Henrik Hassel[1,3]

Jonas Johansson[2,3]

Alexander Cedergren[1,3]

Linn Svegrup[1,3]

Björn Arvidsson[1,3]

[1)]Division of Risk Management and Societal Safety, Lund University

[2)] Division of Industrial Electrical Engineering and Automation, Lund University

[3)] Lund University Center for Risk Assessment and Management

Method to study cascading effects

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Executive Summary

The CascEff-project aims to improve the emergency response in incidents that involve cascading effects, i.e. where system dependencies lead to impacts propagating from one system to other systems. An important basis for this is knowledge about the nature, processes and patterns of cascading effects. One way to gain such knowledge is to study past events. In this report, a methodology for describing and analysing cascading effects, which will be used in the CascEff-project, is presented. The purpose of the method is to enable systematic descriptions of key characteristics of cascading effects in past events and it should be applicable for describing cascading effects among a broad variety of societal sectors and critical infrastructures. In addition, the method should capture the effects of conditions that enable, aggravate, prevent or mitigating cascading effects. The data that will be collected and systematized, using the method, comprise existing empirical data, i.e. information about past events that are gathered from existing written material in terms of official reports, investigations or media reports. In essence the method, which is based on a conceptual model of cascading effects, is comprised by three main steps. The first step is *identifying impacted systems*. This step is performed by, based on the written accounts, finding systems that are either impacted directly by an initiating event, or indirectly due to dependencies to other impacted systems. The systems are categorised by using a developed system categorisation, comprised by 22 system categories, in order to facilitate comparisons across events. The second step is to *describe Dependency Impacts*. This step is about describing the effects on the impacted system due its dependencies to other impacted systems, but not considering the impacted system’s inherent coping capacity. Three categories of Dependency Impacts are described, namely dependency consequences (i.e. type and extent of the consequences), dependency characterises (i.e. interesting aspects of the impacts that are not related to the type and extent of the consequences), and dependency conditions (i.e. circumstances that either aggravated or mitigated the dependency impacts). The third step is to *describe System Impacts* which refers to the effects on the impacted system due to one or several Dependency Impacts, taking and the impacted system’s inherent coping capacity into consideration. As such, the difference between Dependency Impacts and System Impacts is that the Dependency Impacts describe the direct exposure due to a dependency to another impacted system, whereas the System Impacts describe how the system subsequently is affected by this exposure which is contingent on the system’s ability to cope with the exposure. System Impacts are described using the same categories as the Dependency Impacts. Based on the descriptions from these three steps various ways of analysing a particular event can be performed which can be used as a basis to understanding the nature, processes and patterns of cascading effects . Examples of metrics that can be established are relative duration (i.e. duration of the failure in a system in relation to the duration of the failure in the system that caused the cascade) and cascade rapidity (i.e. how quickly a failure spread between two systems). After having applied the suggested method in several pilot case studies, a number of conclusions can be summarised. First, written accounts often do not focus on cascading effects in detail, but rather on the initiating event and direct effects. Furthermore, in some cases cascading effects are mentioned but not enough details are provided. In order to complement the data collection based on written material, some additional data collection, e.g. based on interviews, would be beneficial. Secondly, effects of conditions have also been difficult to find relevant information about so in order to improve on that knowledge some additional efforts would be beneficial. A potential way to do that would be using contrafactual reasoning in a workshop setting.

1 Introduction

The aim of the CascEff-project is to improve the emergency response in incidents involving cascading effects. This will be accomplished by developing knowledge and understanding of cascading effects as well as developing an Incident Evolution Tool which should enable improved decision support. The present report constitutes the deliverable for Task 2.1, which is concerned with developing a method for analysing previous incidents involving cascading effects.

An important part of the CascEff project is to study past events in order to get an understanding of the nature and processes of cascading effects. This is important for example to understand what other or additional challenges can be related to cascading effects when it comes to how to respond to such events. Information and knowledge about cascading effects will especially provide an important input to the incident evolution tool that will be developed in Task 4.2 of the CascEff project. In addition, it will also provide input to other Work Packages and Tasks by highlighting central aspects of cascading effects that need to be considered.

1.1 Aim of Task 2.1

In order to gain knowledge about cascading effects, a systematic and structured methodology for describing and analysing past incidents involving cascading effects needs to be developed, which is the aim of Task 2.1.

From the DoW of the CascEff-project, the goal of Task 2.1 is to develop a methodology to study past incidents involving cascading effects which will be applicable to incidents where multi-sectorial and trans-boundary consequences have arisen. An important part of this methodology should also be to enable capturing conditions that enable, aggregate or mitigate the cascading effects. This methodology should then be used in Task 2.2 and 2.3 to study and analyse past incidents.

1.2 Method development process

The general process of developing the method described in this report is based on the iterative process proposed by Checkland (1993), see Figure 1.1. This process starts by creating a method suggestion, which desirably should be based on previous methods and existing knowledge. The second step is to use the method in its relevant context, and the third step is to evaluate the use of the method. The process of method development then enters an iterative phase, as can be seen in Figure 1.1, where the method is modified in the light of applications and evaluations. This process continues resulting in a successively refined method.

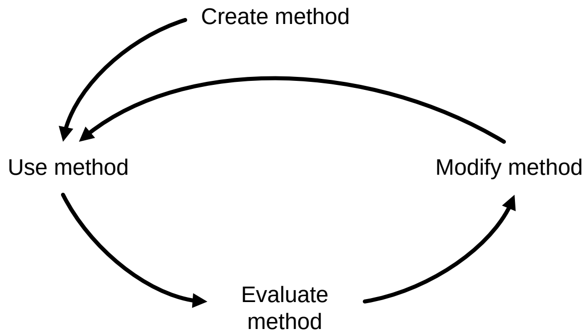

Figure 1.1. The iterative method development process (Adapted from Checkland (1993)).

The method presented in this report is a result of the described method development process in Figure 1.1 where it has been applied in a number of pilot case studies and then subsequently refined. The main building blocks of the method are settled but it is likely that additional applications of the method will give rise to learning, leading to some refinements. But this will mainly be in terms of adding or changing the categories and parameters used (see Chapter 3.3.2 for more details on this).

