hours(Metrics.DurationT);
Metrics.Consequences = DataTreatment.TreatedData.Consequences(ToUse);
Metrics.FunctionalityLoss = Metrics.Consequences./Metrics.BaseLine;
Metrics.ResilienceLoss = Metrics.FunctionalityLoss.*Metrics.Duration;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% FAILURE CAUSES
% Decide what generic failure causes the given failure causes should have
GenericFailureCauses =
    {'BRISTANDE UNDERHÖLL', 'Human';...
    'DIMENSIONERINGSFEL', 'Human';...
    'DJUR', 'Natural';...
    'FABR- ELLER MTRLFEL', 'Technical';...
    'FELAKTIG METOD/INSTRUKTION', 'Human';...
    'FELAKTIG MONT/FVÄRLÄNGGNING', 'Human';...
    'FELMANVÄRER', 'Human';...
    'GRÄVNING', 'Human';...
    'OKÄND', 'Unknown';...
    'PROVNING', 'Human';...

```

```

'REGN, VATTEN','Natural';...
'SABOTAGE','Human';...
'SALT','Natural';...
'SNVA, ISLAST','Natural';...
'SVNRKINGSBROTT','Technical';...
'TRAFIK','Human';...
'TRVNDFALL, SNVA','Natural';...
'TRVNDFALL, VIND','Natural';...
'TRVNDFVLLNING','Human';...
'VIND','Natural';...
'VOSKA','Natural';...
'VOTERVVNDANDE LAST','Human';...
'VVERBELASTNING','Human'};

FailureCausesGeneric = PowerDist.Data.FailureCause;
for k=1:size(GenericFailureCauses,1)
    FailureCausesGeneric(FailureCausesGeneric==GenericFailureCauses(k,1)) = GenericFailureCauses{k,2};
end
Plots.DataChapter.FailureCausesGeneric = removecats(FailureCausesGeneric);
Plots.DataChapter.FailureCausesGeneric = addcats(Plots.DataChapter.FailureCausesGeneric,...
    {'External','Unknown','Missing data'});
Plots.DataChapter.FailureCausesGeneric = reordercats(Plots.DataChapter.FailureCausesGeneric,...
    {'Human','Natural','Technical','External','Unknown','Missing data'});

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% MISSING OR BAD PARAMETERS
[NrRows,~] = size(PowerDist.Data);
MissingParameters = zeros(NrRows,15);
MissingParameters(PowerDist.Data.InterruptionType==FillValueCategorical,2) = 1;
MissingParameters(isnat(PowerDist.Data.StartDate)==1,3) = 1;
MissingParameters(isnat(PowerDist.Data.StartTime)==1,4) = 1;
MissingParameters(isnat(PowerDist.Data.EndDate)==1 | year(PowerDist.Data.EndDate)>2016,5) = 1;
MissingParameters(isnat(PowerDist.Data.EndTime)==1,6) = 1;
MissingParameters(PowerDist.Data.DisconnectingSite==FillValueCategorical,10) = 1;
MissingParameters(PowerDist.Data.FailureSite==FillValueCategorical,11) = 1;
MissingParameters(PowerDist.Data.Network==FillValueCategorical,12) = 1;
MissingParameters(PowerDist.Data.InstallationComponent==FillValueCategorical,13) = 1;
MissingParameters(PowerDist.Data.FailureCause==FillValueCategorical,14) = 1;
MissingParameters(:,15) = 1:NrRows; % the ID of the interruption

MissingParameters(:,1) = sum(MissingParameters(:,2:14),2);
MissingParametersTot = MissingParameters(:,1);
MissingParametersTot = categorical(MissingParametersTot);

%% CREATE TABLES FOR THE FAILURE CAUSES AND MISSING PARAMETERS
% SO THAT WE LATER CAN MAKE (BAR) PLOTS
NrYears = 11;
ForEndLoop = 2005:2015;
for Yr=ForEndLoop
    if Yr==ForEndLoop(1)
        VarNum = str2num(cell2mat(categories(MissingParametersTot))); NrNumbers = size(VarNum,1); %ok<ST2NM>
        Plots.DataChapter.MissingDataAnnual...
            = table;
        Categories = categories(Plots.DataChapter.FailureCausesGeneric); NrCategories = 6;
        Plots.DataChapter.FailureCausesAnnual...
            = table;
        for Variable = 1:NrNumbers
            Plots.DataChapter.MissingDataAnnual.(num2words(VarNum(Variable,1))) ...
                = zeros(NrYears,1);
        end
        for FailureCause= 1:NrCategories
            Plots.DataChapter.FailureCausesAnnual.(strrep(Categories{FailureCause,1},' ','_')) ...
                = zeros(NrYears,1);
        end
        Plots.DataChapter.MissingDataAnnual.Properties.RowNames...
            = YEAR;
        Plots.DataChapter.FailureCausesAnnual.Properties.RowNames...
            = YEAR;
    end
    Y = string(Yr);
    YR = Yr-ForEndLoop(1)+1; %making first year = 1

    Plots.DataChapter.MissingDataAnnual{YR,:} ...
        = transpose(countcats(MissingParametersTot(year(PowerDist.Data.StartDate)==Yr)));
    Plots.DataChapter.FailureCausesAnnual{YR,:} ...
        = transpose(countcats(Plots.DataChapter.FailureCausesGeneric(year(PowerDist.Data.StartDate)==Yr)));
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% SAVE AND SAVE AND SAVE
PowerDist.Metrics = Metrics;
PowerDist.Plots = Plots;
PowerDist.DataTreatment = DataTreatment;

% create a table that shows infrastructure-specific info on where data spans in time
PowerDist.Metrics.FailureCause = PowerDist.Plots.DataChapter.FailureCausesGeneric(ToUse);
PowerDist.TotalDuration = table;
PowerDist.TotalDuration.Start = datetime([2005 01 01]);
PowerDist.TotalDuration.End = datetime([2015 12 31]);
PowerDist.TotalDuration.DurationT = PowerDist.TotalDuration.End - PowerDist.TotalDuration.Start;
PowerDist.TotalDuration.End.Format = 'yyyy-MM-dd HH:mm';
PowerDist.TotalDuration.Start.Format = 'yyyy-MM-dd HH:mm';
PowerDist.TotalDuration.DurationMin = minutes(PowerDist.TotalDuration.DurationT);
%%
clearvars -except PowerDist

save 'SAVEPATH/ALL.mat'

```

## A 2. CHAPTER 4, DATA PRESENTATION

### A 2.1. FAILURE CAUSE, BAR PLOTS

```
%% CHAPTER 04 - FAILURE CAUSE PLOTS
clear;clc;close all;
load('MATFILEPATH/ALL.mat', 'General')
%%
PicFilePathOneDrive = 'PICFILEPATH/04 Data presentation and background/';
Infrastructures = {'Svk','Energiforetagen','Road','Train','SVOA','TelecomAll','KoV'};

fLineWidth = 2.0;
strLineStyle = '-'; % [(Jahre & Fabbe-Costes) | -- | : | -.]
iMarkerSize = 25; % in points
strMarkerType = '.'; % [+ | o | * | . | x | square | diamond | > | < | ^ | v | pentagram | hexagram | {none}]
afMarkerFaceColor = [0.1 0.1 0.1];
afMarkerEdgeColor = [0.3 0.3 0.3];
afFigurePosition = [1 1 50 20]; % [pos_x pos_y width_x width_y]
afColorMap = General.PlotSettings.ColormapBone; % [left bottom width height]
% fonts properties
iFontSize = 20;
strFontUnit = 'points'; % [{points} | normalized | inches | centimeters | pixels]
strFontName = 'Helvetica'; % [Times | Courier | ] TODO complete the list
strFontWeight = 'normal'; % [light | {normal} | demi | bold]
strFontAngle = 'normal'; % [{normal} | italic | oblique] ps: only for axes
strInterpreter = 'tex';

% the two figure's positions in the unified bigger figure
Position1 = [0.0540 0.1534 0.3804 0.7985];
Position2 = [0.4922 0.1534 0.4935 0.7985];
%% GenericFailureCausesBar

% type FinalVersion = 'Yes!' to save a PNG picture file to
% the location given by PicFilePathOneDrive
FinalVersion = 'NEJ FOR FAN';

for k = 1:7

    Infrastructure = Infrastructures{k};
    saveTitle = 'Generic Failure Causes Bar';
    strTitle = [saveTitle ' - ' Infrastructure];

    Infrastructure = Infrastructures{k};
    variableValue = load('MATFILEPATH/ALL.mat',Infrastructure);
    % TEST TO PLOT THE FAILURES OVER TIME
    DataToPlot = variableValue.(Infrastructure).Plots.DataChapter.FailureCausesGeneric;
    DataToPlot = setcats(DataToPlot,{'Human';'Natural';'Technical';'External';'Unknown';'Missing data'});
    DataToPlot = reordercats(DataToPlot,{'Human';'Natural';'Technical';'External';'Unknown';'Missing data'});
    afX1 = categorical(categories(DataToPlot));

    afX1 = reordercats(afX1,{'Human';'Natural';'Technical';'External';'Unknown';'Missing data'});
    afY1 = countcats(DataToPlot);

    figuregcf = figure('Name',strTitle);

    figuregcal = gca;
    figuregcal.Position = Position1;

    strYLabel = 'Count';

    handleToPlot1 = bar(afX1, afY1, 'FaceColor','flat');%,...

    % set the different 'FaceColours' of the stacked bars
    handleToPlot1.CData = [1,1,1;0.761284722222222,0.847222222222222,0.847222222222222;...
        0.569444444444444,0.663194444444444,0.694444444444444;...
        0.430555555555556,0.472222222222222,0.555555555555556;...
        0.277777777777778,0.277777777777778,0.387152777777778;...
        0.125000000000000,0.125000000000000,0.177083333333333];
    set(handleToPlot1, 'FaceAlpha', 0.8000,...
        'EdgeColor', afColorMap(15,:),...
        'LineWidth', 1.3,...
        'BarWidth', 0.7 );

    set(figuregcf, 'Units', 'centimeters',... % [ inches | {centimeters} | normalized | points | !?(pixels)?! | charac-
ters ]
        'Position', afFigurePosition,...
        'PaperPositionMode', 'auto');

    figuregcal.YLim(2) = figuregcal.YLim(2)*1.15;
    set(figuregcal,
        'XGrid', 'on', ... [on | {off}]
        'YGrid', 'on', ... [on | {off}]
        'GridLineStyle', ':', ... [- | -- | {:} | -. | none]
        'XMinorGrid', 'off', ... [on | {off}]
        'YMinorGrid', 'off', ... [on | {off}]
        'MinorGridLineStyle', ':', ... [- | -- | {:} | -. | none]
        'XTickMode', 'Auto', ...
        'YMinorTick', 'off', ... [on | {off}]
        'TickDir', 'out', ... [{in} | out] inside or outside (for 2D)
        'TickLength', [.005 .005], ... length of the ticks
        'XColor', [.1 .1 .1], ... color of x axis
        'YColor', [.1 .1 .1], ... color of y axis
        'XAxisLocation', 'bottom', ... where labels have to be printed [top | {bottom}]
        'YAxisLocation', 'left', ... where labels have to be printed [{left} | right]
        'XDir', 'normal', ... axis increasement direction [{normal} | reverse]
        'YDir', 'normal', ... axis increasement direction [{normal} | reverse]
        'FontName', strFontName, ... kind of fonts of labels
        'FontSize', iFontSize, ... size of fonts of labels
        'FontUnits', strFontUnit, ... units of the size of fonts
```

```

        'FontWeight',      strFontWeight,    ... weight of fonts of labels
        'FontAngle',      strFontAngle,     ... inclination of fonts of labels
        'LineWidth',      fLineWidth);

figuregca1.TitleFontSizeMultiplier = 1.25;
fXLabelRotation = 0.0;
fYLabelRotation = 90.0;

ylabel( strYLabel,
        'FontName',      strFontName,      ...
        'FontUnit',      strFontUnit,      ...
        'FontSize',      iFontSize,        ...
        'FontWeight',    strFontWeight,    ...
        'Interpreter',   strInterpreter);

%
set(get(gca, 'XLabel'), 'Rotation', fXLabelRotation);
set(get(gca, 'YLabel'), 'Rotation', fYLabelRotation);

%%
% PLOT THE FAILURE CAUSES OVER TIME
DataToPlot = variableValue.(Infrastructure).Plots.DataChapter.FailureCausesAnnual;

% we need size of two times the incidents, one gives the start and one
% gives the end.
% PLOT STEM
Categories = {'Human'; 'Natural'; 'Technical'; 'External'; 'Unknown'; 'Missing data'};
[NrYears, ~] = size(DataToPlot);
VarNames = string(DataToPlot.Properties.RowNames);

afX2 = categorical(VarNames);
afY2 = DataToPlot{:, :};

strXLabel = 'Year';
strYLabel = 'Count';
afX2 = categorical(afX2);
barwidth = 0.8/12*NrYears;

figuregca2 = subplot('Position', Position2);
[m, ~] = size(afColorMap);
handleToPlot2 = bar(afX2, afY2, 'stacked');

for l=1:6
    handleToPlot2(l).FaceColor = afColorMap(floor(((6-l+1)/(6))*m), :);
    handleToPlot2(l).FaceAlpha = 0.9000;
    handleToPlot2(l).EdgeColor = afColorMap(15, :);
    handleToPlot2(l).LineWidth = 1.3;
    handleToPlot2(l).LineWidth = 1.3;
    handleToPlot2(l).BarWidth = barwidth;
end

figuregca2.YLim(2) = figuregca2.YLim(2)*1.15;
set(figuregca2,
    'XGrid',      'on',      ... [on | {off}]
    'YGrid',      'on',      ... [on | {off}]
    'GridLineStyle', ':',    ... [- | -- | {:} | -. | none]
    'XMinorGrid', 'off',     ... [on | {off}]
    'YMinorGrid', 'off',     ... [on | {off}]
    'MinorGridLineStyle', ':', ... [- | -- | {:} | -. | none]
    'XTick',      afX2,      ... ticks of x axis
    'YTickLabel', num2cell(figuregca2.YTick), ...
    'YMinorTick', 'off',     ... [on | {off}]
    'TickDir',    'out',     ... [{in} | out] inside or outside (for 2D)
    'TickLength', [.005 .005], ... length of the ticks
    'XColor',     [.1 .1 .1], ... color of x axis
    'YColor',     [.1 .1 .1], ... color of y axis
    'XAxisLocation', 'bottom', ... where labels have to be printed [top | {bottom}]
    'YAxisLocation', 'left',  ... where labels have to be printed [{left} | right]
    'XDir',       'normal',   ... axis increasement direction [{normal} | reverse]
    'YDir',       'normal',   ... axis increasement direction [{normal} | reverse]
    'FontName',   strFontName, ... kind of fonts of labels
    'FontSize',   iFontSize,   ... size of fonts of labels
    'FontUnits',  strFontUnit, ... units of the size of fonts
    'FontWeight', strFontWeight, ... weight of fonts of labels
    'FontAngle',  strFontAngle, ... inclination of fonts of labels
    'LineWidth',  fLineWidth);

fXLabelRotation = 0.0;
fYLabelRotation = 90.0;

%
xlabel( strXLabel,
        'FontName',      strFontName,      ...
        'FontUnit',      strFontUnit,      ...
        'FontSize',      iFontSize,        ...
        'FontWeight',    strFontWeight,    ...
        'Interpreter',   strInterpreter);

%
set(get(figuregca2, 'XLabel'), 'Rotation', fXLabelRotation);
set(get(figuregca2, 'YLabel'), 'Rotation', fYLabelRotation);

atArrayOfHandlesToLines = strTitle;

%See general properties above
astrArrayOfLabels = {'Human'; 'Natural'; 'Technical'; 'External'; 'Unknown'; 'Missing data'};

% - N = North
% - S = South
% - E = East
% - W = West
% - O = Outside the plot
% - B = Best (least conflict with data in plot)
strLegendLocation = 'N'; % combinations of N S E W B O or a vector

strLegendOrientation = 'horizontal'; % [{vertical} horizontal]

%
afEdgeColor = [1.0 1.0 1.0]; % RGB
afTextColor = [0.0 0.0 0.0]; % RGB

%
strInterpreter = 'tex'; % [{tex} | latex | none]

%
legend(atArrayOfHandlesToLines,
    astrArrayOfLabels,
    'Orientation', strLegendOrientation, ...

```

```

'Box',          'off',          ... [on {off}]
'Color',        afEdgeColor,    ... none => transparent
'EdgeColor',    afEdgeColor,    ...
'TextColor',    afTextColor,    ...
'FontSize',     iFontSize-2);

% if FinalVersion = 'Yes!' above, the figures are saved as PNG picture
% files in the location given by PicFilePathOneDrive
PicFileDirNameOneDrive= [PicFilePathOneDrive, '/', saveTitle, '/', saveTitle ' ' Infrastructure, '.png'];
if strcmp(FinalVersion, 'Yes!')==1
    %mkdir([PicFilePathLocal, '/', strTitle, '/'])
    mkdir([PicFilePathOneDrive, '/', saveTitle, '/'])
    saveas(figure(gcf), PicFileDirNameOneDrive)
end

end

```

## A 2.2.MISSING PARAMETERS, STACKED BAR PLOTS

```

%% CHAPTER 04 - MISSING PARAMETERS STACKED ANNUALLY
clear;clc;close all;

MatFilePath      = 'MATFILEPATH/ALL.mat';
PicFilePathOneDrive = 'PICFILEPATH/04 Data presentation and background/';
Infrastructures   = {'SvK', 'Energiforetagen', 'Road', 'Train', 'SVOA'};
AnnualDevelopmentRowNames = {'2005', '2006', '2007', '2008', '2009', '2010', '2011', '2012', '2013', '2014', '2015', '2016', '2017'};
YEAR             = 2005:2017;
General          = load(MatFilePath, 'General');
General          = General.General;

%% 1 GENERAL SETTINGS

% type FinalVersion = 'Yes!' to save a PNG picture file to
% the location given by PicFilePathOneDrive
FinalVersion = 'Yes!';

for k = 1:5
    % TITLE!!!!
    Infrastructure = Infrastructures{k};
    saveTitle     = 'Missing Parmaters Stacked annually';
    strTitle      = [saveTitle ' - ' Infrastructure];

    PreData      = load(MatFilePath, Infrastructure);
    DataToPlot   = PreData.(Infrastructure).Plots.DataChapter.MissingDataAnnual;
    VariableNames = DataToPlot.Properties.VariableNames;
    Years        = DataToPlot.Properties.RowNames;

    MissingDataAnnual = table;
    for VarName       = 1:size(VariableNames,2)
        MissingDataAnnual.(VariableNames{VarName}) = zeros(13,1);
    end
    MissingDataAnnual.Properties.RowNames = AnnualDevelopmentRowNames;
    for Yr                               = 1:size(Years,1)
        Year                             = str2double(Years(Panteli et al.));
        MissingDataAnnual{Year-2005+1,:} = DataToPlot{Yr,:};
    end

    %CREATE THE FIGURE TO SEE THE PROGRESS OF THE CODE
    figure(gcf) = figure('Name', [strTitle ' ', ' Infrastructure']);
    figure(gca) = gca;

    strXLabel   = 'Year';
    strYLabel   = 'Count';

    afX1        = 2005:2017;
    afY1        = MissingDataAnnual{:, :};

    %% SET GENERAL PLOT PROPERTIES
    % we set the plots properties

    % plots properties
    fLineWidth      = 2.0;
    strLineStyle     = '-'; % [(Jahre & Fabbe-Costes) | -- | : | -.]
    iMarkerSize     = 25; % in points
    strMarkerType    = '.'; % [+ | o | * | . | x | square | diamond | > | < | ^ | v | pentagram | hexagram | {none}]
    afMarkerFaceColor = [0.1 0.1 0.1];
    afMarkerEdgeColor = [0.3 0.3 0.3];
    afFigurePosition = [10 10 35 15]; % [pos_x pos_y width_x width_y]
    afAxesPosition   = [2.841111111111111 2.374459027777777 31.71472222222222 11.75554097222222];
    afColorMap       = General.PlotSettings.ColormapBone; % [left bottom width height]
    % fonts properties
    iFontSize        = 18;
    strFontUnit      = 'points'; % [{points} | normalized | inches | centimeters | pixels]
    strFontName      = 'Helvetica'; % [Times | Courier | ] TODO complete the list
    strFontWeight    = 'normal'; % [light | {normal} | demi | bold]
    strFontAngle     = 'normal'; % [{normal} | italic | oblique] ps: only for axes
    strInterpreter   = 'tex'; % [{tex} | latex]

    astrArrayOfLabels = {'None';...
        'One ';...
        'Two ';...
        'Three ';...
        'Four ';...
        'Five ';...
        'Six '};

    LegendLocations = {'NE', 'NE', 'NW', 'NW', 'NW'};
    strLegendLocation = LegendLocations{k}; % combinations of N S E W B O or a vector
    strLegendOrientation = 'vertical'; % [{vertical} horizontal]
    iLegendFontSize    = 16;
    afEdgeColor        = [1.0 1.0 1.0]; % RGB
    afTextColor        = [0.0 0.0 0.0]; % RGB

    %% PLOT AND CHOOSE SETTINGS TO USE, MARK WITH % WHEN SETTING IS NOT WANTED

    % here you can plot several plots (each can have its properties)
    % note: it is convenient to store the handles to the single plots

```

```

% in order to easily manage legends
%
[~,n] = size(afY1);
[m,~] = size(afColorMap);

% takes values in equal steps from colorcode-matric depending on number
% of categories = n

handleToPlot1 = bar(afX1, afY1, 'stacked');
for p=1:n
    handleToPlot1(p).FaceColor = afColorMap(floor(((n-p+1)/(n))*m),:);
    handleToPlot1(p).FaceAlpha = 0.9000;
    handleToPlot1(p).EdgeColor = afColorMap(15,:);
    handleToPlot1(p).LineWidth = 1.3;
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

set(gcf, 'Units', 'centimeters',... % [ inches | {centimeters} | normalized | points | !?(pixels)?! | characters ]
'Position', aFigurePosition,...
'PaperPositionMode', 'auto'); %