1.3 Report outline

This report is outlined as follows

- In Chapter 2, a review of existing empirical approaches to interdependencies and cascading effects is performed. The purpose is to gain inspiration and provide a point of departure for the method proposed in this report.
- In Chapter 3 the method for studying past incidents involving cascading effects is proposed, including the key concepts and conceptual models of cascading effects which is used as a basis for the method.
- In Chapter 4 some reflections are made based on applications of the method in a couple of pilot case studies. The goal is not to focus on the results from the case studies, i.e. the nature of the cascading effects studied. Instead, the goal is to reflect on the process of applying the method in terms of benefits, drawbacks and challenges concerning the method applications.
- In Chapter 5, the main conclusions of the report are presented.

2 Existing empirical methods for describing cascading effects in incidents

In this section, existing empirical approaches will be reviewed with the purpose of providing a foundation for the method presented in section 3. The empirical approaches addressed here, which have been identified in a thorough literature search, are the following:

1. The framework for characterising Infrastructure Failure Interdependencies, IFI, suggested by a re-search group at the University of British Columbia (McDaniels et al. 2007; Chang et al. 2007; Chang et al. 2009). The intention of this framework is to enable the identification of empirical patterns of infrastructure interdependencies primarily related to electric power-related failures.
2. The framework for studying interdependencies in the communication and information infrastructures domain suggested by Rahman et al. (2009).
3. The approach suggested by Zimmerman and colleagues where quantitative metrics are suggested to characterise interdependencies (Zimmerman & Restrepo 2006; Restrepo et al. 2006).
4. The approach suggested Van Eeten et al. (2009) in their systematic review of cascading failures, primarily focusing on the Netherlands.
5. The approach used by Mendonca et al. (2004) where the focus was on the assessment of infrastructure disruptions following the WTC attack.
6. The approach used by Tsuruta et al. (2008) where the focus was on the Kobe and the Mid Niigata earthquakes in Japan.
7. The approach used by Bigger et al. (2009) who studied the effect of interdependencies in a number of U.S. Hurricanes.
8. The approach used by Dueñas-Osorio & Kwasinski (2012) who conducted a case study on an earthquake in Chile using a statistical approach.

The empirical approaches have been analysed with respect to whether they provide support to: 1) the selection of initiating events to consider, 2) the identification of cascading effects, 3) the characterisation of cascading effects and conditions, 4) analysis of cascading effects. The reason for analysing existing methods with respect to these aspects is that they are judged to be highly relevant for this part of the CascEff-project.

2.1 Selection of initiating event to consider

How to choose what type of initiating events to consider and which specific ones to include in an assessment is important since this will influence the scope and the type of cascading effects that will be included. Several of the existing methods have been developed specifically to analyse a certain event or certain type of event. Of course, that does not automatically mean that the method is not useful for other event or event types). In summary, the empirical methods have approached the selection of initiating events in the following ways:

1. The method proposed by McDaniels et al. (2007); Chang et al. (2007); Chang et al. (2009) is restricted to large-scale power outages and events are chosen based on their large-scale consequences.
2. Zimmerman and Restrepo (2006) also focus on electric power outages and do not specify how specific events have been chosen.
3. Van Eeten et al. (2009) are not focusing on particular types of events and the selection of events is based on newspaper searches. However, their choice of search terms gives most attention to electric power systems.
4. Rahman et al. (2009) focus on a wide range of computer-/ICT-related failures.
5. The methods suggested by Mendonca et al. (2004), Tsuruta et al. (2008), Dueñas-Osorio and Kwasinski (2012) and Bigger et al. (2009) constitute case studies with

varying focus (WTC attack, two earthquakes, the 2010 Chile earthquake and three hurricanes in Florida, respectively).

2.2 Identification of cascading effects

Identifying cascading effects in past events is typically the first step in the assessment and characterisation process. Essentially all approaches break down the events down into multiple specific cascading effects where there is a "starting system" (originating, origin, initiator etc.) and an "ending" system (target, affected, terminal, etc.). A few of the methods have performed the identification based on keyword searches in newspaper articles, such as McDaniels et al. (2007); Chang et al. (2007); Chang et al. (2009), and Van Eeten et al. (2009). The choice of search terms then of course becomes very important and quite often considerable manual labor is needed to identify the cascading effect. Inclusion criteria may also be needed. For example, Van Eeten (2009), uses the inclusion criteria that at least 10 000 customers need to be affected in order to include the cascading event. Furthermore, Rahman et al. (2009) use a Communication and Information failure database as a basis for the identification and some others are using interviews, e.g. Bigger et al. (2009), as their data sources.

2.3 Characterisation of cascading effects and conditions

The different empirical approaches perform the characterisation of the cascading effects and conditions in different ways. In Table 2.1 an overview is given regarding what different characteristics are being described about the identified cascading effects in the different approaches. Note that these characteristics are the variables about which information is extracted from incidents that has occurred. Based in on this information various types of analyses may be performed, which is further addressed in Chapter 2.4.

Table 2.1. Overview of the various characteristics used to describe cascading effects (see the list in the beginning of Chapter 2 for explanation of Approach Number).

Approach	Characteristics for describing cascading effects and conditions
1	Outage: Date, Description of event, Initiating event, Spatial extent, Duration, Weather conditions, Temperature. Interdependency: Impacted system, Specific system, Description, Type of Interdependency, Type of infrastructure failure interdependency, Order, System failure [originating], Complexity, Feedback, Operational state, Adaptive potential, Restart time. Consequences: Severity, Type, Number of People [proportion].
2	Fault classification: Fault class, Generic fault, Features: Title, Date, Country, Impact scale, Degree of impact, Simulation, Fault intent, Duration, Financial impact, Public safety, Affected sites, Description, Report source, Report accuracy, Source infrastructure, Affected infrastructure, Affected industry sectors.
3	System, Location, Date, Duration of electric power outage, Duration of infrastructure outage as a consequence of power outage, Component affected.
4	Critical infrastructure sector, Affected critical infrastructure service, Initiating event, Dependency of another affected critical infrastructure service, Common cause event [yes/no], Concerned organization, Start time and date, End/recovery time and date, Country, Geographic area within country, Size of affected area, Textual description of cause, Threat

	category and subcategory, Indication of the consequences and impact, Duration and progress of recovery.
5	Impacted infrastructures, Other infrastructures impacted or not directly or indirectly, Type of interdependency or no interdependency, Day.
6	Origin infrastructure, terminal infrastructure.
7	Hurricane impact, Sequence of events, Operation during emergency, Priorities for service restoration, Upstream dependencies, Critical downstream services, Recovery and restoration processes.

2.4 Analysis of cascading effects

Based on information extracted from incidents that have involved cascading effects there are various ways of analysing the data and generating additionally interesting information about the particular event. The studied approaches have done this in different ways, which is summarised in Table 2.2. Note, though, that the focus here is on analysis of individual events rather than analysing general patterns across a larger number of events, which is not within the scope of this report. Of course, the analysis of individual events of course provides an input to comparative analyses.

Table 2.2. Overview of the various ways of analysing the cascading effects (see the list in the beginning of Chapter 2 for explanation of Approach Number).

Approach	Ways of analysing the cascading effects
1	Impact index (severity and duration), Extent index (Spatial extent, Number of people), Proportion of cascading effects affecting in five different consequence categories, Affected infrastructure in aggregate for the event.
2	Extent of failure, Impact (spatial), Impact (temporal), Public Safety, Failure propagation.
3	Relative duration.
4	**-**
5	Analysis of disruptions over time.
6	Number of propagations to and from a particular infrastructure, Influence diagrams, Interdependency matrices for different event phases.
7	Propagation sequences, Infrastructure interdependency relationships, failure impacts.
8	Time-lag analysis of restoration curves.

2.5 Summary

In summary, the approaches vary in their focus and how they address the different aspects of characterisation and analysis of cascading effects. Few approaches support the choice of type and specific events to address. Rather, this is typically chosen ad hoc with no “higher goal” in mind (such as generalisability). All approaches identify cascading effects, often based on media accounts, although a few also make use of interviews as a source of information. Furthermore, the way cascading effects are characterised varies greatly from description of a large range of factors to just logging originating and affected infrastructure/function. A few approaches include various conditions but this does not seem to be the primary focus. As a conclusion, a lot of inspiration can be drawn from existing approaches when designing the method in the current report, although no individual approach provides a comprehensive blueprint.

3 Proposed method for describing cascading effects in past events

In this section the proposed method for describing cascading effects in past events is outlined. But before presenting the method, underlying key concepts and a conceptual model of cascading effects needs to be introduced. The concepts and the conceptual model have been developed through workshops in the early stages of the CascEff-project as well as through communication of working papers between project partners. The concepts and the model provide common ground between the project partners and are therefore important to introduce here.

3.1 Key concepts

First of all, the concept of cascading effects must be defined. In the CascEff-project cascading effects are defined as:

The impacts of an initiating event where:

1. System dependencies lead to impacts propagating to other systems, and;
2. The combined impacts of the propagated event are of greater consequences than the root impacts, and;
3. Multiple stakeholders and/or responders are involved.

In addition, a number of related concepts must also be defined in order to facilitate the understanding of the subsequent presentation of the conceptual model and the proposed method:

- Initiating event (initiator) - the first in a sequence of natural (e.g. flood), accidental (e.g. fire) or intentional (e.g. bombing) events that may affect one or several systems.
- Originating system - a system in which a failure propagates to another system.
- Dependent system - a system which is negatively affected by a failure in another system.
- Impacted system - a system which is negatively affected by either an initiating event or an originating system.
- Dependency - mechanism whereby a state change in one system can affect the state of another system.
- Interdependency - a mutual dependency between two systems, i.e. system A is dependent on system B and vice versa.
- Incident - a chain of events affecting multiple systems.
- Cascade order - the number of stages in a propagation from a directly impacted system to a particular system that is impacted indirectly.
- Impact - the extent to which a system is affected due to an initiating event or due to a dependency.
- Conditions - circumstances that can enable, prevent, aggravate or mitigate dependencies and impacts.

3.2 Conceptual model

The concepts previously described can be synthesized into a conceptual model describing cascading effects, see Figure 3.1. This model is influenced by the schematic model suggested by Rinaldi et al. (2001).

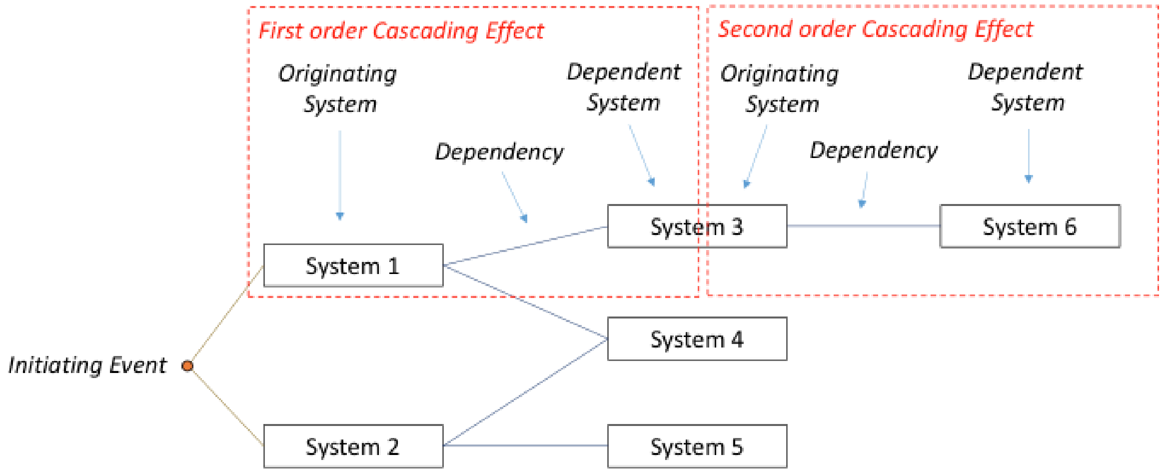

Figure 3.1. Conceptual model of the propagation of effects between systems in an incident that involves cascading effects.