%% 3 SET AXES
set(gca,
'Units', 'centimeters', ...
'Position', afAxesPosition, ...
'XGrid', 'on', ... [on | {off}]
'YGrid', 'on', ... [on | {off}]
'GridLineStyle', ':', ... [- | -- | {:} | -. | none]
'XMinorGrid', 'off', ... [on | {off}]
'YMinorGrid', 'off', ... [on | {off}]
'MinorGridLineStyle', ':', ... [- | -- | {:} | -. | none]
'XTick', afX1, ... ticks of x axis
'YMinorTick', 'off', ... [on | {off}]
'TickDir', 'out', ... [{in} | out] inside or outside (for 2D)
'TickLength', [.005 .005], ... length of the ticks
'XColor', [.1 .1 .1], ... color of x axis
'YColor', [.1 .1 .1], ... color of y axis
'XAxisLocation', 'bottom', ... where labels have to be printed [top | {bottom}]
'YAxisLocation', 'left', ... where labels have to be printed [{left} | right]
'XDir', 'normal', ... axis increase direction [{normal} | reverse]
'YDir', 'normal', ... axis increase direction [{normal} | reverse]
'XLim', [2004.5 2017.5], ... limits for the x-axis
'FontName', strFontName, ... kind of fonts of labels
'FontSize', iFontSize, ... size of fonts of labels
'FontUnits', strFontUnit, ... units of the size of fonts
'FontWeight', strFontWeight, ... weight of fonts of labels
'FontAngle', strFontAngle, ... inclination of fonts of labels
'LineWidth', fLineWidth, % width of the line of the axes

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% 4 SET AXES LABELS
fYLabelRotation = 90.0;
%
xlabel( strXLabel, ...
'FontName', strFontName, ...
'FontUnit', strFontUnit, ...
'FontSize', iFontSize, ...
'FontWeight', strFontWeight, ...
'Interpreter', strInterpreter);
%
ylabel( strYLabel, ...
'FontName', strFontName, ...
'FontUnit', strFontUnit, ...
'FontSize', iFontSize, ...
'FontWeight', strFontWeight, ...
'Interpreter', strInterpreter);
%
set(get(gca, 'XLabel'), 'Rotation', fXLabelRotation);
set(get(gca, 'YLabel'), 'Rotation', fYLabelRotation);

atArrayOfHandlesToLines = strTitle;
%See general properties above

strInterpreter = 'tex'; % [{tex} | latex | none]
%
legend( atArrayOfHandlesToLines, ...
astrArrayOfLabels, ...
'Location', strLegendLocation, ...
'Orientatation', strLegendOrientation, ...
'Box', 'off', ... [on {off}]
'Color', afEdgeColor, ... none => transparent
'EdgeColor', afEdgeColor, ...
'TextColor', afTextColor, ...
'Interpreter', strInterpreter, ...
'FontSize', iLegendFontSize );

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% if FinalVersion = 'Yes!' above, the figures are saved as PNG picture
% files in the location given by PicFilePathOneDrive
PicFileDirNameOneDrive= [PicFilePathOneDrive, '/', saveTitle, '/', saveTitle ' ' Infrastructure, '.png'];
if strcmp(FinalVersion, 'Yes!')==1
    mkdir([PicFilePathLocal, '/', strTitle, '/'])
    mkdir([PicFilePathOneDrive, '/', saveTitle, '/'])
    saveas(figure(gcf), PicFileDirNameOneDrive)
end

end

```



## A 2.3.USABILITY CALCULATIONS – PRE/POST DATA TREATMENT

```

%% DATA QUALITY CALC - RESILIENCE PARAMETERS
clear;clc;close all;

MatFilePath           = 'MATFILEPATH/ALL.mat';
Infrastructures        = {'SvK','Energiforetagen','Road','Train','SVOA','TelecomAll','IP','FixedPhone','Mobile'};
InfrastructureTitles  = {'Electricity transmission',...
    'Electricity distribution',...
    'Transport Road',...
    'Transport Railway',...
    'Drinking water network',...
    'Telecommunication',...
    'Telecommunication IP based',...
    'Telecommunication fixed phone',...
    'Telecommunication mobile'};

DateTimeFormat        = 'yyyy-MM-dd HH:mm';
AnnualDevelopmentRowNames = {'2005','2006','2007','2008','2009','2010','2011','2012','2013','2014','2015','2016','2017'};
rownames              = {'Valid data','Value is zero','Unusable data'};

%% MAKE TABLES FOR THE PLOT DATA!
for k=1:9
    disp(num2str(k))
    Infrastructure           = Infrastructures{k};
    InfrastructureTitle      = InfrastructureTitles{k};
    VarName                 = load(MatFilePath,Infrastructure);
    PreDataTreatment        = VarName.(Infrastructure).DataTreatment.PreDataTreatment;
    PostDataTreatment       = VarName.(Infrastructure).DataTreatment.PostDataTreatment;
    TreatedData             = VarName.(Infrastructure).DataTreatment.TreatedData;
    Data                    = VarName.(Infrastructure).Data;
    NrIncidents             = size(Data,1);

    % make tables and allocate space
    DataQualityTables.(Infrastructure).PreDataTreatment = table;
    DataQualityTables.(Infrastructure).PostDataTreatment = table;
    DataQualityTables.(Infrastructure).AnnualDevelopmentPre = table;
    DataQualityTables.(Infrastructure).AnnualDevelopmentPost = table;

    % Pre-Data Treatment
    % Annual Development
    DataQualityTables.(Infrastructure).AnnualDevelopmentPre.Valid = zeros(13,1);
    DataQualityTables.(Infrastructure).AnnualDevelopmentPre.Zero = zeros(13,1);
    DataQualityTables.(Infrastructure).AnnualDevelopmentPre.Unusable = zeros(13,1);
    DataQualityTables.(Infrastructure).AnnualDevelopmentPre.Properties.RowNames = AnnualDevelopmentRowNames;

    % Data Treatment
    DataQualityTables.(Infrastructure).PreDataTreatment.Total = zeros(3,1);
    DataQualityTables.(Infrastructure).PreDataTreatment.Duration = zeros(3,1);
    DataQualityTables.(Infrastructure).PreDataTreatment.Consequence = zeros(3,1);
    DataQualityTables.(Infrastructure).PreDataTreatment.Properties.RowNames = rownames;

    % Post-Data Treatment
    % Annual Development
    DataQualityTables.(Infrastructure).AnnualDevelopmentPost.Valid = zeros(13,1);
    DataQualityTables.(Infrastructure).AnnualDevelopmentPost.Zero = zeros(13,1);
    DataQualityTables.(Infrastructure).AnnualDevelopmentPost.Unusable = zeros(13,1);
    DataQualityTables.(Infrastructure).AnnualDevelopmentPost.Properties.RowNames = AnnualDevelopmentRowNames;

    % Data Treatment
    DataQualityTables.(Infrastructure).PostDataTreatment.Total = zeros(3,1);
    DataQualityTables.(Infrastructure).PostDataTreatment.Duration = zeros(3,1);
    DataQualityTables.(Infrastructure).PostDataTreatment.Consequence = zeros(3,1);
    DataQualityTables.(Infrastructure).PostDataTreatment.Properties.RowNames = rownames;

    %% Pre-Data Treatment
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    % Annual Development
    ZeroPre = PreDataTreatment.ZeroDuration | PreDataTreatment.ZeroConsequences;
    for YR = 2005:2017
        Yr = YR-2004;
        DataQualityTables.(Infrastructure).AnnualDevelopmentPre.Valid(Yr) = ...
            sum(any(PreDataTreatment{year(Data.Start_DT)==YR,:},2)==0);
        DataQualityTables.(Infrastructure).AnnualDevelopmentPre.Zero(Yr) = ...
            sum(ZeroPre(year(Data.Start_DT)==YR));
        DataQualityTables.(Infrastructure).AnnualDevelopmentPre.Unusable(Yr) = ...
            sum(any(PreDataTreatment{year(Data.Start_DT)==YR,:},2) & ZeroPre(year(Data.Start_DT)==YR)==0);
    end
    % Data consist either of:
    % (1 - Valid data
    % (2 - Value is zero
    % (3 - Unusable data

    % Total
    DataQualityTables.(Infrastructure).PreDataTreatment.Total(1)... (1 - Valid data
        = sum(any(PreDataTreatment{:,1:6},2)==0);
    DataQualityTables.(Infrastructure).PreDataTreatment.Total(2)... (2 - Value is zero
        = sum(PreDataTreatment.ZeroDuration |...
            PreDataTreatment.ZeroConsequences);
    DataQualityTables.(Infrastructure).PreDataTreatment.Total(3)... (3 - Unusable data
        = sum(any(PreDataTreatment{:,1:6},2) & ZeroPre==0);

    if sum(DataQualityTables.(Infrastructure).PreDataTreatment.Total)~=NrIncidents
        disp(['someehing is crazy witt predatatreatment . ' InfrastructureTitle])
    end

    %Duration
    DataQualityTables.(Infrastructure).PreDataTreatment.Duration(1)... (1 - Valid data
        = sum(PreDataTreatment.MissingDuration==0 & ...
            PreDataTreatment.ZeroDuration==0 & ...
            PreDataTreatment.UnrealDuration==0);
    DataQualityTables.(Infrastructure).PreDataTreatment.Duration(2)... (2 - Value is zero
        = sum(PreDataTreatment.ZeroDuration);

    %Consequences
    DataQualityTables.(Infrastructure).PreDataTreatment.Consequence(1)... (1 - Valid data

```

```

= sum(PreDataTreatment.MissingConsequences==0 &...
      PreDataTreatment.ZeroConsequences==0 &...
      PreDataTreatment.UnrealConsequences==0);
DataQualityTables.(Infrastructure).PreDataTreatment.Consequence(2)... (2 - Value is zero
= sum(PreDataTreatment.ZeroConsequences);

%% Post-Data Treatment
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Annual Development
ZeroPost = PostDataTreatment.ZeroDuration | PostDataTreatment.ZeroConsequences;
for YR = 2005:2017
    Yr = YR-2004;
    DataQualityTables.(Infrastructure).AnnualDevelopmentPost.Valid(Yr)...
        = sum(any(PostDataTreatment{year(TreatedData.Start_DT)==YR,:},2)==0);
    DataQualityTables.(Infrastructure).AnnualDevelopmentPost.Zero(Yr)...
        = sum(ZeroPost{year(TreatedData.Start_DT)==YR,:});
    DataQualityTables.(Infrastructure).AnnualDevelopmentPost.Unusable(Yr)...
        = sum(any(PostDataTreatment{year(TreatedData.Start_DT)==YR,:},2) & ZeroPost{year(Treated-
Data.Start_DT)==YR,:}==0);
end

% Data consist either of:
% (1 - Valid data
% (2 - Value is zero
% (3 - Unusable data

% Total
DataQualityTables.(Infrastructure).PostDataTreatment.Total(1)... (1 - Valid data
= sum(any(PostDataTreatment{:,2})==0);
DataQualityTables.(Infrastructure).PostDataTreatment.Total(2)... (2 - Value is zero
= sum(PostDataTreatment.ZeroDuration |...
      PostDataTreatment.ZeroConsequences);
DataQualityTables.(Infrastructure).PostDataTreatment.Total(3)... (3 - Unusable data
= sum(any(PostDataTreatment{:,2}) & ZeroPost==0);

if sum(DataQualityTables.(Infrastructure).PostDataTreatment.Total)~=NrIncidents
    disp(['someehing is crazy witt postdatatreatment . ' InfrastructureTitle])
end
%Duration
DataQualityTables.(Infrastructure).PostDataTreatment.Duration(1)... (1 - Valid data
= sum(PostDataTreatment.MissingDuration==0 &...
      PostDataTreatment.ZeroDuration==0 &...
      PostDataTreatment.UnrealDuration==0);
DataQualityTables.(Infrastructure).PostDataTreatment.Duration(2)... (2 - Value is zero
= sum(PostDataTreatment.ZeroDuration);

%Consequences
DataQualityTables.(Infrastructure).PostDataTreatment.Consequence(1)... (1 - Valid data
= sum(PostDataTreatment.MissingConsequences==0 &...
      PostDataTreatment.ZeroConsequences==0 &...
      PostDataTreatment.UnrealConsequences==0);
DataQualityTables.(Infrastructure).PostDataTreatment.Consequence(2)... (3 - Value is zero
= sum(PostDataTreatment.ZeroConsequences);

end

clearvars -except DataQualityTables General
save('MATFILEPATH/DataQuality.mat')

```

## A 2.4.DATA QUALITY ASSESSMENT STACKED BAR PLOTS, PRE-DATA TREATMENT

```

%% CHAPTER 04 - Pre-DATA TREATMENT QUALITY PLOTS
% FAILURE CAUSE PLOTS
clear;clc;close all;
load('MATFILEPATH/ALL.mat','General')
load('MATFILEPATH/DataQuality')

Infrastructures = {'SvK','Energiforetagen','Road','Train','SVOA','TelecomAll'};
YEARS = [2005,2006,2007,2008,2009,2010,2011,2012,2013,2014,2015,2016,2017];

%% Pre Data Treatment
PicFilePathOneDrive = 'PICFILEPATH/Thesis Parts/04 Data presentation and background/Figures';
saveTitle = 'DataQuality Untreated data';

% type FinalVersion = 'Yes!' to save a PNG picture file to
% the location given by PicFilePathOneDrive
FinalVersion = 'Njaaeee, typ inte';
for k = 1:6

    %PLOT SETTINGS
    fLineWidth = 2.0;
    strLineStyle = '-'; % [(Jahre & Fabbe-Costes) | -- | : | -.]
    iMarkerSize = 25; % in points
    iMarkerType = '+'; % [+ | o | * | . | x | square | diamond | > | < | ^ | v | pentagram | hexagram | (none)]
    afMarkerFaceColor = [0.1 0.1 0.1];
    afMarkerEdgeColor = [0.3 0.3 0.3];
    afFigurePosition = [10 10 35 25]; % [pos_x pos_y width_x width_y]
    Fig1Position = [0.0800 0.5838 0.850 0.3800];
    Fig2Position = [0.0800 0.0900 0.4200 0.4000];
    afColorMap = General.PlotSettings.ColormapBone; % [left bottom width height]
    % fonts properties
    iFontSize = 18;
    strFontUnit = 'points'; % [{points} | normalized | inches | centimeters | pixels]
    strFontName = 'Helvetica'; % [Times | Courier | ] TODO complete the list
    strFontWeight = 'normal'; % [light | normal | demi | bold]
    strFontAngle = 'normal'; % [{normal} | italic | oblique] ps: only for axes

    BarColours = [afColorMap(62,:);... valid
                  afColorMap(46,:);... zero
                  afColorMap(13,:); %unusable

    BarWidth1 = 0.5;
    BarWidth2 = 0.4;

```

```

Infrastructure = Infrastructures(k);
strTitle      = [saveTitle ' - ' Infrastructure];

DataToPlot1   = DataQualityTables.(Infrastructure).AnnualDevelopmentPre;
DataToPlot2   = DataQualityTables.(Infrastructure).PreDataTreatment;
DataToPlot3   = DataQualityTables.(Infrastructure).AnnualDevelopmentPost;
DataToPlot4   = DataQualityTables.(Infrastructure).PostDataTreatment;

% Pre-Data Treatment
% Annual Development
afX1          = YEARS;
afY1          = DataToPlot1{:, :};
%strX1Label    = 'Year';
strY1Label    = 'Count';
% Data Treatment
afX2          = reordercats(categorical(DataToPlot2.Properties.VariableNames), [3 2 1]);
afY2          = transpose(DataToPlot2{:, :});
strX2Label    = 'Untreated data';
strY2Label    = 'Count';

figuregcf     = figure('Name', strTitle, ...
    'Units', 'centimeters', ... % [ inches | {centimeters} | normalized | points | !?{pixels}?! | characters ]
    'Position', afFigurePosition, ...
    'PaperPositionMode', 'auto'); %
ax1           = subplot(2,2,[1 2]);
handleToPlot1 = bar(afX1, afY1, 'stacked');
figuregcal    = gca;
objects       = get(figuregcf);
handles1      = get(handleToPlot1);
figuregcal.Position = Fig1Position;

for h=1:3
    handleToPlot1(h).FaceColor = BarColours(h,:);
    handleToPlot1(h).FaceAlpha = 0.9000;
    handleToPlot1(h).EdgeColor = afColorMap(15,:);
    handleToPlot1(h).LineWidth = 1.1;
    handleToPlot1(h).BarWidth = BarWidth1;
end

figuregcal.YLim(2) = figuregcal.YLim(2)*1.1;
set(figuregcal, ...
    'XGrid', 'on', ... [on | {off}]
    'YGrid', 'on', ... [on | {off}]
    'GridLineStyle', ':', ... [- | -- | {:} | -. | none]
    'XMinorGrid', 'off', ... [on | {off}]
    'YMinorGrid', 'off', ... [on | {off}]
    'MinorGridLineStyle', ':', ... [- | -- | {:} | -. | none]
    'YMinorTick', 'off', ... [on | {off}]
    'TickDir', 'out', ... [{in} | out] inside or outside (for 2D)
    'TickLength', [.005 .005], ... length of the ticks
    'XColor', [.1 .1 .1], ... color of x axis
    'YColor', [.1 .1 .1], ... color of y axis
    'XAxisLocation', 'bottom', ... where labels have to be printed [top | {bottom}]
    'YAxisLocation', 'left', ... where labels have to be printed [{left} | right]
    'XDir', 'normal', ... axis increasement direction [{normal} | reverse]
    'YDir', 'normal', ... axis increasement direction [{normal} | reverse]
    'XLim', [afX1(1)-.5 afX1(end)+.5], ... limits for the x-axis
    'FontName', strFontName, ... kind of fonts of labels
    'FontSize', iFontSize, ... size of fonts of labels
    'FontUnits', strFontUnit, ... units of the size of fonts
    'FontWeight', strFontWeight, ... weight of fonts of labels
    'FontAngle', strFontAngle, ... inclination of fonts of labels
    'LineWidth', fLineWidth);

fXLabelRotation = 0.0;
fYLabelRotation = 90.0;
strInterpreter = 'tex';
%
ylabel( strY1Label, ...
    'FontName', strFontName, ...
    'FontUnit', strFontUnit, ...
    'FontSize', iFontSize, ...
    'FontWeight', strFontWeight, ...
    'Interpreter', strInterpreter);

%
set(get(gca, 'XLabel'), 'Rotation', fXLabelRotation);
set(get(gca, 'YLabel'), 'Rotation', fYLabelRotation);

atArrayOfHandlesToLines = strTitle;

%See general properties above
astrArrayOfLabels = {'Valid data','Value is zero','Unusable data',};

% - N = North
% - S = South
% - E = East
% - W = West
% - O = Outside the plot
% - B = Best (least conflict with data in plot)
strLegendLocation = {'NE','NE','NW','NW','NE','NW','NW','NW'}; % combinations of N S E W B O or a vector

strLegendOrientation = 'vertical'; % [{vertical} horizontal]
%
afEdgeColor = [1.0 1.0 1.0]; % RGB
afTextColor = [0.0 0.0 0.0]; % RGB
%
% [{tex} | latex | none]
%
legend( atArrayOfHandlesToLines, ...
    astrArrayOfLabels, ...
    'Location', strLegendLocation{k}, ...
    'Orientation', strLegendOrientation, ...
    'Box', 'on', ... [on {off}]
    'Color', afEdgeColor, ... none => transparent
    'EdgeColor', afEdgeColor, ...
    'TextColor', afTextColor, ...
    'FontSize', iFontSize);

```

```

ax2 = subplot(2,2,3);
handleToPlot2 = bar(ax2, afY2, 'stacked');
figuregca2 = gca;
handles2 = get(handleToPlot2);
figuregca2.Position = Fig2Position;

for h=1:3
    handleToPlot2(h).FaceColor = BarColours(h,:);
    handleToPlot2(h).FaceAlpha = 0.9000;
    handleToPlot2(h).EdgeColor = afColorMap(15,:);
    handleToPlot2(h).LineWidth = 1;
    handleToPlot2(h).BarWidth = 0.3;
end

figuregca2.YLim(2) = figuregca2.YLim(2)*1.1;
set(figuregca2,
    'XGrid', 'on', ... [on | {off}]
    'YGrid', 'on', ... [on | {off}]
    'GridLineStyle', ':', ... [- | -- | {:} | -. | none]
    'XMinorGrid', 'off', ... [on | {off}]
    'YMinorGrid', 'off', ... [on | {off}]
    'MinorGridLineStyle', ':', ... [- | -- | {:} | -. | none]
    'YMinorTick', 'off', ... [on | {off}]
    'TickDir', 'out', ... [{in} | out] inside or outside (for 2D)
    'TickLength', [.005 .005], ... length of the ticks
    'XColor', [.1 .1 .1], ... color of x axis
    'YColor', [.1 .1 .1], ... color of y axis
    'XAxisLocation', 'bottom', ... where labels have to be printed [top | {bottom}]
    'YAxisLocation', 'left', ... where labels have to be printed [{left} | right]
    'XDir', 'normal', ... axis increase direction [{normal} | reverse]
    'YDir', 'normal', ... axis increase direction [{normal} | reverse]
    'FontName', strFontName, ... kind of fonts of labels
    'FontSize', iFontSize, ... size of fonts of labels
    'FontUnits', strFontUnit, ... units of the size of fonts
    'FontWeight', strFontWeight, ... weight of fonts of labels
    'FontAngle', strFontAngle, ... inclination of fonts of labels
    ...
    'LineWidth', fLineWidth);

fXLabelRotation = 0.0;
fYLabelRotation = 90.0;
strInterpreter = 'tex';
%
ylabel( strYlLabel,
    'FontName', strFontName, ...
    'FontUnit', strFontUnit, ...
    'FontSize', iFontSize, ...
    'FontWeight', strFontWeight, ...
    'Interpreter', strInterpreter);
%
set(get(gca, 'XLabel'), 'Rotation', fXLabelRotation);
set(get(gca, 'YLabel'), 'Rotation', fYLabelRotation);