The main features of this conceptual model are here described. First, an incident always starts with an initiating event which e.g. could be a natural event, such as an earthquake, an accidental event, such as an explosion, or an internal system failure, such as malfunctioning of a technical component. The initiating event gives rise to direct impacts on some other systems of relevance; however, if no further propagation of effects occur (i.e. if these directly impacted systems are the only ones affected), then the incident is not defined as involving any cascading effects. Hence, in order for cascading effects to arise a propagation of effects has to take place from a directly impacted system (originating system) to an indirectly impacted system (dependent system). The resulting effect is defined as a “first-order cascading effect”. If this line of propagation continues, second, third, etc. order cascading effects arise.

3.3 Description of the proposed method

Based on the key concepts and the conceptual model presented in the previous section, the proposed method for the study of past events is here described.

3.3.1 Purpose and delimitations of the method

The purpose of the method is to enable systematic descriptions of key characteristics of cascading effects in past events. It should then be possible to use these descriptive accounts to analyse cascading effects, both by analysing individual cascading effects and by analysing general patterns across different events. However, this latter type of analysis is not part of the method presented here as it is outside the scope of D2.1. However, some possible applications will be briefly presented in Chapter 3.4.

The data that will be collected and systematized, using the method, will comprise existing empirical data, i.e. information about past events that are gathered from existing written material in terms of official reports, investigations or media reports that are written in English or Swedish.

The method should be applicable for describing cascading effects among a broad variety of societal sectors and critical infrastructures; but, in order for an event to be of interest to study using this method, there has to be impacts propagating between different types of systems. Hence, smaller scale cascading effects within a system or network, such as those occurring within electric power systems (see e.g. Zio and Sansavini, 2011) or domino effects within an industrial premise (Reniers and Cozzani, 2013), are not considered as relevant for this project.

Furthermore, the aim of the method is to capture both actual cascading effects, where an impact on a dependent system has taken place, and potential cascading effects, where a dependency exists between a dependent system and an originating system but where an impact on the dependent system did not occur due to some conditions. The reason for including the latter is that valuable learning opportunities with respect to "near misses" should be included, which would not be captured if only extracting information about propagated effects that actually did occur.

Finally, the method should be able to capture the effects of conditions which represent circumstances that affect how the cascading effect develops. This can be in terms of enabling or aggravating a cascading effect, for example if a transportation incident happens to occur at rush hours instead of at night time. It can also be in terms of preventing or mitigating the cascading effect, such as if a response organisation would have more resources available than usual. Conditions play an important role for the method suggested here since they enable the extrapolation and generalization of the findings from a specific context to another context. This is in turn very important in order for the knowledge from past events to be useful for various types of decisions in future events, such as the decision made by emergency responders.

3.3.2 Defining and categorising systems

A key concept in the definition and conceptual model of cascading effects is described above is "system", which needs further elaboration. In general, a system can be defined as "a regularly interacting or interdependent group of items forming a unified whole" [1]. However, the choice of what can be regarded as "a system" in a particular context is subjective, and the choice of system boundaries will clearly affect which phenomena that will be considered as relevant. Hence, this choice is extremely important as it largely determines the focus of the project.

The choice of system boundaries can always be criticised in one way or another since it is always possible to draw the boundaries differently. This is especially the case when dealing with larger, more complex systems. Cilliers, for example, argues that the boundaries of a complex system can never be clearly defined because: "different descriptions of a complex system decompose the system in different ways, [and therefore] the knowledge gained by any description is always relative to the perspective from which the description was made" (Cilliers, 2005, p. 258). Hence, there is no single or true way of describing systems boundaries. We take a pragmatic approach and instead of defining clear-cut system boundaries, we define system categories for which it is easier to argue for inclusion or exclusion of real-life systems. Another benefit of defining system categories is that they can be employed in all case studies and therefore facilitate subsequent aggregated analyses.

The aim of the method, which was described in Chapter 3.3.1, is that it should capture the description of propagations of effects between distinctly different societal sectors, rather than focusing on smaller-scale cascading effects within particular systems, such as within the electric transmission system. In order to develop a system categorization in line with this aim, the area of critical infrastructure protection can be used as a source of inspiration, as this is an area that is concerned with identifying sectors and infrastructures that are essential for the functioning of society. Several different system categorizations have been suggested in the literature.

In Figure 3.2 a number of categorisations of critical infrastructures used in Europe and the U.S. are compared. In the United States, the critical infrastructure categories mentioned in official reports and directives have varied over time (1983-2003); ranging from 3 to 26 different systems (Moteff & Parfomak, 2004). Energy, Transportation, Telecommunications, Water

[1] http://www.merriam-webster.com/, search word: "system", retrieved 2014-11-26.

Supply, Banking and Finance, Emergency Services and Government Continuity are the ones mentioned most frequently in the U.S. reports. The sectors used in the two most recent reports in the study presented by Moteff and Parfomak (2004) are presented in Figure 3.2. The Swedish Civil Contingency Agency (MSB) defines 11 vital societal sectors (i.e. critical infrastructures), with some further division into functions within each sector (Gellerbring et al., 2014). Finally, a research group from the Netherlands divides critical infrastructures into 12 groups, similar to those defined by MSB (see Luiijf et al., 2009).

These three system/sector categorisations are just a few examples that are currently used. A more thorough survey can be found in the International CIIP Handbook (Brunner and Suter, 2008) where the “critical sectors” in 25 nations and 7 international bodies are listed. The fact that several ways of defining and categorising systems is of course accentuated by the fact that societal sectors and critical infrastructures can be described as complex systems (McDaniels et al., 2007; Peters et al., 2008; Rinaldi et al., 2001). Consequently, there is no single standard that can be straightforwardly adopted in the CascEff project, and it is also clear that both the level of detail, labels and system boundaries vary. Hence, within the CascEff project a system categorisation needs to be defined.

Drawing on existing categorisation systems, 22 different systems are here defined. These are illustrated in Figure 3.2 and described in more detail in Table 3.1. Our categorisation has a slightly higher system resolution within the two major sectors Energy and Transportation as well as some additional systems that are deemed essential for the project compared to e.g. the U.S. categorisation.

In Figure 3.2 the system categories in the four categorisations have been ordered by aligning and using the same colours for those categories that are identical or very similar to each other. Furthermore, categories that are unique to one categorisation are presented in white. Noticeable is that only a few system categories are unique to their categorisation, which gives an indication of general agreement between the different categorisations (although the sample is small). Figure 3.2 also demonstrates that, even though the CascEff categorisation contains additional system categories, it is within reasonable agreement with the previous work in the area.

Figure 3.2. Comparison of system categories between CascEff, U.S. reports and executive orders (Moteff & Parfomak, 2004), Swedish Civil Contingency Agency (MSB) (Gellerbring et al., 2014) and a Dutch research group (Luiijf et al., 2009).

It should also be noted that within the frame of the CascEff-project both the list of system categories and their descriptions are constantly and iteratively refined as more knowledge will be gained through the case studies. When having identified a system in a case study, the analyst uses the system category that most closely resembles to the actual system in the case study. This is simply done by comparing the actual system with the descriptions and examples in Table 3.1. In case no pre-existing system category provides a reasonable fit, an additional category needs to be added. Alternatively, the scope of the existing system categories needs to be broadened.

Table 3.1. System categories and how they are demarcated in the CascEff project.

System categories	No.	Description and exemplification
Power Supply	1	Activities and assets that ensure continuous supply of electric power from suppliers to customers, e.g. production, transmission and distribution of electric power.
Telecommunication	2	Activities and assets that ensure electronic communication of information over significant distances, e.g. landline and mobile phone systems, Internet, servers, etc.
Water supply	3	Activities and assets that ensure continuous supply of water from suppliers to customers, including pipes, pumps, water treatment plants, infiltration areas, etc.
Sewage	4	Activities and assets that collect and treat wastewater and day water, such as treatment plants, drain pipes, etc.
Oil and gas	5	Activities and assets that ensure continuous supply of oil and gas products, e.g. production, distribution and processing of oil and gas.
District heating	6	Activities and assets that ensure continuous supply of hot water for heating houses and premises, e.g. heating plants, pumping stations, water pipes.
Health care	7	Activities and assets that provide professional services to people in order to achieve or sustain mental and physical well-being and prevent illness and impaired health, e.g. emergency care, primary care, elderly care, child care, medicine distribution and production, disease control, etc.
Education	8	Activities and assets that contribute to a formalised transfer of knowledge, e.g. primary school, secondary school, universities, etc.
Road transportation	9	Activities and assets that enable transportation of people and goods on roads, e.g. road networks, bridges, tunnels, road maintenance activities, etc.
Rail transportation	10	Activities and assets that enable transportation of people and goods on railways, e.g. railway networks, subways, trams, signal systems, railway maintenance activities, etc.
Air transportation	11	Activities and assets that enable transportation of people and goods by airplane, e.g. airport operations, flight management, airspace security, etc.
Sea transportation	12	Activities and assets that enable transportation of people and goods by sea, lake and waterways, e.g. port operations, shipping

		industry, etc.
Agriculture	13	Activities and assets related to the cultivation of animals and plants in order to support e.g. food, biofuel and medical production, farming, livestock, etc.
Business and industry	14	Activities and assets that enable the production and exchange of goods and services to customers. Activities and assets that are covered in other system categories are not included here.
Media	15	Activities and assets that enable the dissemination of news and other information in society, e.g. radio, television, newspaper, social media, etc.
Financial	16	Activities and assets related to the continuous provision of economic services performed by the financial industry, e.g. insurance, cash availability, central banking system, credit cards, etc.
Governmental	17	Activities and assets that enable the provision of governmental/public services at local, regional and national levels, e.g. municipal government, county administration and national agencies. Activities and assets that are covered in other system categories are not included here.
Emergency response	18	Activities and assets that are necessary to respond to acute events where human life and health, environment or property is threatened, e.g. rescue services (land, sea, etc.), police, ambulances, emergency care, national guard, etc.
The public[1]	19	People in a society or a community and their ability to live a normal life where they have continuous access to the services that characterise a modern society
Environment[2]	20	Flora (i.e. all types of plants), fauna (all type of animals) and the ecosystems in which they habituate, e.g. sea, ocean, forest, etc.
Political	21	The political leadership on local, regional and national level
Food supply	22	Activities and assets that are necessary to produce and distribute food to people, e.g. food producers, wholesaler, food inspections

[1] The public has been modelled as an own individual system since it can take part in a cascading effect.
[2] The environment has been modelled as an own individual system since it can take part in a cascading effect.

3.3.3 Describing impacts

An important part of the CascEff-project is the description of system impacts. It is clear that system impacts are multidimensional, for example due to the fact that societal sectors are very different in nature. Here, the choice is to describe impacts in terms of a number of consequence categories as well as in terms of more general overall system impact level. The consequence categories used are the following:

- Technical consequences encompass the damage and loss of technical components, physical assets, loss of production, etc.

- Organizational consequences relate to the organisations and institutions that manage the systems; encompassing impacts on e.g. organisational capacity, coordination, and information management, etc.
- Social consequences encompass impacts on community such as political instability and civil unrest.
- Human consequences encompass impact on population such as health-issues, reduced well-being, casualties and injuries.
- Economic consequences encompass impacts in terms of direct costs[2].
- Environmental consequences encompass the effects on natural resources, flora and fauna.