% if FinalVersion = 'Yes!' above, the figures are saved as PNG picture
% files in the location given by PicFilePathOneDrive
PicFileDirNameOneDrive= [PicFilePathOneDrive, '/', saveTitle, '/', saveTitle ' ' Infrastructure, '.png'];
if strcmp(FinalVersion, 'Yes!')==1
    %mkdir([PicFilePathLocal, '/', strTitle, '/'])
    mkdir([PicFilePathOneDrive, '/', saveTitle, '/'])
    saveas(figuregcf, PicFileDirNameOneDrive)
end
end

```

## A 3. CHAPTER 5, RESILIENCE METRICS

### A 3.1. DATA QUALITY ASSESSMENT, ADJACENT STACKED BAR PLOTS PRE AND POST-DATA TREATMENT

```
%% CHAPTER 05 - Post-DATA TREATMENT QUALITY PLOTS
clear;clc;close all;
load('MATFILEPATH/ALL.mat','General')
load('MATFILEPATH/DataQuality')
PicFilePathOneDrive = 'PICFILEPATH/05 Metric/';
saveTitle = 'DataQuality Treated data';

Infrastructures = {'SvK','Energiforetagen','Road','Train',...
'SVOA','TelecomAll','IP','FixedPhone','Mobile'};
InfrastructureTitles = {'Electricity transmission',...
'Electricity distribution',...
'Transport Road',...
'Transport Railway',...
'Drinking water network',...
'Telecommunication',...
'Telecommunication IP based',...
'Telecommunication fixed phone',...
'Telecommunication mobile'};

Years = {'2005','2006','2007','2008','2009','2010','2011','2012','2013','2014','2015','2016','2017'};
YEARS = {2005;2006;2007;2008;2009;2010;2011;2012;2013;2014;2015;2016;2017};

% type FinalVersion = 'Yes!' to save a PNG picture file to
% the location given by PicFilePathOneDrive
FinalVersion = 'Nah';
for k = 1:9

    %PLOT SETTINGS
    fLineWidth = 2.0;
    strLineStyle = '-'; % [(Jahre & Fabbe-Costes) | -- | : | -.]
    iMarkerSize = 25; % in points
    strMarkerType = '+'; % [+ | o | * | . | x | square | diamond | > | < | ^ | v | pentagram | hexagram | {none}]
    afMarkerEdgeColor = [0.3 0.3 0.3];
    afFigurePosition = [10 10 35 25]; % [pos_x pos_y width_x width_y]
    Fig1Position = [0.0800 0.5838 0.9000 0.3800];
    Fig2Position = [0.0800 0.1100 0.3600 0.3800];
    Fig3Position = [0.5300 0.1100 0.4500 0.3800];
    afColorMap = General.PlotSettings.ColormapBone; % [left bottom width height]
    % fonts properties
    iFontSize = 18;
    strFontUnit = 'points'; % [{points} | normalized | inches | centimeters | pixels]
    strFontName = 'Helvetica'; % [Times | Courier | ] TODO complete the list
    strFontWeight = 'normal'; % [light | {normal} | demi | bold]
    strFontAngle = 'normal'; % [{normal} | italic | oblique] ps: only for axes

    BarColorMap = [afColorMap(62,:);... valid
afColorMap(46,:);... zero
afColorMap(13,:); %unusable
    BarEdgeColour = [afColorMap(15,:);...
afColorMap(15,:);...
afColorMap(34,:);

    BarWidth1 = 0.5;
    BarWidth2 = 0.4;

    Infrastructure = Infrastructures{k};

    strTitle = [saveTitle ' - ' Infrastructure];

    DataToPlot1 = DataQualityTables.(Infrastructure).AnnualDevelopmentPre;
    DataToPlot2 = DataQualityTables.(Infrastructure).PreDataTreatment;
    DataToPlot3 = DataQualityTables.(Infrastructure).AnnualDevelopmentPost;
    DataToPlot4 = DataQualityTables.(Infrastructure).PostDataTreatment;

    NumGroupsPerAxis = 13;
    NumStackElements = 3;
    NumStacksPerGroup = 2;
    MatrixToPlot = zeros(13,2,3);

    for z=1:3
        MatrixToPlot(:,1,z) = DataToPlot1(:,z);
        MatrixToPlot(:,2,z) = DataToPlot3(:,z);
    end

    % Pre-Data Treatment
    % Annual Development
    afX1 = MatrixToPlot;%YEARS;
    afY1 = YEARS;
    strY1Label = 'Count';

    % Pre-Data Treatment
    afX2 = reordercats(categorical(DataToPlot2.Properties.VariableNames),[3 2 1]);
    afY2 = transpose(DataToPlot2{:,:});

    % Post-Data Treatment
    afX3 = reordercats(categorical(DataToPlot4.Properties.VariableNames),[3 2 1]); afX3(1,4) = {'Used data'};
    afY3 = transpose(DataToPlot4{:,:}); afY3(4,:) = [afY3(1,1);0; 0];

    strX2Label = 'Treated data';
    strY2Label = 'Count';

    plotBarStackGroups(afX1, afY1);
    box on
end
```

```

figuregcal      = gca;

figuregcf      = gcf;
set(figuregcf,'Name',          strTitle,...
    'Units',          'centimeters',...
    'Position',       affFigurePosition,...
    'PaperPositionMode','auto');

objects        = get(figuregcf);
figuregcal.Position = Fig1Position;

figuregcal.YLim(2) = figuregcal.YLim(2)*1.1;
OffSet           = figuregcal.XLim(2)/15*0.5;
figuregcal.XLim(1) = figuregcal.XLim(1) + OffSet;
figuregcal.XLim(2) = figuregcal.XLim(2) - OffSet;

set(figuregcal,
    'XGrid',          'on',          ... [on | {off}]
    'YGrid',          'on',          ... [on | {off}]
    'GridLineStyle',  ':',          ... [- | -- | {:} | -. | none]
    'XMinorGrid',     'off',         ... [on | {off}]
    'YMinorGrid',     'off',         ... [on | {off}]
    'MinorGridLineStyle', ':',      ... [- | -- | {:} | -. | none]
    'YMinorTick',     'off',         ... [on | {off}]
    'TickDir',        'out',         ... [{in} | out] inside or outside (for 2D)
    'TickLength',     [.005 .005],  ... length of the ticks
    'XColor',         [.1 .1 .1],    ... color of x axis
    'YColor',         [.1 .1 .1],    ... color of y axis
    'XAxisLocation',  'bottom',      ... where labels have to be printed [top | {bottom}]
    'YAxisLocation',  'left',        ... where labels have to be printed [{left} | right]
    'XDir',           'normal',      ... axis increase direction [{normal} | reverse]
    'YDir',           'normal',      ... axis increase direction [{normal} | reverse]
    'FontName',       strFontName,   ... kind of fonts of labels
    'FontSize',       iFontSize,     ... size of fonts of labels
    'FontUnits',      strFontUnit,   ... units of the size of fonts
    'FontWeight',     strFontWeight, ... weight of fonts of labels
    'FontAngle',      strFontAngle,  ... inclination of fonts of labels
    'LineWidth',      fLineWidth);

fXLabelRotation = 0.0;
fYLabelRotation = 90.0;
strInterpreter   = 'tex';
%
ylabel( strYLabel,
    'FontName',   strFontName,   ...
    'FontUnit',   strFontUnit,   ...
    'FontSize',   iFontSize,     ...
    'FontWeight', strFontWeight, ...
    'Interpreter', strInterpreter);
%
set(get(gca, 'XLabel'), 'Rotation', fXLabelRotation);
set(get(gca, 'YLabel'), 'Rotation', fYLabelRotation);

atArrayOfHandlesToLines = strTitle;

%See general properties above
astrArrayOfLabels        = {'Valid data','Value is zero','Unusable data',};

% - N = North
% - S = South
% - E = East
% - W = West
% - O = Outside the plot
% - B = Best (least conflict with data in plot)
strLegendLocation        = {'NE','NE','NW','NW','NE','NW','NW','NW','NW','NW','NW'};

strLegendOrientation      = 'vertical'; % [{vertical}] horizontal]
%
afEdgeColor               = [1.0 1.0 1.0]; % RGB
afTextColor               = [0.0 0.0 0.0]; % RGB

%
legend( atArrayOfHandlesToLines,
    astrArrayOfLabels,
    'Location',            strLegendLocation{k}, ...
    'Orientation',         strLegendOrientation, ...
    'Box',                 'on',          ... [on {off}]
    'Color',               afEdgeColor,   ...
    'EdgeColor',           afEdgeColor,   ...
    'TextColor',           afTextColor,   ...
    'FontSize',            iFontSize);

#####      ##### PLOT2 #####
#####      ##### PLOT2 #####

ax2          = subplot('Position',Fig2Position);
handleToPlot2 = bar(ax2, afY2,'stacked');
figuregca2    = gca;
handles2      = get(handleToPlot2);

for h=1:3
    handleToPlot2(h).FaceColor = BarColours(h,:);
    handleToPlot2(h).FaceAlpha = 0.9000;
    handleToPlot2(h).EdgeColor = BarEdgeColour(h,:);
    handleToPlot2(h).LineWidth = 1;
    handleToPlot2(h).BarWidth  = 0.3;
end

figuregca2.YLim(2) = figuregca2.YLim(2)*1.1;
set(figuregca2,
    'XGrid',          'on',          ... [on | {off}]
    'YGrid',          'on',          ... [on | {off}]
    'GridLineStyle',  ':',          ... [- | -- | {:} | -. | none]
    'XMinorGrid',     'off',         ... [on | {off}]
    'YMinorGrid',     'off',         ... [on | {off}]
    'MinorGridLineStyle', ':',      ... [- | -- | {:} | -. | none]
    'YMinorTick',     'off',         ... [on | {off}]
    'TickDir',        'out',         ... [{in} | out] inside or outside (for 2D)
    'TickLength',     [.005 .005],  ... length of the ticks

```

```

'XColor',          [.1 .1 .1],      ... color of x axis
'YColor',          [.1 .1 .1],      ... color of y axis
'XAxisLocation',   'bottom',        ... where labels have to be printed [top | {bottom}]
'YAxisLocation',   'left',          ... where labels have to be printed [{left} | right]
'XDir',            'normal',        ... axis increaseement direction [{normal} | reverse]
'YDir',            'normal',        ... axis increaseement direction [{normal} | reverse]
'FontName',        strFontName,     ... kind of fonts of labels
'FontSize',        iFontSize,       ... size of fonts of labels
'FontUnits',       strFontUnit,     ... units of the size of fonts
'FontWeight',      strFontWeight,   ... weight of fonts of labels
'FontAngle',       strFontAngle,    ... inclination of fonts of labels
...
'LineWidth',       fLineWidth);

fXLabelRotation = 0.0;
fYLabelRotation = 90.0;
strInterpreter    = 'tex';
%
ylabel( strYLabel,      ...
        'FontName',     strFontName,   ...
        'FontUnit',     strFontUnit,   ...
        'FontSize',     iFontSize,     ...
        'FontWeight',   strFontWeight, ...
        'Interpreter',  strInterpreter);
%
set(get(gca, 'XLabel'), 'Rotation', fXLabelRotation);
set(get(gca, 'YLabel'), 'Rotation', fYLabelRotation);

##### PLOT3 #####
##### PLOT3 #####

ax3      = subplot('Position',Fig3Position);
handleToPlot3 = bar(ax3, afY3,'stacked');
figuregca3 = gca;
handles3   = get(handleToPlot3);

for h=1:3
    handleToPlot3(h).FaceColor = BarColours(h,:);
    handleToPlot3(h).FaceAlpha = 0.9000;
    handleToPlot3(h).EdgeColor = BarEdgeColour(h,:);
    handleToPlot3(h).LineWidth = 1;
    handleToPlot3(h).BarWidth  = 0.3*1.1;
end

figuregca3.YLim(2) = figuregca2.YLim(2);
set(figuregca3,
'XGrid',      'on',          ... [on | {off}]
'YGrid',      'on',          ... [on | {off}]
'GridLineStyle', ':',        ... [- | -- | {:} | -. | none]
'XMinorGrid', 'off',         ... [on | {off}]
'YMinorGrid', 'off',         ... [on | {off}]
'MinorGridLineStyle', ':',    ... [- | -- | {:} | -. | none]
'YMinorTick', 'off',         ... [on | {off}]
'TickDir',    'out',         ... [{in} | out] inside or outside (for 2D)
'TickLength', [.005 .005],    ... length of the ticks
'XColor',     [.1 .1 .1],     ... color of x axis
'YColor',     [.1 .1 .1],     ... color of y axis
'XAxisLocation', 'bottom',    ... where labels have to be printed [top | {bottom}]
'YAxisLocation', 'left',      ... where labels have to be printed [{left} | right]
'XDir',        'normal',      ... axis increaseement direction [{normal} | reverse]
'YDir',        'normal',      ... axis increaseement direction [{normal} | reverse]
'FontName',    strFontName,   ... kind of fonts of labels
'FontSize',    iFontSize,     ... size of fonts of labels
'FontUnits',   strFontUnit,   ... units of the size of fonts
'FontWeight',  strFontWeight, ... weight of fonts of labels
'FontAngle',   strFontAngle,  ... inclination of fonts of labels
'LineWidth',   fLineWidth);

fXLabelRotation = 0.0;
fYLabelRotation = 90.0;
strInterpreter    = 'tex';
%
%
ylabel( strYLabel,      ...
        'FontName',     strFontName,   ...
        'FontUnit',     strFontUnit,   ...
        'FontSize',     iFontSize,     ...
        'FontWeight',   strFontWeight, ...
        'Interpreter',  strInterpreter);
%
set(get(gca, 'XLabel'), 'Rotation', fXLabelRotation);
set(get(gca, 'YLabel'), 'Rotation', fYLabelRotation);
uistack(figuregca1,'top')

% if FinalVersion = 'Yes!' above, the figures are saved as PNG picture
% files in the location given by PicFilePathOneDrive
PicFileDirNameOneDrive= [PicFilePathOneDrive,'/',saveTitle,'/',saveTitle ' ' Infrastructure,'.png'];
if strcmp(FinalVersion,'Yes!')==1
    %mkdir([PicFilePathLocal,'/',strTitle,'/'])
    mkdir([PicFilePathOneDrive,'/',saveTitle,'/'])
    saveas(figuregcf,PicFileDirNameOneDrive)
end
end
end

```





# A 4. CHAPTER 6, INDIVIDUAL RESILIENCE ASSESSMENTS

## A 4.1.RESILIENCE CURVES – DATA BUILD 1

```

%% FUNCTIONALITY CURVE data build 1
clear;clc;close all;

MatFile = 'MATFILEPATH/ALL.mat';

Infrastructures = {'SvK','Energifoetagen','Road','Train','SVOA','Mobile','IP','FixedPhone'};
InfrastructureTitles = {'Electricity transmission',...
    'Electricity distribution',...
    'Transport Road',...
    'Transport Railway',...
    'Drinking water network',...
    'Telecommunication',...
    'Telecommunication IP based',...
    'Telecommunication fixed phone',...
    'Telecommunication mobile'};

DateTimeFormat = 'yyyy-MM-dd HH:mm:ss';
%% data production!

% infrastructure 1-8
for Infstrct = 1:8

    % failure cause 1-6
    for FailC = 1:6

        Infrastructure = Infrastructures{Infstrct};
        variableValue = load(MatFile,Infrastructure);

% separate the data according to given infrastructure = 'Infstrct'
% separate the data according to given interruption cause = 'FailC'
        if FailC==1
            FailureCauseToAnalyse = {'Human','Natural','Technical','External','Unknown','Missing data'};
            TableName = 'All';
        elseif FailC==2
            FailureCauseToAnalyse = {'Human'};
            TableName = 'Human';
        elseif FailC==3
            FailureCauseToAnalyse = {'Natural'};
            TableName = 'Natural';
        elseif FailC==4
            FailureCauseToAnalyse = {'Technical'};
            TableName = 'Technical';
        elseif FailC==5
            FailureCauseToAnalyse = {'External'};
            TableName = 'External';
        elseif FailC==6
            FailureCauseToAnalyse = {'Unknown','Missing data'};
            TableName = 'UnknownOrMissingdata';
        end

% only use the data from infrastructure given by 'Infstrct' and 'Infrastructure'
% only use the data from failure cause given by 'FailC' and 'FailureCauseToAnalyse'
        FailuresToUse = any(variableValue.(Infrastructure).Metrics.FailureCause==FailureCauseToAnalyse,2);
        if any(FailuresToUse)
            FailureDataPre = variableValue.(Infrastructure);
            FailureData = variableValue.(Infrastructure).Metrics(FailuresToUse,:);
        elseif any(FailuresToUse)==0
            ResiliencePlots.FunctionalityCurve.(Infrastructure).PreFunctionalityCurve.(TableName) = 'Empty';
            continue
        end

% find out infrastructure-specific numbers for analysis
        Years = unique(year(FailureData.Start_DT));
        NrYears = size(Years,1);
        NrIncidents = size(FailureData,1);

        [y,mon,d] = ymd(FailureData.Start_DT);
        [h,min,s] = hms(FailureData.Start_DT);
        roundedmin = round(s/60);
        FailureData.Start_DT = datetime(y,mon,d,h,min,zeros(NrIncidents,1));

        [y,mon,d] = ymd(FailureData.End_DT);
        [h,min,s] = hms(FailureData.End_DT);

        FailureData.End_DT = datetime(y,mon,d,h,min,zeros(NrIncidents,1));

% we need size of two times the incidents, one gives the start and one
% gives the end for each interruption/failure.
        FunctionalityCurve.InterruptionNr = ...
            vertcat(FailureData.InterruptionNr,FailureData.InterruptionNr);
        FunctionalityCurve.LinePointID = ...
            vertcat((1:NrIncidents).',(1:NrIncidents).');
        FunctionalityCurve.DateTime = ...
            vertcat(FailureData.Start_DT,FailureData.End_DT);
        FunctionalityCurve.FunctionalityChange = ...
            vertcat(FailureData.FunctionalityLoss*(-1),FailureData.FunctionalityLoss*1);

% change order on them after datetime
        tableInorder = struct2table(FunctionalityCurve);
        tableInorder = sortrows(tableInorder,'FunctionalityChange','ascend');
        tableInorder = sortrows(tableInorder,'DateTime','ascend');

% make table to know what data belongs to what year, so that no data is

```

```

% used that actually does not belong to the studied time period
NewYearsTable = tableInorder;
NewYearsEveRow = NewYearsTable(1,:);NewYearsEveRow(1,1)=0;NewYearsEveRow(1,2)=0;NewYearsEveRow(1,4)=0;
NewYearsRow = zeros(NrYears,1);
LastNYrow = 1;

for k=1:NrYears
    NewYearsRow = find(year(NewYearsTable.DateTime)==Years(k),1,'last');
    DateVec = datetime([Years(k) 12 31 23 59 0]); %create new vector for NYE
    NewYearsEveRow.DateTime = DateVec;
    NewYearsTable = vertcat(NewYearsTable(1:NewYearsRow,:),NewYearsEveRow,NewYearsTable(NewYearsRow+1:end,:));
end

FunctionalityCurve = ...
    table2struct(NewYearsTable,'ToScalar',true);
FunctionalityChanges = size(FunctionalityCurve.FunctionalityChange,1);
FunctionalityCurve.Functionality = zeros(FunctionalityChanges,1);

% create new table
FunctionalityCurve.InterruptionNr = vertcat(1, FunctionalityCurve.InterruptionNr,1);
FunctionalityCurve.Functionality = vertcat(1, FunctionalityCurve.Functionality,1);
FunctionalityCurve.DateTime = vertcat(...
    FailureDataPre.TotalDuration.Start,...
    FunctionalityCurve.DateTime,...
    FailureDataPre.TotalDuration.End);
FunctionalityCurve.FunctionalityChange = vertcat(0, FunctionalityCurve.FunctionalityChange,0);
FunctionalityCurve.LinePointID = vertcat(0, FunctionalityCurve.LinePointID,0);
FunctionalityCurve.Functionality(1,1) = ...
    1;

for k = 2:(FunctionalityChanges+2)
    disp([Infrastructure ' ' TableName ' ' num2str(k)])
    FunctionalityCurve.Functionality(k,1) = ...
        FunctionalityCurve.Functionality(k-1,1)+...
        FunctionalityCurve.FunctionalityChange(k,1);

end
ResiliencePlots.FunctionalityCurve.(Infrastructure).PreFunctionalityCurve.(TableName)...
    = struct2table(FunctionalityCurve);
ResiliencePlots.FunctionalityCurve.(Infrastructure).PreFunctionalityCurve.(TableName).DateTime.Format ...
    = DateTimeFormat;

clearvars FunctionalityCurve

end
end

%%
clearvars -except ResiliencePlots
save('MATFILEPATH/Functionality.mat', 'ResiliencePlots','-v7.3','-nocompression')

```

## A 4.2.RESILIENCE CURVES – DATA BUILD 2

```

%% FUNCTIONALITY CURVE data build 2
clear;clc;close all;

MatFile = 'MATFILEPATH/ALL.mat';
load 'MATFILEPATH/Functionality.mat'

Infrastructures = {'SvK','Energiforetagen','Road','Train','SVOA','Mobile','IP','FixedPhone'};
InfrastructureTitles = {'Electricity transmission',...
    'Electricity distribution',...
    'Transport Road',...
    'Transport Railway',...
    'Drinking water network',...
    'Telecommunication',...
    'Telecommunication IP based',...
    'Telecommunication fixed phone',...
    'Telecommunication mobile'};

TableNames = {'All','Human','Natural','Technical','External','UnknownOrMissingdata'};
DateTimeFormat = 'yyyy-MM-dd HH:mm';

%% data production!