3.3.4 Formal model for describing cascading effects

A fundamental aspect of the method is the use of a more detailed formal model for describing cascading effects in past events, which is based on the conceptual model illustrated in Figure 3.1. Hence, additional and more specific concepts and characteristics need to be introduced. In Figure 3.3 an overview of this model is presented and in Figure 3.4 an illustration of key concepts and characteristics for a system is shown which also is used to structure the different steps of the method. The main differences between the conceptual model presented earlier and this formal model are:

1. In this model (contrary to the conceptual model presented earlier) it is sufficient that a dependency between two systems has been identified in the written account of an incident. This indicates a potential for a cascading effect but that the cascade did not take place due to some conditions being in a fortunate state. For example, due to successful flood protection of a power plant no power outage occurred.
2. The concepts of Dependency Impacts (DI) and System Impacts (SI) are introduced.
   a) Dependency Impacts refer to the effects on the impacted system due its dependencies to other impacted systems given some dependency conditions but excluding the impacted system’s inherent coping capacity. An example of a Dependency Impact could be that a failure in the transportation system lead to 25% of the hospital staff is not able to get to their workplace.
   b) System Impacts refer to the resulting effects on the impacted system due to one or several Dependency Impacts and given its inherent coping capacity and system conditions. An example of a System Impact would be that no critical surgeries can be performed due to loss of 25% of the staff since no alternative personnel can be called in.
3. The role of the impacted system’s coping capacity has been clarified. The coping capacity constitutes the system’s ability to sustain effects due to dependencies, i.e. to avoid System Impacts given some Dependency Impacts. This could for example be in the form of redundancies or back-up systems.
4. The role of conditions has been clarified in the model, as is also clear from the descriptions of Dependency and System Impacts, where a separation is made between Dependency Conditions and System Conditions:
   a) An example of a Dependency Condition is when the transportation failure happens to occur in rush hour, which means that an increasing number of staff will not make it to the hospital compared to what otherwise would have been the case.
   b) An example of a System Condition is when the loss of 25% staff leads to a larger impact on the hospital during vacation time period than compared to other time periods due to a reduced redundancy and larger difficulty to call in additional staff.

[2] Note that indirect cost will, or at least ideally, be included when explicitly modelling the cascading effects.

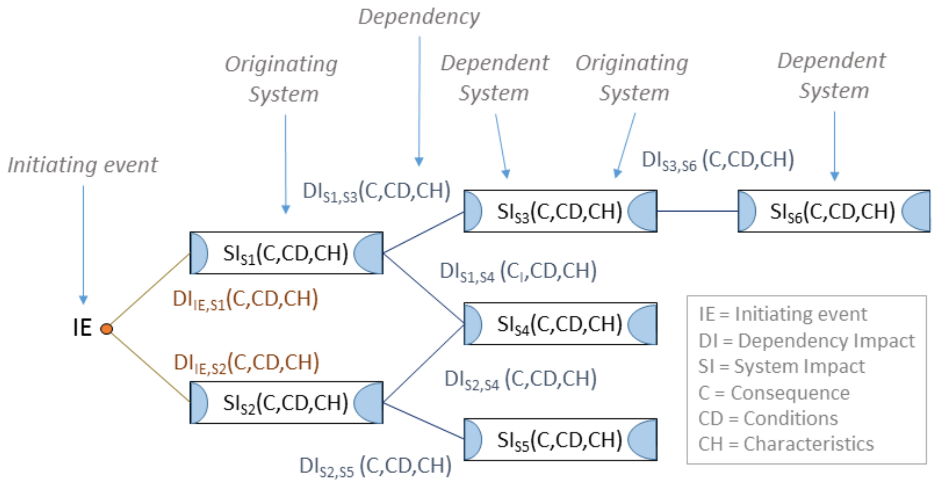

Figure 3.3. Formal model for the study of past events.

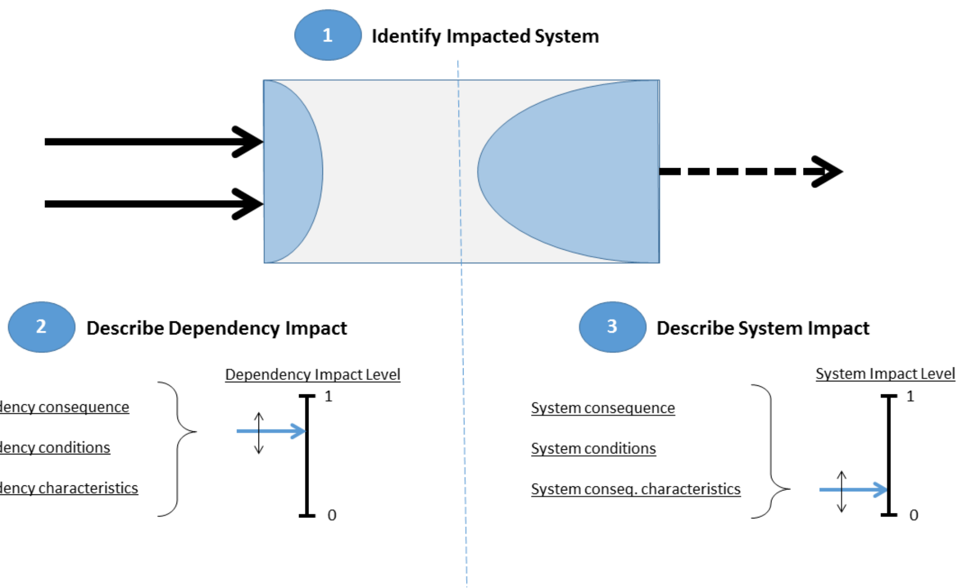

Figure 3.4. Overview of how dependencies and impacts are being described using the proposed method.

3.3.5 Method overview

When describing a past event using the formal model, the event is broken down by looking at individual impacted systems separately, which is seen in Figure 3.4. The three main steps of the method can also be seen in Figure 3.4 and consists of: Step 1 – Identify impacted systems, Step 2 – Describe Dependency Impacts and Step 3 – Describe System Impacts.

Steps 2 and 3 are both about characterisation of impacts. The general purpose of the description is to enable the subsequent assessment of general patterns that can be of interest especially for incident management (as this is the context of the CascEff project). The choice of characteristics has been highly influenced by previous research on dependencies and cascading effects (e.g. McDaniels et al., 2007; Rinaldi et al., 2001; Rahman et al., 2009; Zimmerman and Restrepo, 2006; Dueñas-Osorio and Kwasinski, 2012); see Chapter 2 for additional details). In addition, the choice of characteristics has also been based on communication with other CascEff partners to get their view on which characteristics that can be of relevance for the project.

Each step of the method is described in detail in Sections 3.3.6-3.3.8. Note that steps 1-3 are typically performed using an iterative approach rather than a linear one. This means that when an impacted system has been identified (Step 1) this is followed by describing Dependency and System Impacts for this system before returning to Step 1 and identifying additional impacted systems.

3.3.6 Step 1 – Identify impacted systems

The first step of the method constitutes identifying systems that have been impacted either due to an initiating event or due to the existence of a dependency to an originating system, which has been impacted. In addition, systems that are described as potentially impacted but were not due to some specific and traceable conditions are also identified here; see Chapter 3.3.1 for an explanation of why this is done.

In order to identify an impacted system, an explicit statement of an effect or a potential effect needs to be made in the written material. One example of a statement referring to an impacted system is that "the loss of power and communications led to missed orders and enquiries [for business and industry]" as was the case in the UK floods in 2007 (Pitt review, 2008). Furthermore, an explicit statement about the existence of a dependency between two systems, but where this dependency has not caused an impact from an originating system to a dependent system, would also be included as an impacted system here. Typically, such dependencies are only mentioned in the written accounts when it was close to having caused an impact, i.e. a "near miss", but did not due to the presence of some favourable conditions.

When having identified an impacted system it is categorised in one of the system categories presented in Table 3.1. Of course, it should be noted that this is not always straightforward since the system definitions and categories used in investigation reports or media accounts might be vague or not consistent with the system categories used here. Hence, this is a source of uncertainty, which must be acknowledged when using the information generated by the application of the method.

It should also be noted that a single system may be influenced several times since it can be affected in several different stages of an event. For example, a certain system could be affected directly by the initiating event; but also indirectly due to a dependency to another system that has also been affected by the initiating event. In addition, sometimes the impacts are very diverse; for example a system may be struck by one type of impact on short-term but another type of impact on long-term; or having one type of impact locally and another type of impact nationally. Hence, when there are different dependencies leading to different impacts for a given system, Dependency and System impacts (Steps 2-3) will described several times for that system.

3.3.7 Step 2 – Describe Dependency Impacts

The second step of the method is to describe the Dependency Impact for each impacted system. The purpose of describing Dependency Impacts is to get an understanding of how and to what extent a system is exposed to strain when a system on which it depends on has been impacted.

The description of Dependency Impacts is done by using three different categories: dependency consequences, dependency characteristics, and dependency conditions. If there are multiple dependencies that affect a system, as is the case for system 4 in Figure 3.3 (which for example would be the case when a combined failure in both rail and road transportation gives rise to a severe impact on fuel distribution), each of these dependency impacts are described individually.

3.3.7.1 Dependency consequences

This category describes the type of and the magnitude of the consequences due to the dependency or dependencies. This is done using the consequence categories previously described in Section 3.3.3. The approach is to extract as much concrete information as possible from the written material. But rather than extracting the information only in ”free text”-form, various measures are defined in order to standardise the way consequences are described. The reason for this is that free text information would be more difficult to subsequently make use of in a subsequent systematic analysis where comparison of different cascading effects and events are necessary. Therefore the approach used here is to iteratively define relevant measures as additional incidents are studied. In Table 3.2 the measures in each category that have been identified so far through the case studies in each category are presented.

Table 3.2. List of measures describing the different dependency consequence categories.

Category	Measures
Technical	Reduced quality of a required input Reduced quantity of a required input Loss of components Increased load Damaged buildings Loss of production
Organisational	Affected organisational units Reduced staffing
Social	People affected by social unrest People mistrusting authorities
Human	Fatalities Injuries Homeless Evacuated Mental health injuries People that has lost critical services
Economic	Direct economic costs
Environmental	Polluted land Polluted forest Polluted sea Dead animals

3.3.7.2 Dependency characteristics

The reason for addressing dependency characteristics is that they contribute to understanding the nature and mechanism of the dependencies. This in turn may be important for decision-makers, such as incident commanders, when considering how to respond or manage events that involve or may involve cascading effects. The categories described in Table 3.3 will be used.

Table 3.3. Categories describing dependency characteristics.

Categories	Description/possible values
Dependency type	Functional - when the state of a system is dependent on the output(s) of another system. Geographical - systems that are located in the same area and where changes in the local environment can create state changes in all of them Logical - when a state change in one system results in a state change in another, without any of the other dependencies occurring, e.g. due to human decisions and actions.
Location and spatial extent	The geographical location(-s) and the size of the geographic area where the Dependency Impacts occur. Described by coordinates defining one or several geographical areas.
System extent	Describes the proportion of specific impacted subsystem(s) within the system affected by the Dependency Impact. Categorised into: Single, Few, Majority, All.
Starting and ending time	Describes when Dependency Impacts initially occur and ends – described by Date and Time.

3.3.7.3 Dependency conditions

As explained earlier, describing important conditions that either aggravate or mitigate a Dependency impact is of relevance in order to be able to generalise the information gathered and knowledge gained about events that has involved cascading effects to other contexts. For example, if the same event would occur during another time of the year, is it likely that it will lead to similar types of impacts or will it be more or less serious?

The approach chosen here is to extract the conditions that are explicitly mentioned as being important in the written accounts of the events. Of course, a large variety of additional conditions could potentially be specified for the particular event; however, if no explicit statement is provided about the relevance of the conditions it will not be included as it would be difficult to draw the line between factors to include and factors to not to include.

The categories described in Table 3.4 have been identified as relevant when describing dependency conditions. In addition, whether it was a mitigating or aggravating condition is also noted when doing the case studies. Furthermore, a special case is when conditions are described for potentially impacted systems, then the conditions that were important for the event to not give rise to a Dependency Impact are described.