% infrastructure 1-8
for Infstrct = 1:8

    % failure cause 1-6
    for FailC = 1:6

        % LOAD CORRECT DATA
        strTitle = 'Functionality Curve ';
        Infrastructure = Infrastructures{Infstrct};
        VariableValue = load(MatFile,Infrastructure);
        InfrastructureTitle = InfrastructureTitles{Infstrct};
        TableName = TableNames{FailC};

        % make sure the tables are there
        if istable(ResiliencePlots.FunctionalityCurve.(Infrastructure).PreFunctionalityCurve.(TableName))==0
            ResiliencePlots.FunctionalityCurve.(Infrastructure).FunctionalityCurveElement.(TableName) = 'Empty';
            disp('better luck becoming a firefighter')
            continue
        end

        FunctionalityCurve = ResiliencePlots.FunctionalityCurve.(Infrastructure).PreFunctionalityCurve.(TableName);
        TotalDuration = VariableValue.(Infrastructure).TotalDuration;
        NrElements = TotalDuration.DurationMin;
        Functionality = FunctionalityCurve.Functionality;
        Events_DT = FunctionalityCurve.DateTime;
        EventMinute = minutes(Events_DT - (TotalDuration.Start-minutes(1)));
        ElementResilience = zeros(NrElements,1);
    end
end

```

```

Events = size(Events_DT,1);

for Event = 1:(Events-1)
    disp([Infrastructure ' ' TableName ' ' num2str(Event)])
    if EventMinute(Event)~=EventMinute(Event+1)
        ElementResilience(EventMinute(Event):(EventMinute(Event+1)-1)) = Functionality(Event);
    elseif EventMinute(Event)==EventMinute(Event+1)
        continue
    % make sure that the data used is correct
    else
        disp('Nooww the boiled pork is fried, never forget about that')
    end
end

% last tiny little element(s)
ElementResilience(EventMinute(Events):end) = Functionality(Events);

TimeMinutes = minutes(0:(size(ElementResilience,1)-1)).';
Element_DT = (TotalDuration.Start + TimeMinutes);
% last little thing for next infrastructure is to delete this poor fella
clearvars ElementMinute
ResiliencePlots.FunctionalityCurve.(Infrastructure).FunctionalityCurveElement.(TableName) = table;
ResiliencePlots.FunctionalityCurve.(Infrastructure).FunctionalityCurveElement.(TableName).ElementResilience = ElementResilience;
ResiliencePlots.FunctionalityCurve.(Infrastructure).FunctionalityCurveElement.(TableName).DateTime = Element_DT;
end

ResiliencePlots.TotalDuration.(Infrastructure) = TotalDuration;
end

%%
clearvars -except ResiliencePlots
save('MATFILEPATH/FunctionalityCurveElement.mat','ResiliencePlots','-v7.3')

```

## A 4.3.RESILIENCE CURVES – PLOT ELECTRICITY DISTRIBUTION AS EXAMPLE

```

%% CHAPTER 06 - EXAMPLIFICATION OF INDIVIDUAL RESILIENCE CURVES, sorted by interruption cause
% Example is of ELECTRICITY DISTRIBYTION/ENERGIFVARETAGEN
clear;clc;close all;

load('MATFILEPATH/ALL.mat','General');
load('MATFILEPATH/FunctionalityCurveElement.mat','ResiliencePlots')

%% REALLY NICE PLOTS
PicFilePathOneDrive = 'PICFILEPATH/06 RAA each infrastructure/';
InfrastructureTitles = {'Electricity transmission',...
    'Electricity distribution',...
    'Transport Road',...
    'Transport Railway',...
    'Drinking water network',...
    'Telecommunication',...
    'Telecommunication IP based',...
    'Telecommunication fixed phone',...
    'Telecommunication mobile'};
TableNames = {'All','Human','Natural','Technical','External','UnknownOrMissingdata'};

afColorMap = General.PlotSettings.ColormapBone; % [left bottom width height]
fLineWidth = 1.0;
strLineStyle = '-'; % [(Jahre & Fabbe-Costes) | -- | : | -.]
iMarkerSize = 25; % in point
strMarkerType = '.'; % [+ | o | * | . | x | square | diamond | > | < | ^ | v | pentagram | hexagram | {none}]
afMarkerFaceColor = General.PlotSettings.ColormapBone(15,:);
afMarkerEdgeColor = General.PlotSettings.ColormapBone(15,:);
afPlotLineWidth = .6;
astrPlotLineStyles = [{'-'},...1
{':'},...2
{'--'},...3
{'.'},...4
{'-.'},...5
{'-'}];% 6
astrPlotLineStyle = astrPlotLineStyles{6};
aafPlotLineColor = [General.PlotSettings.ColormapBone(25,:);...
    General.PlotSettings.ColormapBone(30,:);...
    General.PlotSettings.ColormapBone(34,:);...
    General.PlotSettings.ColormapBone(38,:);...
    General.PlotSettings.ColormapBone(42,:);...
    General.PlotSettings.ColormapBone(46,:)];

aafPlotMarkerFaceColor = [[0.1 0.1 0.1] ; [0.2 0.2 0.2] ;...
    [0.3 0.3 0.3] ; [0.4 0.4 0.4] ;...
    [0.5 0.5 0.5] ; [0.6 0.6 0.6]]; % RGB
aafPlotMarkerEdgeColor = [[0.3 0.3 0.3] ; [0.4 0.4 0.4] ;...
    [0.5 0.5 0.5] ; [0.6 0.6 0.6] ;...
    [0.7 0.7 0.7] ; [0.8 0.8 0.8]]; % RGB
afFigurePosition = [10 10 45 45*3.6/15.49];
afAxesPosition = [0.105177777777778 0.16148507295174 0.852311111111111 0.811362149270481];

aafPlotLineColorZero = General.PlotSettings.ColormapBone(19,:);
astrPlotLineStyleZero = astrPlotLineStyles{3};
afPlotLineWidthZero = 1.1;

% fonts properties
iFontSize = 24;
strFontUnit = 'points';
strFontName = 'Helvetica';
strFontWeight = 'normal';
strFontAngle = 'normal';
strInterpreter = 'tex';

Years = 2005:2016;
Inf = 2; %Infrastructure ID (Electricity distribution = 2)

```

```

% devide the plots in three-years-intervals
YearsPlots = [2005:2007;...
              2008:2010;...
              2011:2013;...
              2014:2016];

% type FinalVersion = 'Yes!' to save a PNG picture file to
% the location given by PicFilePathOneDrive
FinalVersion = 'NJAUmjau';
%%

for k = 1:6 %each interruption cause
    Infrastructure = Infrastructures{Inf};

    if ischar(ResiliencePlots.FunctionalityCurve.(Infrastructure).FunctionalityCurveElement.(TableNames{k}))
        continue
    end

    % load data
    ToUse = ResiliencePlots.FunctionalityCurve.(Infrastructure).FunctionalityCurveElement.(TableNames{k}).DateTime<...
            ResiliencePlots.TotalDuration.(Infrastructure).End;
    afX = ResiliencePlots.FunctionalityCurve.(Infrastructure).FunctionalityCurveElement.(TableNames{k}).DateTime(ToUse);
    afY = ResiliencePlots.FunctionalityCurve.(Infrastructure).FunctionalityCurveElement.(TableNames{k}).ElementResilience(ToUse);

    strYLabel1 = 'Functionality' ;

    for Yr = 1:4
        Years = YearsPlots(Yr,:);
        TableName = TableNames{k};
        strLabel = Infrastructures{1};
        strTitle = ['Functionality Curve Plot - ' Infrastructure ' ' TableName ' ' num2str(Years)];
        saveTitle = 'Functionality Curve Plot';

        afX1 = afX;
        afY1 = afY;
        figuregcf = figure(...
            'Name', strTitle, ...
            'Units', 'centimeters', ...
            'Position', affFigurePosition, ...
            'PaperType', 'A4', ...
            'PaperPositionMode', 'auto');

        figuregca = axes('Position', afAxesPosition);

        handleToPlot = stairs(
            afX1, ...
            afY1, ...
            'LineStyle', astrPlotLineStyle, ...
            'LineWidth', afPlotLineWidth, ...
            'Color', aafPlotLineColor(k,:));

        set(figuregca,
            'XGrid', 'on', ... [on | {off}]
            'YGrid', 'on', ... [on | {off}]
            'GridLineStyle', ':', ... [- | -- | {:} | -. | none]
            'XMinorGrid', 'on', ... [on | {off}]
            'YMinorGrid', 'on', ... [on | {off}]
            'MinorGridLineStyle', ':', ... [- | -- | {:} | -. | none]
            'YMinorTick', 'off', ... [on | {off}]
            'TickDir', 'out', ... [(in) | out] inside or outside (for 2D)
            'TickLength', [.005 .005], ... length of the ticks
            'XColor', [.1 .1 .1], ... color of x axis
            'YColor', [.1 .1 .1], ... color of y axis
            'XAxisLocation', 'bottom', ... where labels have to be printed [top | {bottom}]
            'YAxisLocation', 'left', ... where labels have to be printed [{left} | right]
            'XDir', 'normal', ... axis increase direction [{normal} | reverse]
            'YDir', 'normal', ... axis increase direction [{normal} | reverse]
            'XLim', [datetime([Years(1) 1 1 0 0 0]) datetime([Years(end)+1 1 1 0 0 0])],...
            'YLim', [0.96 1.001], ... limits for the y-axis
            'FontName', strFontName, ... kind of fonts of labels
            'FontSize', iFontSize, ... size of fonts of labels
            'FontUnits', strFontUnit, ... units of the size of fonts
            'FontWeight', strFontWeight, ... weight of fonts of labels
            'FontAngle', strFontAngle, ... inclination of fonts of labels
            'LineWidth', fLineWidth);

        fYLabelRotation = 90.0;
        ylabel(strYLabel1,
            'FontName', strFontName, ...
            'FontUnit', strFontUnit, ...
            'FontSize', iFontSize, ...
            'FontWeight', strFontWeight, ...
            'Interpreter', strInterpreter);
        set(get(gca, 'YLabel'), 'Rotation', fYLabelRotation);
        % make a line to display full functionality = 100%
        ZeroLineX = figuregca.XLim;
        ZeroLineY = [1 1];

        hold on
        plot(ZeroLineX,ZeroLineY,...
            'LineWidth', afPlotLineWidthZero, ...
            'Color', aafPlotLineColorZero,...
            'LineStyle', astrPlotLineStyleZero);

        hold off

        uistack(handleToPlot,'top') % so that it stays above the zero-line (full functionality)

        PicFileDirNameOneDrive = [PicFilePathOneDrive,'/',saveTitle,'/',Infrastructure,'/',strTitle ' ' Infrastructure,'.png'];

    % if FinalVersion = 'Yes!' above, the figures are saved as PNG picture
    % files in the location given by PicFilePathOneDrive
    if strcmp(FinalVersion,'Yes!')==1
        %mkdir([PicFilePathLocal,'/',strTitle,'/'])
        mkdir([PicFilePathOneDrive,'/',saveTitle,'/',Infrastructure,'/'])
        saveas(figuregcf,PicFileDirNameOneDrive)
    end
end

```

end

## A 4.4. RESILIENCE VALUE TABLES – BY INTERRUPTION CAUSE

```

%% CHAPTER 06 RESULT TABLE - FAILURE CUASES
clear;clc;close all;
load 'MATFILEPATH/FunctionalityCurveElement.mat'
%% BUILD RESILIENCE METRIC TABLE
Infrastructures = {'SvK','Energiforetagen','Road','Train','SVOA','Mobile','IP','FixedPhone'};
InfrastructureTitles = {'Electricity transmission',...
    'Electricity distribution',...
    'Transport Road',...
    'Transport Railway',...
    'Drinking water network',...
    'Telecommunication',...
    'Telecommunication IP based',...
    'Telecommunication fixed phone',...
    'Telecommunication mobile'};

MatFilePath = 'MATFILEPATH/ALL.mat';
%%
for Inf = 1:8

    Infrastructure = Infrastructures{Inf};
    InfrastructureTitle = InfrastructureTitles{Inf};
    VarName = load(MatFilePath,Infrastructure);
    TotalDuration = VarName.(Infrastructure).TotalDuration;

    NrFailureCause = 5;
    FailureCauses = {'All','Human','Natural','Technical','External','UnknownOrMissingdata'};

    % create a table for the results
    IndividualResilienceMetricTables.(Infrastructure) = table;
    IndividualResilienceMetricTables.(Infrastructure).DurationMean = zeros(NrFailureCause+1,1);
    IndividualResilienceMetricTables.(Infrastructure).DurationVariance = zeros(NrFailureCause+1,1);
    IndividualResilienceMetricTables.(Infrastructure).DurationMax = zeros(NrFailureCause+1,1);
    IndividualResilienceMetricTables.(Infrastructure).FunctionalityLossMean = zeros(NrFailureCause+1,1);
    IndividualResilienceMetricTables.(Infrastructure).FunctionalityLossVariance = zeros(NrFailureCause+1,1);
    IndividualResilienceMetricTables.(Infrastructure).FunctionalityLossMax = zeros(NrFailureCause+1,1);
    IndividualResilienceMetricTables.(Infrastructure).ResilienceLossMean = zeros(NrFailureCause+1,1);
    IndividualResilienceMetricTables.(Infrastructure).ResilienceLossVariance = zeros(NrFailureCause+1,1);
    IndividualResilienceMetricTables.(Infrastructure).ResilienceLossMax = zeros(NrFailureCause+1,1);
    IndividualResilienceMetricTables.(Infrastructure).ResilienceMean = zeros(NrFailureCause+1,1);
    IndividualResilienceMetricTables.(Infrastructure).RowNames = FailureCauses;
    IndividualResilienceMetricTables.(Infrastructure).Properties.RowNames = FailureCauses;

    % create a table for rounded values
    IndividualResilienceMetricTables.([Infrastructure '_rounded']) = table;
    IndividualResilienceMetricTables.([Infrastructure '_rounded']).DurationMean = cell(NrFailureCause+1,1);
    IndividualResilienceMetricTables.([Infrastructure '_rounded']).DurationVariance = cell(NrFailureCause+1,1);
    IndividualResilienceMetricTables.([Infrastructure '_rounded']).DurationMax = cell(NrFailureCause+1,1);
    IndividualResilienceMetricTables.([Infrastructure '_rounded']).FunctionalityLossMean = cell(NrFailureCause+1,1);
    IndividualResilienceMetricTables.([Infrastructure '_rounded']).FunctionalityLossVariance = cell(NrFailureCause+1,1);
    IndividualResilienceMetricTables.([Infrastructure '_rounded']).FunctionalityLossMax = cell(NrFailureCause+1,1);
    IndividualResilienceMetricTables.([Infrastructure '_rounded']).ResilienceLossMean = cell(NrFailureCause+1,1);
    IndividualResilienceMetricTables.([Infrastructure '_rounded']).ResilienceLossVariance = cell(NrFailureCause+1,1);
    IndividualResilienceMetricTables.([Infrastructure '_rounded']).ResilienceLossMax = cell(NrFailureCause+1,1);
    IndividualResilienceMetricTables.([Infrastructure '_rounded']).ResilienceMean = cell(NrFailureCause+1,1);
    IndividualResilienceMetricTables.([Infrastructure '_rounded']).RowNames = FailureCauses;
    IndividualResilienceMetricTables.([Infrastructure '_rounded']).Properties.RowNames = FailureCauses;

%%
for FCause = 1:6

    FailureCause = FailureCauses{FCause};
    disp([Infrastructure ' ' FailureCause])

    if ischar(ResiliencePlots.FunctionalityCurve.(Infrastructure).FunctionalityCurveElement.(FailureCause))
        continue
    end

    FunctionalityFailureCause = ResiliencePlots.FunctionalityCurve.(Infrastructure).PreFunctionalityCurve.(Failure-
Cause).Functionality(...
    ResiliencePlots.FunctionalityCurve.(Infrastructure).PreFunctionalityCurve.(Fail-
ureCause).DateTime...
    <ResiliencePlots.TotalDuration.(Infrastructure).End);
    ElementFailureCause = ResiliencePlots.FunctionalityCurve.(Infrastructure).FunctionalityCurveElement...
    .(FailureCause).ElementResilience(ResiliencePlots.FunctionalityCurve...
    .(Infrastructure).FunctionalityCurveElement.(FailureCause).DateTime...
    <ResiliencePlots.TotalDuration.(Infrastructure).End);

    if FailureCause == categorical({'UnknownOrMissingdata'})
        MetricsFailureCause = ...
            VarName.(Infrastructure).Metrics(VarName.(Infrastructure).Metrics.FailureCause=='Unknown')|...
            VarName.(Infrastructure).Metrics.FailureCause=='Missing data',:);
    elseif FailureCause == categorical({'All'})
        MetricsFailureCause = ...
            VarName.(Infrastructure).Metrics;
    else
        MetricsFailureCause = ...
            VarName.(Infrastructure).Metrics(...
            VarName.(Infrastructure).Metrics.FailureCause==FailureCause,:);
    end

    IndividualResilienceMetricTables.(Infrastructure).DurationMean(FCause) = mean(MetricsFailureCause.Duration);
    IndividualResilienceMetricTables.(Infrastructure).DurationVariance(FCause) = var(MetricsFailureCause.Duration);
    IndividualResilienceMetricTables.(Infrastructure).DurationMax(FCause) = max(MetricsFailureCause.Duration);
    IndividualResilienceMetricTables.(Infrastructure).FunctionalityLossMean(FCause) = mean(1-FunctionalityFailure-
Cause)*10^3;
    IndividualResilienceMetricTables.(Infrastructure).FunctionalityLossVariance(FCause) = var(1-FunctionalityFailureCause)*10^6;
    IndividualResilienceMetricTables.(Infrastructure).FunctionalityLossMax(FCause) = max(1-FunctionalityFailureCause)*10^3;
    IndividualResilienceMetricTables.(Infrastructure).ResilienceLossMean(FCause) = mean(1-ElementFailureCause)*10^6;
    IndividualResilienceMetricTables.(Infrastructure).ResilienceLossVariance(FCause) = var(1-ElementFailureCause)*10^6;
    IndividualResilienceMetricTables.(Infrastructure).ResilienceLossMax(FCause) = max(1-ElementFailureCause);
    IndividualResilienceMetricTables.(Infrastructure).ResilienceMean(FCause) = mean(ElementFailureCause);

    precision=3; % precision/number of significant digits
    IndividualResilienceMetricTables.([Infrastructure '_rounded']).DurationMean{FCause} ...

```

```

        = num2str(IndividualResilienceMetricTables.(Infrastructure).DurationMean(FCause),precision);
IndividualResilienceMetricTables.([Infrastructure 'rounded']).DurationVariance{FCause} ...
        = num2str(IndividualResilienceMetricTables.(Infrastructure).DurationVariance{FCause},precision);
IndividualResilienceMetricTables.([Infrastructure 'rounded']).DurationMax{FCause} ...
        = num2str(IndividualResilienceMetricTables.(Infrastructure).DurationMax{FCause},precision);
IndividualResilienceMetricTables.([Infrastructure 'rounded']).FunctionalityLossMean{FCause} ...
        = num2str(IndividualResilienceMetricTables.(Infrastructure).FunctionalityLossMean{FCause},preci-
sion);
IndividualResilienceMetricTables.([Infrastructure 'rounded']).FunctionalityLossVariance{FCause} ...
        = num2str(IndividualResilienceMetricTables.(Infrastructure).FunctionalityLossVariance{FCause},preci-
sion);
IndividualResilienceMetricTables.([Infrastructure 'rounded']).FunctionalityLossMax{FCause} ...
        = num2str(IndividualResilienceMetricTables.(Infrastructure).FunctionalityLossMax{FCause},precision);
IndividualResilienceMetricTables.([Infrastructure 'rounded']).ResilienceLossMean{FCause} ...
        = num2str(IndividualResilienceMetricTables.(Infrastructure).ResilienceLossMean{FCause},precision);
IndividualResilienceMetricTables.([Infrastructure 'rounded']).ResilienceLossVariance{FCause} ...
        = num2str(IndividualResilienceMetricTables.(Infrastructure).ResilienceLossVariance{FCause},preci-
sion);
IndividualResilienceMetricTables.([Infrastructure 'rounded']).ResilienceLossMax{FCause} ...
        = num2str(IndividualResilienceMetricTables.(Infrastructure).ResilienceLossMax{FCause},precision);
% 5 significant digits for resilience mean
IndividualResilienceMetricTables.([Infrastructure 'rounded']).ResilienceMean{FCause} ...
        = num2str(IndividualResilienceMetricTables.(Infrastructure).ResilienceMean{FCause},'%#.5g');
end
% create excel table
writetable(IndividualResilienceMetricTables.([Infrastructure 'rounded']),[TABLEPATH/06 RAA each infrastructure/Failure Causes/'
Infrastructure 'rounded.xlsx'])
end
%%
clearvars -except IndividualResilienceMetricTables
save('MATFILEPATH/ResilienceMetricTable_FailureCauses')

```

## A 4.5.ANNUAL RESILIENCE LEVEL – STEP CURVE BUILD

```

%% CHAPTER 06 - ANNUAL RESILIENCE LEVELS, STEP CURVE BUILD
clear;clc;close all;
load 'MATFILEPATH/FunctionalityCurveElement.mat'
%% Resilience Average StepCurve
Infrastructure = {'SvK','Energiforetagen','Road','Train','SVOA','Mobile','IP','FixedPhone'};
InfrastructureTitles = {'Electricity transmission',...
    'Electricity distribution',...
    'Transport Road',...
    'Transport Railway',...
    'Drinking water network',...
    'Telecommunication',...
    'Telecommunication IP based',...
    'Telecommunication fixed phone',...
    'Telecommunication mobile'};
TableNames = {'All','Human','Natural','Technical','External','UnknownOrMissingdata'};
DateTimeFormat = 'yyyy-MM-dd HH:mm';
MatFilePath = 'MATFILEPATH/ALL.mat';
YEAR = {'2005', '2006', '2007', '2008', '2009', '2010', '2011', '2012', '2013', '2014', '2015', '2016', '2017'};
Years = size(YEAR,2);

%%
for FailC = 1:6
    TableName = TableNames{FailC};

    % allocate space
    ResilienceAveragePlotAll = table;
    ResilienceAveragePlotAll.SvKStart = NaT(Years,1);
    ResilienceAveragePlotAll.SvKEnd = NaT(Years,1);
    ResilienceAveragePlotAll.SvKMeanResilience = zeros(Years,1);
    ResilienceAveragePlotAll.EnergiforetagenStart = NaT(Years,1);
    ResilienceAveragePlotAll.EnergiforetagenEnd = NaT(Years,1);
    ResilienceAveragePlotAll.EnergiforetagenMeanResilience = zeros(Years,1);
    ResilienceAveragePlotAll.RoadStart = NaT(Years,1);
    ResilienceAveragePlotAll.RoadEnd = NaT(Years,1);
    ResilienceAveragePlotAll.RoadMeanResilience = zeros(Years,1);
    ResilienceAveragePlotAll.TrainStart = NaT(Years,1);
    ResilienceAveragePlotAll.TrainEnd = NaT(Years,1);
    ResilienceAveragePlotAll.TrainMeanResilience = zeros(Years,1);
    ResilienceAveragePlotAll.SVOAStart = NaT(Years,1);
    ResilienceAveragePlotAll.SVOAEnd = NaT(Years,1);
    ResilienceAveragePlotAll.SVOAMeanResilience = zeros(Years,1);
    ResilienceAveragePlotAll.MobileStart = NaT(Years,1);
    ResilienceAveragePlotAll.MobileEnd = NaT(Years,1);
    ResilienceAveragePlotAll.MobileMeanResilience = zeros(Years,1);
    ResilienceAveragePlotAll.IPStart = NaT(Years,1);
    ResilienceAveragePlotAll.IPEnd = NaT(Years,1);
    ResilienceAveragePlotAll.IPMeanResilience = zeros(Years,1);
    ResilienceAveragePlotAll.FixedPhoneStart = NaT(Years,1);
    ResilienceAveragePlotAll.FixedPhoneEnd = NaT(Years,1);
    ResilienceAveragePlotAll.FixedPhoneMeanResilience = zeros(Years,1);
    ResilienceAveragePlotAll.Properties.RowNames = YEAR;

    for k = 1:8 % all infrastructures
        Infrastructure = Infrastructures{k};
        InfrastructureTitle = InfrastructureTitles{k};
        VarName = load(MatFilePath,Infrastructure);
        Start = VarName.(Infrastructure).TotalDuration.Start;
        End = VarName.(Infrastructure).TotalDuration.End;
        Data = ResiliencePlots.FunctionalityCurve.(Infrastructure).FunctionalityCurveElement.(TableName);
        if istable(Data)==0
            continue
        end
        FunctionalityElementVec = ResiliencePlots.FunctionalityCurve.(Infrastructure).FunctionalityCurveElement.(TableName).ElementRe-
silience;
        DateTimeElementVec = ResiliencePlots.FunctionalityCurve.(Infrastructure).FunctionalityCurveElement.(TableName).DateTime;

        for Year=year(Start):year(End)
            disp([InfrastructureTitle,' ',TableName,' ',num2str(Year)])
            YR = Year-2004; % row of data

            if Year==year(End)

```

```

ResilienceAveragePlotAll.([Infrastructure 'Start']) (YR) ...
    = DateTimeElementVec(find(year(DateTimeElementVec)==Year,1,'first'));
ResilienceAveragePlotAll.([Infrastructure 'End' ]) (YR) ...
    = End;
ResilienceAveragePlotAll.([Infrastructure 'MeanResilience' ]) (YR) ...
    = mean(FunctionalityElementVec(find(year(DateTimeElementVec)==Year,1,'first'):end));
elseif Year==year(Start)
ResilienceAveragePlotAll.([Infrastructure 'Start']) (YR) ...
    = Start;
ResilienceAveragePlotAll.([Infrastructure 'End' ]) (YR) ...
    = DateTimeElementVec(find(year(DateTimeElementVec)==Year,1,'last'));
ResilienceAveragePlotAll.([Infrastructure 'MeanResilience' ]) (YR) ...
    = mean(FunctionalityElementVec(1:find(year(DateTimeElementVec)==Year,1,'last')));
else
ResilienceAveragePlotAll.([Infrastructure 'Start']) (YR) ...
    = DateTimeElementVec(find(year(DateTimeElementVec)==Year,1,'first'));
ResilienceAveragePlotAll.([Infrastructure 'End' ]) (YR) ...
    = DateTimeElementVec(find(year(DateTimeElementVec)==Year,1,'last'));
ResilienceAveragePlotAll.([Infrastructure 'MeanResilience' ]) (YR) ...
    = mean(FunctionalityElementVec(year(DateTimeElementVec)==Year));

end
end

NrYears = year(End)-year(Start)+1;
ResilienceAveragePlot. (Infrastructure) = table;
ResilienceAveragePlot. (Infrastructure).DateTime = NaT((NrYears*2),1);
ResilienceAveragePlot. (Infrastructure).MeanResilience = zeros((NrYears*2),1);

for m=1:(NrYears*2)
    Year = (floor(m/2-0.1)+year(Start));
        disp([InfrastructureTitle, ' ', num2str(Year)])

    if m == 1
        ResilienceAveragePlot. (Infrastructure).DateTime(m) ...
            = Start;
        ResilienceAveragePlot. (Infrastructure).MeanResilience(m) ...
            = mean(FunctionalityElementVec(1:find(year(DateTimeElementVec)==Year,1,'last')));
    elseif m == 2
        ResilienceAveragePlot. (Infrastructure).DateTime(m) ...
            = DateTimeElementVec(find(year(DateTimeElementVec)==Year,1,'last'));
        ResilienceAveragePlot. (Infrastructure).MeanResilience(m) ...
            = mean(FunctionalityElementVec(1:find(year(DateTimeElementVec)==Year,1,'last')));
    elseif m == NrYears*2
        ResilienceAveragePlot. (Infrastructure).DateTime(m) ...
            = End;
        ResilienceAveragePlot. (Infrastructure).MeanResilience(m) ...
            = mean(FunctionalityElementVec(find(year(DateTimeElementVec)==Year,1,'first'):find(DateTimeElementVec==End)));
    elseif m == NrYears*2-1
        ResilienceAveragePlot. (Infrastructure).DateTime(m) ...
            = DateTimeElementVec(find(year(DateTimeElementVec)==Year,1,'first'));
        ResilienceAveragePlot. (Infrastructure).MeanResilience(m) ...
            = mean(FunctionalityElementVec(find(year(DateTimeElementVec)==Year,1,'first')));
    elseif mod(m,2)==1 %odd
        ResilienceAveragePlot. (Infrastructure).DateTime(m) ...
            = DateTimeElementVec(find(year(DateTimeElementVec)==Year,1,'first'));
        ResilienceAveragePlot. (Infrastructure).MeanResilience(m) ...
            = mean(FunctionalityElementVec(year(DateTimeElementVec)==Year));
    elseif mod(m,2)==0 %even
        ResilienceAveragePlot. (Infrastructure).DateTime(m) ...
            = DateTimeElementVec(find(year(DateTimeElementVec)==Year,1,'last'));
        ResilienceAveragePlot. (Infrastructure).MeanResilience(m) ...
            = mean(FunctionalityElementVec(year(DateTimeElementVec)==Year));
    end
end
ResiliencePlots.ResilienceAveragePlot. (Infrastructure). (TableName) = ResilienceAveragePlot;
end

ResiliencePlots.ResilienceAveragePlot. (Infrastructure). (TableName).ResilienceAveragePlotAll = ResilienceAveragePlotAll;
end

%%
clearvars -except ResiliencePlots
save('MATFILEPATH/ResiliencePlotsALL', 'ResiliencePlots')

```

## A 4.6.ANNUAL RESILIENCE LEVEL – STEP CURVE PLOT

```

clear;clc;close all;
%% CHAPTER 06 ANNUAL RESILIENCE LEVEL - STEP CURVE PLOT
load ('MATFILEPATH/ALL.mat', 'General');
load ('MATFILEPATH/ResiliencePlotsALL\FailureCause'
PicFilePathOneDrive = 'PICFILEPATH\06 RAA each infrastructure/';
InfrastructureNames = {'SvK','Energiforetagen','Road','Train','SVOA','Mobile','IP','FixedPhone'};
InfrastructureTitles = {'Electricity transmission',...
    'Electricity distribution',...
    'Transport Road',...
    'Transport Railway',...
    'Drinking water network',...
    'Telecommunication',...
    'Telecommunication IP based',...
    'Telecommunication fixed phone',...
    'Telecommunication mobile'};

TableNames = {'All','Human','Natural','Technical','External','UnknownOrMissingdata'};
%% REALLY NICE PLOTS
afColorMap = General.PlotSettings.ColormapBone; % [left bottom width height]
fLineWidth = 1.5;
strLineStyle = '-'; % [(Jahre & Fabbe-Costes) | -- | : | -.]
iMarkerSize = 25; % in points
strMarkerType = 'o'; % [+ | o | * | . | x | square | diamond | > | < | ^ | v | pentagram | hexagram | {none}]

afPlotLineWidth = 3.0;%[1.1, 1.5, 1.8, 1.6, 1.3, 0.3];
astrPlotLineStyles = ['-'],...1

```



```

        {'-.'}, ...2
        {'--'}, ...3
        {'.'}, ...4
        {'-.'}, ...5
        {'-'}];% 6
astrPlotLineStyle = astrPlotLineStyle{6};
aafPlotLineColor = General.PlotSettings.ColormapBone(35,:);
aafPlotLineColorZero= General.PlotSettings.ColormapBone(15,:);
astrPlotLineStyleZero= astrPlotLineStyle{3};
afPlotLineWidthZero = 1.0;

aiPlotMarkerSize = 20;
astrPlotMarkerType = [{'x'}, ...
                      {'+'}, ...
                      {'o'}, ...
                      {'*'}, ...
                      {'diamond'}];
aafPlotMarkerFaceColor = afColorMap(15,:);
aafPlotMarkerEdgeColor = afColorMap(15,:);
afFigurePosition = [10 10 45 45*5.5/15.89];
afAxesPosition1 = [0.105177777777778 0.16148507295174 0.852311111111111 0.811362149270481];
afAxesPosition2 = [0.450079365079362 0.477032407407407 0.384023809523807 0.43];

% fonts properties
iFontSize = 24;
strFontUnit = 'points'; % [{points} | normalized | inches | centimeters | pixels]
strFontName = 'Helvetica'; % [Times | Courier | ] TODO complete the list
strFontWeight = 'normal'; % [light | {normal} | demi | bold]
strFontAngle = 'normal'; % [{normal} | italic | oblique] ps: only for axes
strInterpreter = 'tex';

xTick = datetime([2005 01 01];...
                 [2006 01 01];...
                 [2007 01 01];...
                 [2008 01 01];...
                 [2009 01 01];...
                 [2010 01 01];...
                 [2011 01 01];...
                 [2012 01 01];...
                 [2013 01 01];...
                 [2014 01 01];...
                 [2015 01 01];...
                 [2016 01 01];...
                 [2017 01 01];...
                 [2018 01 01]);
xTickLabel = num2cell(2005:1:2018);
xLim = [xTick(1) xTick(end)];
yLim = [0.984 1.001];
ZeroLineX = xLim;
ZeroLineY = [1 1];

% type FinalVersion = 'Yes!' to save a PNG picture file to
% the location given by PicFilePathOneDrive
FinalVersion = 'MAYBE YOU are the one for me and my thesis?';
%%
for k=1:8
    Infrastructure = Infrastructures{k};
    strTitle = ['Resilience Step Curve ' Infrastructure];
    saveTitle = 'Resilience Step Curve';

    afX1 = ResiliencePlots.ResilienceAveragePlot.(Infrastructure{k}).DateTime;
    afY1 = ResiliencePlots.ResilienceAveragePlot.(Infrastructure{k}).MeanResilience;

    strYLabel1 = 'Mean resilience level' ;
    strXLabel1 = 'Year' ;

    figuregcf = figure(
        'Name', strTitle, ...
        'Units', 'centimeters', ...
        'Position', afFigurePosition, ...
        'PaperType', 'A4', ...
        'PaperPositionMode', 'auto');

    figuregca = axes(
        'Position', afAxesPosition1);

    handleToPlot = stairs(afX1, afY1,
        'LineStyle', astrPlotLineStyle, ...
        'LineWidth', afPlotLineWidth, ...
        'Color', aafPlotLineColor, ...
        'Marker', astrPlotMarkerType{1}, ...
        'MarkerSize', aiPlotMarkerSize, ...
        'MarkerFaceColor', aafPlotMarkerFaceColor, ...
        'MarkerEdgeColor', aafPlotMarkerEdgeColor);

%
    set(figuregca,
        'XGrid', 'on', ... [on | {off}]
        'YGrid', 'on', ... [on | {off}]
        'GridLineStyle', ':', ... [- | -- | {:} | -. | none]
        'XMinorGrid', 'off', ... [on | {off}]
        'YMinorGrid', 'off', ... [on | {off}]
        'MinorGridLineStyle', ':', ... [- | -- | {:} | -. | none]
        'XTick', xTick, ... ticks of x axis
        'YMinorTick', 'off', ... [on | {off}]
        'TickDir', 'out', ... [{in} | out] inside or outside (for 2D)
        'TickLength', [.005 .005], ... length of the ticks
        'XColor', [.1 .1 .1], ... color of x axis
        'YColor', [.1 .1 .1], ... color of y axis
        'XAxisLocation', 'bottom', ... where labels have to be printed [top | {bottom}]
        'YAxisLocation', 'left', ... where labels have to be printed [{left} | right]
        'XDir', 'normal', ... axis increasement direction [{normal} | reverse]
        'YDir', 'normal', ... axis increasement direction [{normal} | reverse]
        'XLim', xLim, ... limits for the x-axis
        'YLim', yLim, ... limits for the y-axis
        'FontName', strFontName, ... kind of fonts of labels

```

```

        'FontSize',          iFontSize,          ... size of fonts of labels
        'FontUnits',        strFontUnit,        ... units of the size of fonts
        'FontWeight',        strFontWeight,        ... weight of fonts of labels
        'FontAngle',         strFontAngle,         ... inclination of fonts of labels
        'LineWidth',         fLineWidth);

fXLabelRotation = 0.0;
fYLabelRotation = 90.0;
%
xlabel( strXLabel1,          strFontName,          ...
        'FontName',          strFontUnit,          ...
        'FontUnit',          iFontSize,            ...
        'FontSize',          strFontWeight,         ...
        'Interpreter',       strInterpreter);
%
ylabel( strYLabel1,          strFontName,          ...
        'FontName',          strFontUnit,          ...
        'FontUnit',          iFontSize,            ...
        'FontSize',          strFontWeight,         ...
        'Interpreter',       strInterpreter);
%
set(get(gca, 'XLabel'), 'Rotation', fXLabelRotation);
set(get(gca, 'YLabel'), 'Rotation', fYLabelRotation);
hold on

plot(ZeroLineX,ZeroLineY,...
     'LineWidth',            afPlotLineWidthZero,...
     'Color',                aafPlotLineColorZero,...
     'LineStyle',            astrPlotLineStyleZero);

hold off
%
atArrayOfHandlesToLines = strTitle;
box on

astrArrayOfLabels = InfrastructureTitles();
% - N = North
% - S = South
% - E = East
% - W = West
% - O = Outside the plot
% - B = Best (least conflict with data in plot)
strLegendLocation = 'E'; % combinations of N S E W B O or a vector

strLegendOrientation = 'vertical'; % [{vertical} horizontal]
%
afEdgeColor = [1.0 1.0 1.0]; % RGB
afTextColor = [0.0 0.0 0.0]; % RGB

legend( atArrayOfHandlesToLines,
        astrArrayOfLabels,
        'Position',          [0.651785714285714 0.493388457718278 0.24793956043956 0.227513227513227],...
        'Orientation',       strLegendOrientation,
        'Box',                'off',
        'Color',              [1 1 1],
        'EdgeColor',          afEdgeColor,
        'TextColor',          afTextColor,
        'Interpreter',       strInterpreter);

% if FinalVersion = 'Yes!' above, the figures are saved as PNG picture
% files in the location given by PicFilePathOneDrive
PicFileDirNameOneDrive= [PicFilePathOneDrive, '/', saveTitle, '/', saveTitle ' ' Infrastructure, '.png'];
if strcmp(FinalVersion, 'Yes!')==1
    mkdir([PicFilePathOneDrive, '/', saveTitle, '/'])
    saveas(figure(gcf), PicFileDirNameOneDrive)
end
end

```

## A 4.7. RESILIENCE VALUE TABLES – YEARLY

```

%% CHAPTER 06 RESULT TABLE - DEVIDED YEARLY
clear;clc;close all;
load 'MATFILEPATH/FunctionalityCurveElement.mat'
%% BUILD RESILIENCE METRIC TABLE
InfrastructureStruct = {'SvK', 'Energiforetagen', 'Road', 'Train', 'SVOA', 'Mobile', 'IP', 'FixedPhone'};
InfrastructureTitles = {'Electricity transmission',...
    'Electricity distribution',...
    'Transport Road',...
    'Transport Railway',...
    'Drinking water network',...
    'Telecommunication',...
    'Telecommunication IP based',...
    'Telecommunication fixed phone',...
    'Telecommunication mobile'};

MatFilePath = 'MATFILEPATH/ALL.mat';
%%
for Inf = 1:8

    % LOAD DATA
    Infrastructure = InfrastructureStruct{Inf};
    InfrastructureTitle = InfrastructureTitles{Inf};
    VarName = load(MatFilePath, Infrastructure);
    TotalDuration = VarName.(Infrastructure).TotalDuration;
    FunctionalityAll = ResiliencePlots.FunctionalityCurve.(Infrastructure).PreFunctionalityCurve.All...
        (ResiliencePlots.FunctionalityCurve.(Infrastructure).PreFunctionalityCurve.All.DateTime<...
        ResiliencePlots.TotalDuration.(Infrastructure).End,:);

    ElementAll = ResiliencePlots.FunctionalityCurve.(Infrastructure).FunctionalityCurveElement.All...
        (ResiliencePlots.FunctionalityCurve.(Infrastructure).FunctionalityCurveElement.All.DateTime<...
        ResiliencePlots.TotalDuration.(Infrastructure).End,:);

    Metrics = VarName.(Infrastructure).Metrics;

    Years = year(TotalDuration.Start):year(TotalDuration.End);
    NrYears = size(Years,2);
    YEARS = cellstr(num2str(transpose(Years)));
    YEARS(end+1) = {'All'; %ok<SAGROW>}
end

```

```

%%

% create vectors for each variable in the matrix/table
IndividualResilienceMetricTables.(Infrastructure) = table;
IndividualResilienceMetricTables.(Infrastructure).DurationMean = zeros(NrYears+1,1);
IndividualResilienceMetricTables.(Infrastructure).DurationVariance = zeros(NrYears+1,1);
IndividualResilienceMetricTables.(Infrastructure).DurationMax = zeros(NrYears+1,1);
IndividualResilienceMetricTables.(Infrastructure).FunctionalityLossMean = zeros(NrYears+1,1);
IndividualResilienceMetricTables.(Infrastructure).FunctionalityLossVariance = zeros(NrYears+1,1);
IndividualResilienceMetricTables.(Infrastructure).FunctionalityLossMax = zeros(NrYears+1,1);
IndividualResilienceMetricTables.(Infrastructure).ResilienceLossMean = zeros(NrYears+1,1);
IndividualResilienceMetricTables.(Infrastructure).ResilienceLossVariance = zeros(NrYears+1,1);
IndividualResilienceMetricTables.(Infrastructure).ResilienceLossMax = zeros(NrYears+1,1);
IndividualResilienceMetricTables.(Infrastructure).ResilienceMean = zeros(NrYears+1,1);
IndividualResilienceMetricTables.(Infrastructure).Row_Names(:) = YEARS;
IndividualResilienceMetricTables.(Infrastructure).Properties.RowNames = YEARS;

% create a table for rounded values
IndividualResilienceMetricTables.([Infrastructure '_rounded']) = table;
IndividualResilienceMetricTables.([Infrastructure '_rounded']).DurationMean = cell(NrYears+1,1);
IndividualResilienceMetricTables.([Infrastructure '_rounded']).DurationVariance = cell(NrYears+1,1);
IndividualResilienceMetricTables.([Infrastructure '_rounded']).DurationMax = cell(NrYears+1,1);
IndividualResilienceMetricTables.([Infrastructure '_rounded']).FunctionalityLossMean = cell(NrYears+1,1);
IndividualResilienceMetricTables.([Infrastructure '_rounded']).FunctionalityLossVariance = cell(NrYears+1,1);
IndividualResilienceMetricTables.([Infrastructure '_rounded']).FunctionalityLossMax = cell(NrYears+1,1);
IndividualResilienceMetricTables.([Infrastructure '_rounded']).ResilienceLossMean = cell(NrYears+1,1);
IndividualResilienceMetricTables.([Infrastructure '_rounded']).ResilienceLossVariance = cell(NrYears+1,1);
IndividualResilienceMetricTables.([Infrastructure '_rounded']).ResilienceLossMax = cell(NrYears+1,1);
IndividualResilienceMetricTables.([Infrastructure '_rounded']).ResilienceMean = cell(NrYears+1,1);
IndividualResilienceMetricTables.([Infrastructure '_rounded']).Row_Names(:) = YEARS;
IndividualResilienceMetricTables.([Infrastructure '_rounded']).Properties.RowNames = YEARS;

%%
for Year = 1:size(Years,2)+1

disp([Infrastructure num2str(Year)])

if Year==NrYears+1
    ElementYear = ElementAll.ElementResilience;
    FunctionalityYear = FunctionalityAll.Functionality;
    MetricsYear = Metrics;
else
    Yr = Years(Year);
    DateTimesElementYear = year(ElementAll.DateTime)==Yr;
    DateTimesFunctionalityYear = year(FunctionalityAll.DateTime)==Yr;
    StartDTsMetrics = year(Metrics.Start_DT)==Yr;

    ElementYear = ElementAll.ElementResilience(DateTimesElementYear);
    FunctionalityYear = FunctionalityAll.Functionality(DateTimesFunctionalityYear);
    MetricsYear = Metrics(StartDTsMetrics,:);
end
if size(MetricsYear,1)==0
    MetricsYear.Duration(1)=NaN;
end
if size(FunctionalityYear,1)==0
    FunctionalityYear = NaN;
end

IndividualResilienceMetricTables.(Infrastructure).DurationMean(Year) = mean(MetricsYear.Duration);
IndividualResilienceMetricTables.(Infrastructure).DurationVariance(Year) = var(MetricsYear.Duration);
IndividualResilienceMetricTables.(Infrastructure).DurationMax(Year) = max(MetricsYear.Duration);
IndividualResilienceMetricTables.(Infrastructure).FunctionalityLossMean(Year) = mean(1-FunctionalityYear)*10^3;
IndividualResilienceMetricTables.(Infrastructure).FunctionalityLossVariance(Year) = var(1-FunctionalityYear)*10^6;
IndividualResilienceMetricTables.(Infrastructure).FunctionalityLossMax(Year) = max(1-FunctionalityYear)*10^3;
IndividualResilienceMetricTables.(Infrastructure).ResilienceLossMean(Year) = mean(1-ElementYear)*10^6;
IndividualResilienceMetricTables.(Infrastructure).ResilienceLossVariance(Year) = var(1-ElementYear)*10^6;
IndividualResilienceMetricTables.(Infrastructure).ResilienceLossMax(Year) = max(1-ElementYear);
IndividualResilienceMetricTables.(Infrastructure).ResilienceMean(Year) = mean(ElementYear);

precision=3;% precision/number of significant digits
IndividualResilienceMetricTables.([Infrastructure '_rounded']).DurationMean{Year} = num2str(IndividualResilienceMetricTables.(Infrastructure).DurationMean(Year),precision);
IndividualResilienceMetricTables.([Infrastructure '_rounded']).DurationVariance{Year} = num2str(IndividualResilienceMetricTables.(Infrastructure).DurationVariance(Year),precision);
IndividualResilienceMetricTables.([Infrastructure '_rounded']).DurationMax{Year} = num2str(IndividualResilienceMetricTables.(Infrastructure).DurationMax(Year),precision);
IndividualResilienceMetricTables.([Infrastructure '_rounded']).FunctionalityLossMean{Year} = num2str(IndividualResilienceMetricTables.(Infrastructure).FunctionalityLossMean(Year),precision);
IndividualResilienceMetricTables.([Infrastructure '_rounded']).FunctionalityLossVariance{Year} = num2str(IndividualResilienceMetricTables.(Infrastructure).FunctionalityLossVariance(Year),precision);
IndividualResilienceMetricTables.([Infrastructure '_rounded']).FunctionalityLossMax{Year} = num2str(IndividualResilienceMetricTables.(Infrastructure).FunctionalityLossMax(Year),precision);
IndividualResilienceMetricTables.([Infrastructure '_rounded']).ResilienceLossMean{Year} = num2str(IndividualResilienceMetricTables.(Infrastructure).ResilienceLossMean(Year),precision);
IndividualResilienceMetricTables.([Infrastructure '_rounded']).ResilienceLossVariance{Year} = num2str(IndividualResilienceMetricTables.(Infrastructure).ResilienceLossVariance(Year),precision);
IndividualResilienceMetricTables.([Infrastructure '_rounded']).ResilienceLossMax{Year} = num2str(IndividualResilienceMetricTables.(Infrastructure).ResilienceLossMax(Year),precision);
% 5 significant digits for resilience mean
IndividualResilienceMetricTables.([Infrastructure '_rounded']).ResilienceMean{Year} = num2str(IndividualResilienceMetricTables.(Infrastructure).ResilienceMean(Year),'%.5g');
end

% create excel table
writetable(IndividualResilienceMetricTables.([Infrastructure '_rounded']),[TABLEPATH\06 RAA each infrastructure/Yearly/' Infrastructure '_rounded.xlsx'])
end
%%
clearvars -except IndividualResilienceMetricTables
save('MATFILEPATH/ResilienceMetricTable_IndividualInfrastructure')

```



# A 5. CHAPTER 7, RESILIENCE COMPARISON

## A 5.1.DURATION HISTOGRAMS

```
%% CHAPTER 07 DURATION HISTOGRAMS
clear;clc;close all;
load 'MATFILEPATH/ALL'
MatFile = 'MATFILEPATH/ALL';
PicFilePathOneDrive = 'PICFILEPATH/07 RAA Comparison/Duration histograms';
%%
Infrastructures = {'SvK','Energiforetagen','Road','Train','SVOA','TelecomAll','Mobile','IP','FixedPhone'};
InfrastructureTitles = {'Electricity transmission',...
    'Electricity distribution',...
    'Transport Road',...
    'Transport Railway',...
    'Drinking water network',...
    'Telecommunication',...
    'Telecommunication IP based',...
    'Telecommunication fixed phone',...
    'Telecommunication mobile'};

fLineWidth = 2.0;
strLineStyle = '-'; % [(Jahre & Fabbe-Costes) | -- | : | -.]
iMarkerSize = 25; % in points
strMarkerType = '.'; % [+ | o | * | . | x | square | diamond | > | < | ^ | v | pentagram | hexagram | {none}]
afMarkerFaceColor = [0.1 0.1 0.1];
afMarkerEdgeColor = [0.3 0.3 0.3];
afFigurePosition = [10 10 25 25*5.5/7.6]; % [pos_x pos_y width_x width_y]
afAxesPosition1 = [0.10517777777778 0.16148507295174 0.8523111111111111 0.811362149270481];
afAxesPosition2 = [0.465601587301584 0.47118271043771 0.384023809523807 0.43];
afColorMap = General.PlotSettings.ColormapBone;
% fonts properties
iFontSize = 24;
strFontUnit = 'points'; % [{points} | normalized | inches | centimeters | pixels]
strFontName = 'Helvetica'; % [Times | Courier | ] TODO complete the list
strFontWeight = 'normal'; % [light | {normal} | demi | bold]
strFontAngle = 'normal'; % [{normal} | italic | oblique] ps: only for axes
strInterpreter = 'tex';

%% Duration Histogram
% type FinalVersion = 'Yes!' to save a PNG picture file to
% the location given by PicFilePathOneDrive
FinalVersion = 'nah, not really?';

for k = [1:5 7:9]

    Infrastructure = Infrastructures{k};
    strTitle = ['Duration Histogram - ' Infrastructure];
    saveTitle = 'Duration Histogram';
    variableValue = load(MatFile,Infrastructure);
    % TEST TO PLOT THE FAILURES OVER TIME
    DataToPlot = variableValue.(Infrastructure).Metrics.DurationT; % (promille)
    DataToPlot.Format = 'h';

    TmaxBigWindow = 12;
    Bins2ndHist = 22;

    [Nraw,edges] = histcounts(DataToPlot,'BinMethod','hour');
    N=Nraw/sum(Nraw);

    [N2raw,edges2] = histcounts(DataToPlot(DataToPlot>hours(TmaxBigWindow)),Bins2ndHist);
    N2=N2raw/sum(Nraw);

    durMax = max(edges2);

    if k== 3 % for road data, as it does not have a second miniplot
        afX1 = edges(1:13);
        afY1 = [N(1:11) sum(N(12:end))];

        xLim = [hours(0) hours(12)];
    else
        afX1 = edges(1:(TmaxBigWindow+2));
        afY1 = [N(1:TmaxBigWindow) sum(N((TmaxBigWindow+1):end))];
        xLim = [hours(0) hours(13)];

        afX2 = edges2;
        afY2 = N2;
        strYLabel2 = 'Fraction';
        strXLabel2 = 'Duration >12';
    end

    YScale1 = 'linear';
    YScale2 = 'linear';

    strYLabel1 = 'Fraction';
    strXLabel1 = 'Duration';

    figure(gcf) = ...
        figure(...
            'Name', strTitle, ...
            'Units', 'centimeters', ... % [ inches | {centimeters} | normalized | points | !?(pixels)?! | char-
acters ]
            'Position', afFigurePosition, ...
            'PaperPositionMode', 'auto');

    figure(gcf) = axes(...
        'Units', 'normalized', ...
```

```

        'Position',          afAxesPosition1);
if k~=3
    figurecax2 = axes('Position',afAxesPosition2);
end
axes(figurecax1) %#ok<LAXES>
handleToPlot1 = histogram(...)
    'BinEdges',          afX1,          ...
    'BinCounts',         afY1,          ...
    'FaceColor',         afColorMap(50,:), ...
    'FaceAlpha',         .9 ,          ...
    'EdgeColor',         afColorMap(15,:), ...
    'LineWidth',         1.3);

set(figurecax1,
    'XGrid',             'on',          ... [on | {off}]
    'YGrid',             'on',          ... [on | {off}]
    'GridLineStyle',     ':',          ... [- | -- | {:} | -. | none]
    'XMinorGrid',        'off',         ... [on | {off}]
    'YMinorGrid',        'off',         ... [on | {off}]
    'MinorGridLineStyle', ':',          ... [- | -- | {:} | -. | none]
    'XTick',             hours(0:2:12), ... ticks of x axis
    'YTick',             0:0.1:1,      ... ticks of y axis
    'YMinorTick',        'off',         ... [on | {off}]
    'TickDir',           'out',         ... [{in} | out] inside or outside (for 2D)
    'TickLength',        [.005 .005],  ... length of the ticks
    ...
    'XColor',            [.1 .1 .1],    ... color of x axis
    'YColor',            [.1 .1 .1],    ... color of y axis
    'XAxisLocation',     'bottom',      ... where labels have to be printed [top | {bottom}]
    'YAxisLocation',     'left',        ... where labels have to be printed [{left} | right]
    'XDir',              'normal',      ... axis increase direction [{normal} | reverse]
    'YDir',              'normal',      ... axis increase direction [{normal} | reverse]
    'YScale',            YScale1,       ...
    'XLim',              xLim,          ... limits for the x-axis
    'YLim',              [0 1],         ... limits for the y-axis
    'FontName',          strFontName,   ... kind of fonts of labels
    'FontSize',          iFontSize,     ... size of fonts of labels
    'FontUnits',         strFontUnit,   ... units of the size of fonts
    'FontWeight',        strFontWeight, ... weight of fonts of labels
    'FontAngle',         strFontAngle,  ... inclination of fonts of labels
    'LineWidth',         fLineWidth);

fXLabelRotation = 0.0;
fYLabelRotation = 90.0;
%
xlabel( strXLabel1,
    'FontName',          strFontName,   ...
    'FontUnit',          strFontUnit,   ...
    'FontSize',          iFontSize,     ...
    'FontWeight',        strFontWeight, ...
    'Interpreter',       strInterpreter);
%
ylabel( strYLabel1,
    'FontName',          strFontName,   ...
    'FontUnit',          strFontUnit,   ...
    'FontSize',          iFontSize,     ...
    'FontWeight',        strFontWeight, ...
    'Interpreter',       strInterpreter);
%
set(get(gca, 'XLabel'), 'Rotation', fXLabelRotation);
set(get(gca, 'YLabel'), 'Rotation', fYLabelRotation);
##### % SECOND LITTLE PLOTT , we call her plottie %
#####
if k~=3
    axes(figurecax2) %#ok<LAXES>

    handleToPlot2 = histogram(...)
        'BinEdges',          afX2,          ...
        'BinCounts',         afY2,          ...
        'FaceColor',         afColorMap(50,:), ...
        'FaceAlpha',         .9 ,          ...
        'EdgeColor',         afColorMap(30,:), ...
        'LineWidth',         1.1);

    set(figurecax2,
        'XGrid',             'on',          ... [on | {off}]
        'YGrid',             'on',          ... [on | {off}]
        'GridLineStyle',     ':',          ... [- | -- | {:} | -. | none]
        'XMinorGrid',        'off',         ... [on | {off}]
        'YMinorGrid',        'off',         ... [on | {off}]
        'MinorGridLineStyle', ':',          ... [- | -- | {:} | -. | none]
        'YMinorTick',        'off',         ... [on | {off}]
        'TickDir',           'out',         ... [{in} | out] inside or outside (for 2D)
        'TickLength',        [.005 .005]*.8, ... length of the ticks
        'XColor',            [.1 .1 .1],    ... color of x axis
        'YColor',            [.1 .1 .1],    ... color of y axis
        'XAxisLocation',     'bottom',      ... where labels have to be printed [top | {bottom}]
        'YAxisLocation',     'left',        ... where labels have to be printed [{left} | right]
        'XDir',              'normal',      ... axis increase direction [{normal} | reverse]
        'YDir',              'normal',      ... axis increase direction [{normal} | reverse]
        'YScale',            YScale2,       ...
        'XLim',              [afX2(1) (afX2(end)+1)], ... limits for the x-axis
        'YLim',              [0 figurecax2.YLim(2)*1.15], ... limits for the y-axis
        'FontName',          strFontName,   ... kind of fonts of labels
        'FontSize',          iFontSize-1,   ... size of fonts of labels
        'FontUnits',         strFontUnit,   ... units of the size of fonts
        'FontWeight',        strFontWeight, ... weight of fonts of labels
        'FontAngle',         strFontAngle,  ... inclination of fonts of labels
        'LineWidth',         fLineWidth);

    fXLabelRotation = 0.0;
    fYLabelRotation = 90.0;
%
    xlabel( strXLabel2,
        'FontName',          strFontName,   ...
        'FontUnit',          strFontUnit,   ...
        'FontSize',          iFontSize-1,   ...
        'FontWeight',        strFontWeight, ...

```

```

        'Interpreter',      strInterpreter);
%
ylabel( strYLabel2,
        'FontName',        strFontName,      ...
        'FontUnit',        strFontUnit,      ...
        'FontSize',        iFontSize-1,      ...
        'FontWeight',      strFontWeight,    ...
        'Interpreter',      strInterpreter);

set(get(gca, 'XLabel'), 'Rotation', fXLabelRotation);
set(get(gca, 'YLabel'), 'Rotation', fYLabelRotation);
end
%
if k==3
    durMax = hours(12);
end
if k==3 % Create textbox for max value, but not for road
    annotation(figuregcf, 'textbox', ...
        [0.84277777777778 0.0926892929292925 0.0356888888888888 0.0584969696969697], ...
        'String', {'>'}, ...
        'LineStyle', 'none', ...
        'FontSize', 24, ...
        'FontName', 'Helvetica Neue', ...
        'FitBoxToText', 'off');
end

    annotation(figuregcf, 'textbox', ...
        [0.58495555555557 0.6523103030303 0.237066666666667 0.189140202020201], ...
        'String', {'[max(duration) = ' num2str(hours(durMax)) ' hr']}, ...
        'LineStyle', 'none', ...
        'FontSize', 20, ...
        'FontName', 'Helvetica Neue', ...
        'FitBoxToText', 'off');

% if FinalVersion = 'Yes!' above, the figures are saved as PNG picture
% files in the location given by PicFilePathOneDrive
PicFileDirNameOneDrive= [PicFilePathOneDrive, '/', saveTitle, '/', saveTitle ' ' Infrastructure, '.png'];
if strcmp(FinalVersion, 'Yes!')==1
    mkdir([PicFilePathOneDrive, '/', saveTitle, '/'])
    saveas(figuregcf, PicFileDirNameOneDrive)
end
end

```

## A 5.2.FUNCTIONALITY LOSS HISTOGRAMS

```

%% CHAPTER 07 FUNCTIONALITY LOSS HISTOGRAMS
clear;clc;close all;
load('MATFILEPATH/ALL','General');
MatFile = 'MATFILEPATH/ALL';
PicFilePathOneDrive = 'PICFILEPATH/07 RAA Comparison/Consequence histograms';
%%
Infrastructures = {'SvK','Energiforetagen','Road','Train','SVOA','TelecomAll','Mobile','IP','FixedPhone'};
InfrastructureTitles= {'Electricity transmission',...
    'Electricity distribution',...
    'Transport Road',...
    'Transport Railway',...
    'Drinking water network',...
    'Telecommunication',...
    'Telecommunication IP based',...
    'Telecommunication fixed phone',...
    'Telecommunication mobile'};

fLineWidth = 2.0;
strLineStyle = '-'; % [(Jahre & Fabbe-Costes) | -- | : | -.]
iMarkerSize = 25; % in points
strMarkerType = '.'; % [+ | o | * | . | x | square | diamond | > | < | ^ | v | pentagram | hexagram | {none}]
afMarkerFaceColor = [0.1 0.1 0.1];
afMarkerEdgeColor = [0.3 0.3 0.3];
afFigurePosition = [10 10 25 25*5.5/7.6]; % [pos_x pos_y width_x width_y]
afAxesPosition1 = [0.105177777777778 0.16148507295174 0.852311111111111 0.811362149270481];
afAxesPosition2 = [0.450079365079362 0.477032407407407 0.384023809523807 0.43];
afColorMap = General.PlotSettings.ColormapBone; % [left bottom width height]
% fonts properties
iFontSize = 24;
strFontUnit = 'points'; % [{points} | normalized | inches | centimeters | pixels]
strFontName = 'Helvetica'; % [Times | Courier | ] TODO complete the list
strFontWeight = 'normal'; % [light | {normal} | demi | bold]
strFontAngle = 'normal'; % [{normal} | italic | oblique] ps: only for axes
strInterpreter = 'tex';

%% FunctionalityLoss Histogram,
% type FinalVersion = 'Yes!' to save a PNG picture file to
% the location given by PicFilePathOneDrive
FinalVersion = 'Yes?!?!?';

BinWidth = 0.00004;
NrBinsPlot1 = 50;
NrBinsPlot2 = 20;
yLimit = [0 1];
ytick = '0:0.1:1';

for k = [1:5 7:9]

    Infrastructure = Infrastructures{k};
    saveTitle = 'Consequence Histogram';
    strTitle = [saveTitle ' - ' Infrastructure];
    variableValue = load(MatFile,Infrastructure);

    DataToPlot = variableValue.(Infrastructure).Metrics.FunctionalityLoss;
    [N1,edges] = histcounts(DataToPlot,'BinWidth',BinWidth);
    N = N1/sum(N1);

    [N2raw,edges2] = histcounts(DataToPlot(DataToPlot>(BinWidth*NrBinsPlot1)),NrBinsPlot2);
    N2 = N2raw/sum(N1);

    if size(edges,2)<NrBinsPlot1+2
        edges(1,(size(edges,2)+1):(NrBinsPlot1+2)) = (edges(size(edges,2))+BinWidth):BinWidth:(BinWidth*(NrBinsPlot1+1));
        N(1,(size(N,2)+1):(NrBinsPlot1+1)) = 0;
        secondplot = false;
    else
        secondplot = true;
    end

    Fmax = num2str(max(edges2));

    YScale1 = 'linear';
    YScale2 = 'linear';

    afX1 = edges(1:NrBinsPlot1+2);
    afY1 = [N(1:NrBinsPlot1) sum(N(NrBinsPlot1+1:end))];
    strYLabel1 = 'Fraction';
    strXLabel1 = 'F_{L}';

    afX2 = edges2;
    afY2 = N2;%
    strYLabel2 = 'Fraction';
    strXLabel2 = 'F_{L}';

    figure(gcf = ...
        figure(...
            'Name', strTitle,...
            'Units', 'centimeters', ... % [ inches | {centimeters} | normalized | points | !?(pixels)?! | characters
        ]
        'Position', afFigurePosition, ...
        'PaperPositionMode', 'auto');

    figuregcax1 = axes(...
        'Units', 'normalized', ...
        'Position', afAxesPosition1);

    if secondplot ==1
        figuregcax2 = axes('Position',afAxesPosition2);
    end

    axes(figuregcax1) %ok<LAXES>
    handleToPlot1 = histogram(...
        'BinEdges', afX1, ...
        'BinCounts', afY1, ...

```



```

'FaceColor',          afColorMap(50,:), ...
'FaceAlpha',          0.9000, ...
'EdgeColor',          afColorMap(15,:), ...
'LineWidth',          1.3);

set(figuregcax1, ...
    'XGrid',           'on', ... [on | {off}]
    'YGrid',           'on', ... [on | {off}]
    'GridLineStyle',   ':', ... [- | -- | {:} | -. | none]
    'XMinorGrid',      'off', ... [on | {off}]
    'YMinorGrid',      'off', ... [on | {off}]
    'MinorGridLineStyle', ':', ... [- | -- | {:} | -. | none]
    'YTick',           str2num(ytick), ... ticks of y axis
    'YMinorTick',      'off', ... [on | {off}]
    'TickDir',         'out', ... [(in) | out] inside or outside (for 2D)
    'TickLength',      [.005 .005], ... length of the ticks
    'XColor',          [.1 .1 .1], ... color of x axis
    'YColor',          [.1 .1 .1], ... color of y axis
    'XAxisLocation',   'bottom', ... where labels have to be printed [top | {bottom}]
    'YAxisLocation',   'left', ... where labels have to be printed [{left} | right]
    'XDir',            'normal', ... axis increasement direction [{normal} | reverse]
    'YDir',            'normal', ... axis increasement direction [{normal} | reverse]
    'XLim',            [0 0.0020+0.00004], ... limits for the x-axis
    'YLim',            yLimit, ... limits for the y-axis
    'YScale',          YScale1, ...
    'FontName',        strFontName, ... kind of fonts of labels
    'FontSize',        iFontSize, ... size of fonts of labels
    'FontUnits',       strFontUnit, ... units of the size of fonts
    'FontWeight',      strFontWeight, ... weight of fonts of labels
    'FontAngle',       strFontAngle, ... inclination of fonts of labels
    'LineWidth',       fLineWidth); %ok<ST2NM>

fXLabelRotation = 0.0;
fYLabelRotation = 90.0;

%
xlabel( strXLabel1, ...
    'FontName',        strFontName, ...
    'FontUnit',        strFontUnit, ...
    'FontSize',        iFontSize, ...
    'FontWeight',      strFontWeight, ...
    'Interpreter',     strInterpreter);

%
ylabel( strYLabel1, ...
    'FontName',        strFontName, ...
    'FontUnit',        strFontUnit, ...
    'FontSize',        iFontSize, ...
    'FontWeight',      strFontWeight, ...
    'Interpreter',     strInterpreter);

%
set(get(gca, 'XLabel'), 'Rotation', fXLabelRotation);
set(get(gca, 'YLabel'), 'Rotation', fYLabelRotation);

annotation(figuregcf, 'textbox', ...
    [0.899222222222223 0.0926892929292921 0.0356888888888888 0.0584969696969699], ...
    'String',          {'>'}, ...
    'LineStyle',        'none', ...
    'FontSize',        24, ...
    'FontName',        'Helvetica Neue', ...
    'FitBoxToText',     'off');

%Create textbox
annotation(figuregcf, 'textbox', ...
    [0.564788888888893 0.73030626262626 0.172566666666666 0.15794181818181], ...
    'String',          ['max(F_L) = ' Fmax ], ...
    'LineStyle',        'none', ...
    'FontSize',        20, ...
    'FontName',        'Helvetica Neue', ...
    'FitBoxToText',     'off');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SECOND LITTLE PLOTTIE %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if secondplot == 1
    axes(figuregcax2) %ok<LAXES>
    handleToPlot2 = histogram( ...
        'BinEdges',    afX2, ...
        'BinCounts',   afY2, ...
        'FaceColor',    afColorMap(50,:), ...
        'FaceAlpha',    0.8000, ...
        'EdgeColor',    afColorMap(30,:), ...
        'LineWidth',    1.1);

    set(figuregcax2, ...
        'XGrid',        'on', ... [on | {off}]
        'YGrid',        'on', ... [on | {off}]
        'GridLineStyle', ':', ... [- | -- | {:} | -. | none]
        'XMinorGrid',   'off', ... [on | {off}]
        'YMinorGrid',   'off', ... [on | {off}]
        'MinorGridLineStyle', ':', ... [- | -- | {:} | -. | none]
        'YMinorTick',   'off', ... [on | {off}]
        'TickDir',      'out', ... [(in) | out] inside or outside (for 2D)
        'TickLength',   [.005 .005]*.8, ... length of the ticks
        'XColor',       [.1 .1 .1], ... color of x axis
        'YColor',       [.1 .1 .1], ... color of y axis
        'XAxisLocation', 'bottom', ... where labels have to be printed [top | {bottom}]
        'YAxisLocation', 'left', ... where labels have to be printed [{left} | right]
        'XDir',         'normal', ... axis increasement direction [{normal} | reverse]
        'YDir',         'normal', ... axis increasement direction [{normal} | reverse]
        'YScale',       YScale2, ...
        'XLim',         [afX2(1) (afX2(end))], ... limits for the x-axis
        'YLim',         [0 figuregcax2.YLim(2)*1.15], ... limits for the y-axis
        'FontName',     strFontName, ... kind of fonts of labels
        'FontSize',     iFontSize-1, ... size of fonts of labels
        'FontUnits',    strFontUnit, ... units of the size of fonts
        'FontWeight',   strFontWeight, ... weight of fonts of labels
        'FontAngle',    strFontAngle, ... inclination of fonts of labels
        'LineWidth',    fLineWidth);

    fXLabelRotation = 0.0;

```

```

        fYLabelRotation = 90.0;

%
    xlabel( strXLabel2,
        'FontName',      strFontName,    ...
        'FontUnit',      strFontUnit,    ...
        'FontSize',      iFontSize-1,    ...
        'FontWeight',    strFontWeight,  ...
        'Interpreter',    strInterpreter);

%
    ylabel( strYLabel2,
        'FontName',      strFontName,    ...
        'FontUnit',      strFontUnit,    ...
        'FontSize',      iFontSize-1,    ...
        'FontWeight',    strFontWeight,  ...
        'Interpreter',    strInterpreter);

    set(get(gca, 'XLabel'), 'Rotation', fXLabelRotation);
    set(get(gca, 'YLabel'), 'Rotation', fYLabelRotation);
end

% if FinalVersion = 'Yes!' above, the figures are saved as PNG picture
% files in the location given by PicFilePathOneDrive
PicFileDirNameOneDrive= [PicFilePathOneDrive, '/', saveTitle, '/', saveTitle ' ' Infrastructure, '.png'];
if strcmp(FinalVersion, 'Yes!')==1
    %mkdir([PicFilePathLocal, '/', strTitle, '/'])
    mkdir([PicFilePathOneDrive, '/', saveTitle, '/'])
    saveas(figure(gcf, PicFileDirNameOneDrive)
end
end
end

```

## A 5.3.ANNUAL RESILIENCE LEVEL – STEP CURVE PLOT ALL INFRASTRUCTURES

```

%% CHAPTER 07 ANNUAL RESILIENCE LEVEL - STEP CURVE PLOT

clear;clc;close all;
load ('MATFILEPATH/ALL.mat', 'General');
load 'MATFILEPATH/ResiliencePlotsALLFailureCause'
PicFilePathOneDrive = 'PICFILEPATH/07 Comparison/';
InfrastructureNames = {'SvK','Energiforetagen','Road','Train','SVOA','Mobile','IP','FixedPhone'};
InfrastructureTitles= {'Electricity transmission',...
    'Electricity distribution',...
    'Transport Road',...
    'Transport Railway',...
    'Drinking water network',...
    'Telecommunication',...
    'Telecommunication IP based',...
    'Telecommunication fixed phone',...
    'Telecommunication mobile'};

TableNames = {'All','Human','Natural','Technical','External','UnknownOrMissingdata'};

%% REALLY NICE PLOTS
% type FinalVersion = 'Yes!' to save a PNG picture file to
% the location given by PicFilePathOneDrive
FinalVersion = 'WEEEeeeeeeell, maaayybeee soon?!?!?';

afColorMap = General.PlotSettings.ColormapBone; % [left bottom width height]
fLineWidth = 1.5;
strLineStyle = '-'; % [(Jahre & Fabbe-Costes) | -- | : | -.]
iMarkerSize = 25; % in points
strMarkerType = '+'; % [+ | o | * | . | x | square | diamond | > | < | ^ | v | pentagram | hexagram | {none}]
afMarkerFaceColor = [0.1 0.1 0.1];
afMarkerEdgeColor = [0.3 0.3 0.3];
afFigurePosition = [10 10 45 45*8/15.89]; % [pos_x pos_y width_x width_y]

% fonts properties
iFontSize = 24;
strFontUnit = 'points'; % [{points} | normalized | inches | centimeters | pixels]
strFontName = 'Helvetica'; % [Times | Courier | ] TODO complete the list
strFontWeight = 'normal'; % [light | {normal} | demi | bold]
strFontAngle = 'normal'; % [{normal} | italic | oblique] ps: only for axes

afPlotLineWidth = [1.9, 1.9, 1.9, 1.9, 1.9, 1.9, 1.9, 1.9];
astrPlotLineStyle = [{'-.'}, {'.'}, {...},
    {'--'}, {'.'}, {...},
    {'-.'}, {'-.'}, {...},
    {'-.'}, {'-.'}];

aafPlotLineColor = [afColorMap(18,:);...
    afColorMap(22,:);...
    afColorMap(26,:);...
    afColorMap(30,:);...
    afColorMap(34,:);...
    afColorMap(28,:);...
    afColorMap(24,:);...
    afColorMap(20,:);];

aiPlotMarkerSize = [14, 9, 12, 9, 9, 9, 9, 9]; % size in points
astrPlotMarkerType = [{'diamond'}, {'x'}, {...},
    {'+'}, {'p'}, {...},
    {'^'}, {'.'}, {...},
    {'s'}, {'*'}];

aafPlotMarkerFaceColor = [[0.1 0.1 0.1] ; [0.2 0.2 0.2] ;...
    [0.3 0.3 0.3] ; [0.4 0.4 0.4] ;...
    [1 1 1] ; [0.6 0.6 0.6]]; % RGB
aafPlotMarkerEdgeColor = [[0.7 0.7 0.7] ; [0.4 0.4 0.4] ;...
    [0 0 0] ; [0.6 0.6 0.6] ;...
    [0.4 0.4 0.4] ; [0.8 0.8 0.8] ;...
    [0.4 0.4 0.4] ; [0.8 0.8 0.8]]; % RGB

xTick = datetime([2005 01 01];...
    [2006 01 01];...
    [2007 01 01];...
    [2008 01 01];...
    [2009 01 01];...

```

```

                [2010 01 01];...
                [2011 01 01];...
                [2012 01 01];...
                [2013 01 01];...
                [2014 01 01];...
                [2015 01 01];...
                [2016 01 01];...
                [2017 01 01];...
                [2018 01 01]];
xTickLabel      = num2cell(2005:1:2018);
xLim            = [xTick(1) xTick(end)];

strTitle = 'Resilience Yearly Mean';
saveTitle = strTitle;
Infrastructure = 'ALL';

figuregcf = figure(...
    'Name',                strTitle,          ...
    'Units',                'centimeters',     ...
    'Position',             afFigurePosition,  ...
    'PaperType',            'A4',              ...
    'PaperPositionMode',    'auto');
figuregca      = gca;

strYLabel      = 'Mean resilience level' ;
strXLabel      = 'Year' ;

afX1           = ResiliencePlots.ResilienceAveragePlot.(Infrastructures{1}).DateTime;
afY1           = ResiliencePlots.ResilienceAveragePlot.(Infrastructures{1}).MeanResilience;
strLabel1      = Infrastructures{1};

afX2           = ResiliencePlots.ResilienceAveragePlot.(Infrastructures{2}).DateTime;
afY2           = ResiliencePlots.ResilienceAveragePlot.(Infrastructures{2}).MeanResilience;
strLabel2      = Infrastructures{2};

afX3           = ResiliencePlots.ResilienceAveragePlot.(Infrastructures{3}).DateTime;
afY3           = ResiliencePlots.ResilienceAveragePlot.(Infrastructures{3}).MeanResilience;
strLabel3      = Infrastructures{3};

afX4           = ResiliencePlots.ResilienceAveragePlot.(Infrastructures{4}).DateTime;
afY4           = ResiliencePlots.ResilienceAveragePlot.(Infrastructures{4}).MeanResilience;
strLabel4      = Infrastructures{4};

afX5           = ResiliencePlots.ResilienceAveragePlot.(Infrastructures{5}).DateTime;
afY5           = ResiliencePlots.ResilienceAveragePlot.(Infrastructures{5}).MeanResilience;
strLabel5      = Infrastructures{5};

afX6           = ResiliencePlots.ResilienceAveragePlot.(Infrastructures{6}).DateTime;
afY6           = ResiliencePlots.ResilienceAveragePlot.(Infrastructures{6}).MeanResilience;
strLabel6      = Infrastructures{6};

afX7           = ResiliencePlots.ResilienceAveragePlot.(Infrastructures{7}).DateTime;
afY7           = ResiliencePlots.ResilienceAveragePlot.(Infrastructures{7}).MeanResilience;
strLabel7      = Infrastructures{7};

afX8           = ResiliencePlots.ResilienceAveragePlot.(Infrastructures{8}).DateTime;
afY8           = ResiliencePlots.ResilienceAveragePlot.(Infrastructures{8}).MeanResilience;
strLabel8      = Infrastructures{8};

hold on
handleToPlot1 = stairs(
afX1,
afY1,
'LineStyle',    astrPlotLineStyle{6},
'LineWidth',    afPlotLineWidth(1),
'Color',        aafPlotLineColor(1,:),
'Marker',       astrPlotMarkerType{1},
'MarkerSize',   aiPlotMarkerSize(1),
'MarkerFaceColor', aafPlotLineColor(1,:),
'MarkerEdgeColor', aafPlotMarkerEdgeColor(1,:));

handleToPlot2 = stairs(
afX2,
afY2,
'LineStyle',    astrPlotLineStyle{6},
'LineWidth',    afPlotLineWidth(2),
'Color',        aafPlotLineColor(2,:),
'Marker',       astrPlotMarkerType{2},
'MarkerSize',   aiPlotMarkerSize(2),
'MarkerFaceColor', aafPlotLineColor(2,:),
'MarkerEdgeColor', aafPlotMarkerEdgeColor(2,:));

handleToPlot3 = stairs(
afX3,
afY3,
'LineStyle',    astrPlotLineStyle{6},
'LineWidth',    afPlotLineWidth(3),
'Color',        aafPlotLineColor(3,:),
'Marker',       astrPlotMarkerType{3},
'MarkerSize',   aiPlotMarkerSize(3),
'MarkerFaceColor', aafPlotLineColor(3,:),
'MarkerEdgeColor', aafPlotMarkerEdgeColor(3,:));

handleToPlot4 = stairs(
afX4,
afY4,
'LineStyle',    astrPlotLineStyle{6},
'LineWidth',    afPlotLineWidth(4),
'Color',        aafPlotLineColor(4,:),
'Marker',       astrPlotMarkerType{4},
'MarkerSize',   aiPlotMarkerSize(4),
'MarkerFaceColor', aafPlotLineColor(4,:),
'MarkerEdgeColor', aafPlotMarkerEdgeColor(4,:));

handleToPlot5 = stairs(
afX5,
afY5,
'LineStyle',    astrPlotLineStyle{6},

```

```

'LineWidth',      afPlotLineWidth(5),      ...
'Color',          aafPlotLineColor(5,:),    ...
'Marker',         astrPlotMarkerType(5),    ...
'MarkerSize',     aiPlotMarkerSize(5),      ...
'MarkerFaceColor', aafPlotLineColor(5,:),   ...
'MarkerEdgeColor', aafPlotMarkerEdgeColor(5,:);

handleToPlot6 = stairs(
afX6,
afY6,
'LineStyle',      astrPlotLineStyle{6},    ...
'LineWidth',      afPlotLineWidth(6),      ...
'Color',          aafPlotLineColor(6,:),    ...
'Marker',         astrPlotMarkerType(6),    ...
'MarkerSize',     aiPlotMarkerSize(6),      ...
'MarkerFaceColor', aafPlotLineColor(6,:),   ...
'MarkerEdgeColor', aafPlotMarkerEdgeColor(6,:);

handleToPlot7 = stairs(
afX7,
afY7,
'LineStyle',      astrPlotLineStyle{6},    ...
'LineWidth',      afPlotLineWidth(7),      ...
'Color',          aafPlotLineColor(7,:),    ...
'Marker',         astrPlotMarkerType(7),    ...
'MarkerSize',     aiPlotMarkerSize(7),      ...
'MarkerFaceColor', aafPlotLineColor(7,:),   ...
'MarkerEdgeColor', aafPlotMarkerEdgeColor(7,:);

handleToPlot8 = stairs(
afX8,
afY8,
'LineStyle',      astrPlotLineStyle{6},    ...
'LineWidth',      afPlotLineWidth(8),      ...
'Color',          aafPlotLineColor(8,:),    ...
'Marker',         astrPlotMarkerType(8),    ...
'MarkerSize',     aiPlotMarkerSize(8),      ...
'MarkerFaceColor', aafPlotLineColor(8,:),   ...
'MarkerEdgeColor', aafPlotMarkerEdgeColor(8,:);

set(gca,
'Position',      [0.0835185185185185 0.11 0.890567901234568 0.864034930555555],...
'XGrid',         'on',                     ... [on | {off}]
'YGrid',         'on',                     ... [on | {off}]
'GridLineStyle', ':',                     ... [- | -- | {:} | -. | none]
'XMinorGrid',    'on',                     ... [on | {off}]
'YMinorGrid',    'on',                     ... [on | {off}]
'MinorGridLineStyle', ':',                 ... [- | -- | {:} | -. | none]
'XTick',         xTick,                     ... ticks of x axis
'XTickLabel',    xTickLabel,                ...
'XMinorTick',    'off',                     ... [on | {off}]
'YMinorTick',    'off',                     ... [on | {off}]
'TickDir',       'out',                     ... [{in} | out] inside or outside (for 2D)
'TickLength',    [.005 .005],               ... length of the ticks
'XColor',        [.1 .1 .1],                ... color of x axis
'YColor',        [.1 .1 .1],                ... color of y axis
'XAxisLocation', 'bottom',                 ... where labels have to be printed [top | {bottom}]
'YAxisLocation', 'left',                   ... where labels have to be printed [{left} | right]
'XDir',          'normal',                  ... axis increasement direction [{normal} | reverse]
'YDir',          'normal',                  ... axis increasement direction [{normal} | reverse]
'XLim',          xLim,                      ... limits for the x-axis
'YLim',          [0.984 1.001],             ... limits for the y-axis
'FontName',      strFontName,               ... kind of fonts of labels
'FontSize',      iFontSize,                 ... size of fonts of labels
'FontUnits',     strFontUnit,               ... units of the size of fonts
'FontWeight',    strFontWeight,             ... weight of fonts of labels
'FontAngle',     strFontAngle,              ... inclination of fonts of labels
'LineWidth',     fLineWidth,                % width of the line of the axes

fXLabelRotation = 0.0;
fYLabelRotation = 90.0;
strInterpreter = 'tex';

%
xlabel( strXLabel,
'FontName',      strFontName,      ...
'FontUnit',      strFontUnit,      ...
'FontSize',      iFontSize,        ...
'FontWeight',    strFontWeight,    ...
'Interpreter',   strInterpreter);

%
ylabel( strYLabel,
'FontName',      strFontName,      ...
'FontUnit',      strFontUnit,      ...
'FontSize',      iFontSize,        ...
'FontWeight',    strFontWeight,    ...
'Interpreter',   strInterpreter);

%
set(get(gca, 'XLabel'), 'Rotation', fXLabelRotation);
set(get(gca, 'YLabel'), 'Rotation', fYLabelRotation);

atArrayOfHandlesToLines = strTitle;
box on

astrArrayOfLabels = InfrastructureTitles;

% - N = North
% - S = South
% - E = East
% - W = West
% - O = Outside the plot
% - B = Best (least conflict with data in plot)
strLegendLocation = 'SW'; % combinations of N S E W B O or a vector

strLegendOrientation = 'vertical'; % [{vertical} horizontal]

%

```

```

afEdgeColor      = [1.0 1.0 1.0]; % RGB
afTextColor      = [0.0 0.0 0.0]; % RGB

%
legend( atArrayOfHandlesToLines, ...
        astrArrayOfLabels, ...
        'Position', [0.119059082892417 0.163148622663617 0.339450617283951 0.335559772376543], ...
        'Orientation', strLegendOrientation, ...
        'Box', 'off', ... [on {off}]
        'Color', [1 1 1], ... none => transparent
        'EdgeColor', afEdgeColor, ...
        'TextColor', afTextColor, ...
        'Interpreter', strInterpreter);

% fix the line's layering so that they become more visible
uistack(handleToPlot1,'bottom')
uistack(handleToPlot3,'top')

hold off

% if FinalVersion = 'Yes!' above, the figures are saved as PNG picture
% files in the location given by PicFilePathOneDrive
PicFilePathOneDrive = [PicFilePathOneDrive, '/', saveTitle, '/', saveTitle ' ' Infrastructure, '.png'];
if strcmp(FinalVersion, 'Yes!')==1
    %mkdir([PicFilePathLocal, '/', strTitle, '/'])
    mkdir([PicFilePathOneDrive, '/', saveTitle, '/'])
    saveas(figure(gcf), PicFilePathOneDrive)
end

```

## A 5.4. RESILIENCE VALUE TABLE ALL INFRASTRUCTURES

```

%% CHAPTER 07 RESILIENCE VALUE TABLE - ALL INFRASTRUCTURES
clear;clc;close all;
load 'MATFILEPATH/FunctionalityCurveElement.mat'

InfrastructureResilience = { 'SvK', 'Energiforetagen', 'Road', 'Train', 'SVOA', 'Mobile', 'IP', 'FixedPhone' };
InfrastructureTitles = { 'Electricity transmission', ...
    'Electricity distribution', ...
    'Transport Road', ...
    'Transport Railway', ...
    'Drinking water network', ...
    'Telecommunication', ...
    'Telecommunication IP based', ...
    'Telecommunication fixed phone', ...
    'Telecommunication mobile' };

MatFilePath = '/Users/musse/Documents/Skola/Examensarbete/Infrastructure Resilience/Data/ALL/ALL.mat';

% create vectors for each variable in the matrix/table
ResilienceMetricTables = table;
ResilienceMetricTables.DurationMean = zeros(8,1);
ResilienceMetricTables.DurationVariance = zeros(8,1);
ResilienceMetricTables.DurationMax = zeros(8,1);
ResilienceMetricTables.FunctionalityLossMean = zeros(8,1);
ResilienceMetricTables.FunctionalityLossVariance = zeros(8,1);
ResilienceMetricTables.FunctionalityLossMax = zeros(8,1);
ResilienceMetricTables.ResilienceLossMean = zeros(8,1);
ResilienceMetricTables.ResilienceLossVariance = zeros(8,1);
ResilienceMetricTables.ResilienceLossMax = zeros(8,1);
ResilienceMetricTables.ResilienceMean = zeros(8,1);
ResilienceMetricTables.Properties.RowNames = InfrastructureTitles;
ResilienceMetricTables.Row_Names(:) = InfrastructureTitles;
% create a table for rounded numbers
ResilienceMetricTables_Rounded = table;
ResilienceMetricTables_Rounded.DurationMean = cell(8,1);
ResilienceMetricTables_Rounded.DurationVariance = cell(8,1);
ResilienceMetricTables_Rounded.DurationMax = cell(8,1);
ResilienceMetricTables_Rounded.FunctionalityLossMean = cell(8,1);
ResilienceMetricTables_Rounded.FunctionalityLossVariance = cell(8,1);
ResilienceMetricTables_Rounded.FunctionalityLossMax = cell(8,1);
ResilienceMetricTables_Rounded.ResilienceLossMean = cell(8,1);
ResilienceMetricTables_Rounded.ResilienceLossVariance = cell(8,1);
ResilienceMetricTables_Rounded.ResilienceLossMax = cell(8,1);
ResilienceMetricTables_Rounded.ResilienceMean = cell(8,1);
ResilienceMetricTables_Rounded.Row_Names(:) = InfrastructureTitles;

ResilienceRanking = table;
ResilienceRanking.InfrastructureTitles = transpose(InfrastructureTitles);
ResilienceRanking.Ranking = zeros(8,1);
ResilienceRanking.ResilienceLossMean = cell(8,1);
ResilienceRanking.ComparisomnFactor = cell(8,1);

for k = 1:8

    disp(num2str(k))
    Infrastructure = InfrastructureResilience{k};
    InfrastructureTitle = InfrastructureTitles{k};
    VarName = load(MatFilePath, Infrastructure);
    DateTimesFunctionality = ResiliencePlots.FunctionalityCurve.(Infrastructure).PreFunctionalityCurve.All.DateTime<ResiliencePlots.To-
talDuration.(Infrastructure).End;
    DateTimesElement = ResiliencePlots.FunctionalityCurve.(Infrastructure).FunctionalityCurveElement.All.DateTime<Resilien-
cePlots.TotalDuration.(Infrastructure).End;
    Functionality = ResiliencePlots.FunctionalityCurve.(Infrastructure).PreFunctionalityCurve.All.Functionality(DateTimesFunc-
tionality);
    FunctionalityElement = ResiliencePlots.FunctionalityCurve.(Infrastructure).FunctionalityCurveElement.All.ElementResili-
ence(DateTimesElement);

    Metrics = VarName.(Infrastructure).Metrics;
    TotalDuration = VarName.(Infrastructure).TotalDuration;

    ResilienceMetricTables.DurationMean(k) = mean(Metrics.Duration);
    ResilienceMetricTables.DurationVariance(k) = var(Metrics.Duration);
    ResilienceMetricTables.DurationMax(k) = max(Metrics.Duration);
    ResilienceMetricTables.FunctionalityLossMean(k) = mean(1-Functionality)*10^3;
    ResilienceMetricTables.FunctionalityLossVariance(k) = var(1-Functionality)*10^6;

```

```

ResilienceMetricTables.FunctionalityLossMax(k) = max(1-Functionality)*10^3;
ResilienceMetricTables.ResilienceLossMean(k) = mean(1-FunctionalityElement)*10^6;
ResilienceMetricTables.ResilienceLossVariance(k) = var(1-FunctionalityElement)*10^6;
ResilienceMetricTables.ResilienceLossMax(k) = max(1-FunctionalityElement);
ResilienceMetricTables.ResilienceMean(k) = mean(FunctionalityElement);

precision=3;% precision/number of significant digits
ResilienceMetricTables_Rounded.DurationMean{k} = num2str(ResilienceMetricTables.DurationMean(k),precision);
ResilienceMetricTables_Rounded.DurationVariance{k} = num2str(ResilienceMetricTables.DurationVariance(k),precision);
ResilienceMetricTables_Rounded.DurationMax{k} = num2str(ResilienceMetricTables.DurationMax(k),precision);
ResilienceMetricTables_Rounded.FunctionalityLossMean{k} = num2str(ResilienceMetricTables.FunctionalityLossMean(k),precision);
ResilienceMetricTables_Rounded.FunctionalityLossVariance{k} = num2str(ResilienceMetricTables.FunctionalityLossVariance(k),precision);
ResilienceMetricTables_Rounded.FunctionalityLossMax{k} = num2str(ResilienceMetricTables.FunctionalityLossMax(k),precision);
ResilienceMetricTables_Rounded.ResilienceLossMean{k} = num2str(ResilienceMetricTables.ResilienceLossMean(k),precision);
ResilienceMetricTables_Rounded.ResilienceLossVariance{k} = num2str(ResilienceMetricTables.ResilienceLossVariance(k),precision);
ResilienceMetricTables_Rounded.ResilienceLossMax{k} = num2str(ResilienceMetricTables.ResilienceLossMax(k),precision);
% 5 significant digits for resilience mean
ResilienceMetricTables_Rounded.ResilienceMean{k} = num2str(ResilienceMetricTables.ResilienceMean(k), '%#.5g');
end
%% create a result table for the comparison factor
ResilienceRanking.ResilienceLossMean = ResilienceMetricTables_Rounded.ResilienceLossMean;
ResilienceRanking.ComparisomnFactor = round(ResilienceMetricTables.ResilienceLossMean/ResilienceMetricTables.ResilienceLossMean(1));
ResilienceRanking = sortrows(ResilienceRanking, 'ComparisomnFactor', 'ascend');
ResilienceRanking.Ranking(:) = 1:8;

writetable(ResilienceMetricTables_Rounded, 'TABLEPATH/07 Comparison/AllInfrastructures_rounded.xlsx')
writetable(ResilienceRanking, 'TABLEPATH/07 Comparison/ResilienceRanking.xlsx')
clearvars -except ResilienceMetricTables ResilienceMetricTables_Rounded ResilienceRanking

%%
save('MATFILEPATH/ResilienceMetricTableAll', 'ResilienceMetricTables')

```

## A 5.5.RESILIENCE CURVES – ALL PLOTTED

```

%% CHAPTER 07 RESILIENCE CURVE PLOT - ALL INFRASTRUCTURES
clear;clc;close all;
load('MATFILEPATH/ALL.mat','General');
load('MATFILEPATH/FunctionalityCurveElement.mat');

PicFilePathOneDrive = '/Users/musse/OneDrive/Exjobb/Resilience/Thesis Parts/06 RAA each infrastructure/Figures';
Infrastructures = {'SvK', ...1
'Energiforetagen', ...2
'Road', ...3
'Train', ...4
'SVOA', ...5
'Mobile', ...6
'IP', ...7
'FixedPhone'}; % 8

InfrastructureTitles = {'Electricity Transmission', ...
'Electricity Distribution', ...
'Transport Road', ...
'Transport Railway', ...
'Water Supply', ...
'Telecommunication Mobile', ...
'Telecommunication Broadband Services',...
'Telecommunication Fixed Telephony'};

TableNames = {'All','Human','Natural','Technical','External','UnknownOrMissingdata'};

afColorMap = General.PlotSettings.ColormapBone; % [left bottom width height]
fLineWidth = 1.0;
strLineStyle = '-'; % [(Jahre & Fabbe-Costes) | -- | : | -.]
iMarkerSize = 25; % in point
strMarkerType = '-'; % [+ | o | * | . | x | square | diamond | > | < | ^ | v | pentagram | hexagram | {none}]
afMarkerFaceColor = General.PlotSettings.ColormapBone(15,:);
afMarkerEdgeColor = General.PlotSettings.ColormapBone(15,:);
afPlotLineWidth = [1.6,...1
0.7,...2
0.8,...3
0.8,...4
0.8,...5
1.0,...6
0.8,...7
1.0];% 8

astrPlotLineStyle = [{'-'}, ...1
{'-'}, ...2
{'-'}, ...3
{'-'}, ...4
{'-'}, ...5
{'-'}, ...6
{'-'}, ...7
{'-'}, ...8
{'-'}]; % 9

%%
aafPlotLineColor = [afColorMap(10,:);...1
afColorMap(30,:);...2
afColorMap(41,:);...3
afColorMap(58,:);...4
afColorMap(32,:);...5
afColorMap(28,:);...6
afColorMap(24,:);...7
afColorMap(35,:);...8];% 8

aafPlotMarkerFaceColor = [[0.1 0.1 0.1] ; [0.2 0.2 0.2] ;...
[0.3 0.3 0.3] ; [0.4 0.4 0.4] ;...
[0.5 0.5 0.5] ; [0.6 0.6 0.6]]; % RGB
aafPlotMarkerEdgeColor = [[0.3 0.3 0.3] ; [0.4 0.4 0.4] ;...
[0.5 0.5 0.5] ; [0.6 0.6 0.6] ;...
[0.7 0.7 0.7] ; [0.8 0.8 0.8]]; % RGB
afFigurePosition = [10 10 45 45*3.6/15.49];

```

```

afAxesPosition      = [0.105177777777778 0.16148507295174 0.852311111111111 0.811362149270481];

aafPlotLineColorZero = General.PlotSettings.ColormapBone(19,:);

afPlotLineWidthZero  = 1.2;

% fonts properties
iFontSize            = 24;
strFontUnit          = 'points';
strFontName          = 'Helvetica';
strFontWeight        = 'normal';
strFontAngle         = 'normal';
strInterpreter       = 'tex';

Years    = 2005:2016;
Inf      = 4;

YearsPlots = 2005:2018;

% type FinalVersion = 'Yes!' to save a PNG picture file to
% the location given by PicFilePathOneDrive
FinalVersion = 'WEEL IS IT TIME??!?!';

%%

for k = 1:6

    Infrastructure = Infrastructures{Inf};

    strYLabel1     = 'Functionality';

    strTitle       = 'Functionality Curve Plot - ALL ';
    saveTitle      = 'Functionality Curve Plot';

    figuregcf = figure(...
        'Name',          strTitle,          ...
        'Units',         'centimeters',     ...
        'Position',      afFigurePosition,  ...
        'PaperType',     'A4',              ...
        'PaperPositionMode', 'auto');

    figuregca = axes('Position', afAxesPosition);

    afX1      = ResiliencePlots.FunctionalityCurve.(Infrastructures{1}).FunctionalityCurveElement.All.DateTime;
    afY1      = ResiliencePlots.FunctionalityCurve.(Infrastructures{1}).FunctionalityCurveElement.All.ElementResilience;
    strLabel1 = Infrastructures{1};

    afX2      = ResiliencePlots.FunctionalityCurve.(Infrastructures{2}).FunctionalityCurveElement.All.DateTime;
    afY2      = ResiliencePlots.FunctionalityCurve.(Infrastructures{2}).FunctionalityCurveElement.All.ElementResilience;
    strLabel2 = Infrastructures{2};

    afX3      = ResiliencePlots.FunctionalityCurve.(Infrastructures{3}).FunctionalityCurveElement.All.DateTime;
    afY3      = ResiliencePlots.FunctionalityCurve.(Infrastructures{3}).FunctionalityCurveElement.All.ElementResilience;
    strLabel3 = Infrastructures{3};

    afX4      = ResiliencePlots.FunctionalityCurve.(Infrastructures{4}).FunctionalityCurveElement.All.DateTime;
    afY4      = ResiliencePlots.FunctionalityCurve.(Infrastructures{4}).FunctionalityCurveElement.All.ElementResilience;
    strLabel4 = Infrastructures{4};

    afX5      = ResiliencePlots.FunctionalityCurve.(Infrastructures{5}).FunctionalityCurveElement.All.DateTime;
    afY5      = ResiliencePlots.FunctionalityCurve.(Infrastructures{5}).FunctionalityCurveElement.All.ElementResilience;
    strLabel5 = Infrastructures{5};

    afX6      = ResiliencePlots.FunctionalityCurve.(Infrastructures{6}).FunctionalityCurveElement.All.DateTime;
    afY6      = ResiliencePlots.FunctionalityCurve.(Infrastructures{6}).FunctionalityCurveElement.All.ElementResilience;
    strLabel6 = Infrastructures{6};

    afX7      = ResiliencePlots.FunctionalityCurve.(Infrastructures{7}).FunctionalityCurveElement.All.DateTime;
    afY7      = ResiliencePlots.FunctionalityCurve.(Infrastructures{7}).FunctionalityCurveElement.All.ElementResilience;
    strLabel7 = Infrastructures{7};

    afX8      = ResiliencePlots.FunctionalityCurve.(Infrastructures{8}).FunctionalityCurveElement.All.DateTime;
    afY8      = ResiliencePlots.FunctionalityCurve.(Infrastructures{8}).FunctionalityCurveElement.All.ElementResilience;
    strLabel8 = Infrastructures{8};

    hold on

    handleToPlot1 = stairs(
        afX1,          ...
        afY1,          ...
        'LineStyle',    astrPlotLineStyle{1}, ...
        'LineWidth',    afPlotLineWidth(1),   ...
        'Color',        aafPlotLineColor(1,:));

    handleToPlot2 = stairs(
        afX2,          ...
        afY2,          ...
        'LineStyle',    astrPlotLineStyle{2}, ...
        'LineWidth',    afPlotLineWidth(2),   ...
        'Color',        aafPlotLineColor(2,:));

    handleToPlot3 = stairs(
        afX3,          ...
        afY3,          ...
        'LineStyle',    astrPlotLineStyle{3}, ...
        'LineWidth',    afPlotLineWidth(3),   ...
        'Color',        aafPlotLineColor(3,:));

    handleToPlot4 = stairs(
        afX4,          ...
        afY4,          ...
        'LineStyle',    astrPlotLineStyle{4}, ...
        'LineWidth',    afPlotLineWidth(4),   ...
        'Color',        aafPlotLineColor(4,:));

    handleToPlot5 = stairs(
        afX5,          ...
        afY5,          ...
        'LineStyle',    astrPlotLineStyle{5}, ...
        'LineWidth',    afPlotLineWidth(5),   ...

```

```

'Color',          aafPlotLineColor(5,:));

handleToPlot6 = stairs(
afX6,              ...
afY6,              ...
'LineStyle',       astrPlotLineStyle{6},    ...
'LineWidth',       afPlotLineWidth(6),      ...
'Color',           aafPlotLineColor(6,:));

handleToPlot7 = stairs(
afX7,              ...
afY7,              ...
'LineStyle',       astrPlotLineStyle{7},    ...
'LineWidth',       afPlotLineWidth(7),      ...
'Color',           aafPlotLineColor(7,:));

handleToPlot8 = stairs(
afX8,              ...
afY8,              ...
'LineStyle',       astrPlotLineStyle{8},    ...
'LineWidth',       afPlotLineWidth(8),      ...
'Color',           aafPlotLineColor(8,:));

set(figuregca,
'XGrid',           'on',                    ... [on | {off}]
'YGrid',           'on',                    ... [on | {off}]
'GridLineStyle',   ':',                    ... [- | -- | {:} | -. | none]
'XMinorGrid',      'on',                    ... [on | {off}]
'YMinorGrid',      'on',                    ... [on | {off}]
'MinorGridLineStyle', ':',                ... [- | -- | {:} | -. | none]
'YMinorTick',      'off',                   ... [on | {off}]
'TickDir',         'out',                   ... [{in} | out] inside or outside (for 2D)
'TickLength',      [.005 .005],             ... length of the ticks
'XColor',          [.1 .1 .1],              ... color of x axis
'YColor',          [.1 .1 .1],              ... color of y axis
'XAxisLocation',   'bottom',                ... where labels have to be printed [top | {bottom}]
'YAxisLocation',   'left',                  ... where labels have to be printed [{left} | right]
'XDir',            'normal',                 ... axis increase direction [{normal} | reverse]
'YDir',            'normal',                 ... axis increase direction [{normal} | reverse]
'XLim',            [datetime([Years(1) 1 1 0 0 0]) datetime([Years(end)+1 1 1 0 0 0])],...
'YLim',            [0.84 1.02],             ...
'FontName',        strFontName,             ... kind of fonts of labels
'FontSize',        iFontSize,               ... size of fonts of labels
'FontUnits',       strFontUnit,             ... units of the size of fonts
'FontWeight',      strFontWeight,           ... weight of fonts of labels
'FontAngle',       strFontAngle,            ... inclination of fonts of labels
...
'LineWidth',       fLineWidth);

fYLabelRotation = 90.0;
ylabel( strYLabel1,
'FontName',        strFontName,             ...
'FontUnit',        strFontUnit,             ...
'FontSize',        iFontSize,               ...
'FontWeight',      strFontWeight,           ...
'Interpreter',     strInterpreter);

set(get(gca, 'YLabel'), 'Rotation', fYLabelRotation);

ZeroLineX          = figuregca.XLim;
ZeroLineY          = [1 1];

hold off

atArrayOfHandlesToLines = strTitle;
strLegendOrientation = 'vertical';           % [{vertical} horizontal]
astrArrayOfLabels     = InfrastructureTitles;
strLegendLocation     = 'SW';                % combinations of N S E W B O or a vector
afEdgeColor           = [1.0 1.0 1.0];      % RGB
afTextColor           = [0.0 0.0 0.0];      % RGB

legend( atArrayOfHandlesToLines,
astrArrayOfLabels,
'Location',          strLegendLocation,
'Orientation',       strLegendOrientation,
'Box',               'off',                  ... [on {off}]
'Color',             [1 1 1],               ... none => transparent
'EdgeColor',         afEdgeColor,
'TextColor',         afTextColor,
'Interpreter',       strInterpreter);

uistack(handleToPlot4,'bottom')
uistack(handleToPlot2,'top')

box on
% if FinalVersion = 'Yes!' above, the figures are saved as PNG picture
% files in the location given by PicFilePathOneDrive
PicFileDirNameOneDrive= [PicFilePathOneDrive, '/', saveTitle, '/', Infrastructure, '/', strTitle ' ' Infrastructure, '.png'];
if strcmp(FinalVersion, 'Yes!')==1
%mkdir([PicFilePathLocal, '/', strTitle, '/'])
mkdir([PicFilePathOneDrive, '/', saveTitle, '/', Infrastructure, '/'])
saveas(figuregcf, PicFileDirNameOneDrive)
end
end

```



## A 6. GENERAL PLOT SETTINGS

### COLOR MAP – (BONE)

```
%% GENERAL PLOT SETTING COLORMAP (BONE)
```

```
General.PlotSettings.ColormapBone = ...  
[0,0,0,0.005208333333333333;  
 0.01388888888888889,0.01388888888888889,0.02430555555555556;  
 0.02777777777777778,0.02777777777777778,0.04340277777777778;  
 0.04166666666666667,0.04166666666666667,0.06250000000000000;  
 0.05555555555555556,0.05555555555555556,0.08159722222222222;  
 0.06944444444444445,0.06944444444444445,0.10069444444444444;  
 0.08333333333333333,0.08333333333333333,0.11979166666666667;  
 0.09722222222222222,0.09722222222222222,0.13888888888888889;  
 0.11111111111111111,0.11111111111111111,0.15798611111111111;  
 0.12500000000000000,0.12500000000000000,0.17708333333333333;  
 0.13888888888888889,0.13888888888888889,0.19618055555555556;  
 0.15277777777777778,0.15277777777777778,0.21527777777777778;  
 0.16666666666666667,0.16666666666666667,0.23437500000000000;  
 0.18055555555555556,0.18055555555555556,0.25347222222222222;  
 0.19444444444444444,0.19444444444444444,0.27256944444444444;  
 0.20833333333333333,0.20833333333333333,0.29166666666666667;  
 0.22222222222222222,0.22222222222222222,0.31076388888888889;  
 0.23611111111111111,0.23611111111111111,0.32986111111111111;  
 0.25000000000000000,0.25000000000000000,0.34895833333333333;  
 0.26388888888888889,0.26388888888888889,0.36805555555555556;  
 0.27777777777777778,0.27777777777777778,0.38715277777777778;  
 0.29166666666666667,0.29166666666666667,0.40625000000000000;  
 0.30555555555555556,0.30555555555555556,0.42534722222222222;  
 0.31944444444444444,0.31944444444444444,0.44444444444444444;  
 0.33333333333333333,0.33854166666666667,0.45833333333333333;  
 0.34722222222222222,0.35763888888888889,0.47222222222222222;  
 0.36111111111111111,0.37673611111111111,0.48611111111111111;  
 0.37500000000000000,0.39583333333333333,0.50000000000000000;  
 0.38888888888888889,0.41493055555555556,0.51388888888888889;  
 0.40277777777777778,0.43402777777777778,0.52777777777777778;  
 0.41666666666666667,0.45312500000000000,0.54166666666666667;  
 0.43055555555555556,0.47222222222222222,0.55555555555555556;  
 0.44444444444444444,0.49131944444444444,0.56944444444444444;  
 0.45833333333333333,0.51041666666666667,0.58333333333333333;  
 0.47222222222222222,0.52951388888888889,0.59722222222222222;  
 0.48611111111111111,0.54861111111111111,0.61111111111111111;  
 0.50000000000000000,0.56770833333333333,0.62500000000000000;  
 0.51388888888888889,0.58680555555555556,0.63888888888888889;  
 0.52777777777777778,0.60590277777777778,0.65277777777777778;  
 0.54166666666666667,0.62500000000000000,0.66666666666666667;  
 0.55555555555555556,0.64409722222222222,0.68055555555555556;  
 0.56944444444444444,0.66319444444444444,0.69444444444444444;  
 0.58333333333333333,0.68229166666666667,0.70833333333333333;  
 0.59722222222222222,0.70138888888888889,0.72222222222222222;  
 0.61111111111111111,0.72048611111111111,0.73611111111111111;  
 0.62500000000000000,0.73958333333333333,0.75000000000000000;  
 0.63888888888888889,0.75868055555555556,0.76388888888888889;  
 0.65277777777777778,0.77777777777777778,0.77777777777777778;  
 0.67447916666666667,0.79166666666666667,0.79166666666666667;  
 0.69618055555555556,0.80555555555555556,0.80555555555555556;  
 0.71788194444444444,0.81944444444444444,0.81944444444444444;  
 0.73958333333333333,0.83333333333333333,0.83333333333333333;  
 0.76128472222222222,0.84722222222222222,0.84722222222222222;  
 0.78298611111111111,0.86111111111111111,0.86111111111111111;  
 0.80468750000000000,0.87500000000000000,0.87500000000000000;  
 0.82638888888888889,0.88888888888888889,0.88888888888888889;  
 0.84809027777777778,0.90277777777777778,0.90277777777777778;  
 0.86979166666666667,0.91666666666666667,0.91666666666666667;  
 0.89149305555555556,0.93055555555555556,0.93055555555555556;  
 0.91319444444444444,0.94444444444444444,0.94444444444444444;  
 0.93489583333333333,0.95833333333333333,0.95833333333333333;  
 0.95659722222222222,0.97222222222222222,0.97222222222222222;  
 0.97829861111111111,0.98611111111111111,0.98611111111111111;  
 1,1,1];  
%% Save  
GeneralSave = General;  
clearvars -except GeneralSave  
  
load 'MATFILEPATH/ALL.mat'  
clearvars General  
  
General = GeneralSave;  
clearvars GeneralSave  
save('MATFILEPATH/ALL.mat')
```