Table 3.4. Categories describing dependency conditions.

Categories	Description/example of possible values
Weather conditions	Cold, Warm, Rain, Snow, Windy
Timing	Time of year, Time of week, Time of day
Type of location	Urban, Rural, Metropolitan, Coast
Initial event type	Natural, Accidental, Intentional
Operational state	Above normal capacity, Reduced capacity

3.3.7.4 Dependency Impact Level

After characterising the three sub-categories of the Dependency Impact, an aggregated dependency impact is estimated, called Dependency Impact level. This can be seen as a measure of the extent of the dependency impact aggregated across all dependencies. It will, admittedly, be a rough judgment made by the analyst, but it is argued considered to be useful when subsequently analysing and modelling cascading effects. For example in order to get a sense of whether a relatively small system impact in one system gives rise to very large subsequent dependency impacts on other systems; or whether a rather small dependency impact may give rise to large system impacts for some systems (which e.g. could indicate a very low coping capacity).

In Table 3.5 the different levels of the Dependency Impact are presented. This measure should be judged and interpreted with reference to the spatial and system extent that has been stated previously in the Dependency characteristics. This means that the impacts only should be described for the specific systems that have been impacted in the stated geographic area, e.g. only the Primary schools within the Education system and within the London area. If the reference instead would have been the whole system category, e.g. all parts of the Education system and the whole nation, the same impact would obviously "score" lower on the Dependency Impact Level scale.

Table 3.5. Dependency Impact Levels and description of each level.

Level	Description
3	Major Dependency Impact
2	Moderate Dependency Impact
1	Minor Dependency Impact
0	No Dependency Impact

3.3.8 Step 3 – Describe System Impacts

The third step of the method is to describe the System Impact for each impacted system. As described in Chapter 3.3.4 System Impacts refer to effects on the impacted system due to one or several Dependency Impacts, taking and the impacted system's inherent coping capacity into consideration. As such, the difference between Dependency Impacts and System Impacts is that the Dependency Impact describes the direct exposure, e.g. two water pumps in the water distribution system were flooded due to a failure in the sewage system. System Impact, then, describes how the system subsequently is impacted by this exposure, e.g. the water distribution system was redundant which only lead to some minor issues with low water pressure, or on the other extreme, that it lead to complete system collapse.

The characterisation is done by using three different sub-categories – similar to what was done for the Dependency Impact: system consequences, system consequence characteristics, and system conditions. However, unlike the description of Dependency Impacts, the description of System Impacts is done considering all impacts due to the dependencies (if more than one).

3.3.8.1 System consequences

This category describes the type of and the magnitude of the system consequences. This is done using the consequence categories previously described in section 3.3.3 and the procedure is the same as when characterising the dependency consequences (see Chapter 3.3.7.1). In Table 3.6 the measures that have been identified so far in each category are presented – note that it is similar but not identical to the measures presented for Dependency consequences.

Table 3.6. List of measures describing the different system consequence categories.

Category	Measures
Technical	Loss of components Increased load Damaged buildings Loss of production
Organisational	Affected organisational units Reduced staffing
Social	People affected by social unrest People mistrusting authorities
Human	Fatalities Injuries Homeless Evacuated Mental health injuries People that has lost critical services
Economic	Direct economic costs
Environmental	Polluted land Polluted forest Polluted sea Dead animals

3.3.8.2 System consequence characteristics

System consequence characteristics describe aspects of the consequences that are not captured by the system consequence categories in Table 3.7 (which relate to descriptions of consequence severity). Instead, the system consequence characteristics capture other interesting aspects of the consequences that can contribute to a better understanding of the nature of dependencies and impacts. For example, this includes information on whether it is likely that a dependent system is impacted "across geographical boundaries", which would convey important information to response organizations since it would inform them that a large number of other organisations would become involved in the response to the event. In Table 3.7 the categories used to describe system consequence characteristics are presented.

Table 3.7. Categories describing system consequence characteristics.

Categories	Description/possible values
Location and spatial extent	The geographical location(-s) and the size of the geographic area where the System Impacts occur. Described by coordinates defining one or several geographical areas.
System extent	Describes the proportion of specific impacted systems/functions within the particular system category that is affected by the System Impact. Categorised into: Single, Few, Majority, All.
Starting and Ending time	Describes when the Impacted System is impacted and back to more or less normal functioning. Described by Date and Time.

3.3.8.3 System conditions

In addition to conditions that affect the Dependency Impacts, which were described in Chapter 3.3.7.3, there are also conditions that can aggravate or mitigate the System Impacts, i.e. circumstances that, if they would change, would give rise to different System Impacts although the Dependency Impacts were the same. For example, looking at the water distribution example again, the system impacts due to failure in two water pumps would be larger if there was a large demand on the water distribution system at the failure occurrence (e.g. summertime, during hours of high industrial production, etc.).

The procedure for identifying system conditions is the same as when characterising the dependency conditions (see Chapter 3.3.7.3). In Table 3.8 the categories that have been identified so far are presented – note that they are similar but not identical to the categories presented for Dependency conditions.

Table 3.8. Categories describing dependency conditions.

Categories	Description/ Example of possible values
Weather conditions	Cold, Warm, Rain, Snow, Windy
Timing	Time of year, Time of week, Time of day
Type of location	Urban, Rural, Metropolitan, Coast
Initial event type	Natural, Accidental, Intentional
Operational state	Above normal capacity, Reduced capacity
Coping capacity	Buffers, preparedness plans, external resources

3.3.8.4 System Impact Level

After having characterised the three sub-categories of the System Impact the aggregated System Impact, called the System Impact Level, will also be estimated. This can be seen as a measure of the impacts on what the system aims to accomplish, i.e. related to the descriptions of the systems as presented in Table 3.1. The System Impact Level will, similar to the estimation of the Dependency Impact Level, generally be a rough judgment made by the analyst, but it is considered to be useful when subsequently analysing and modelling cascading effects (as was discussed in Chapter 3.3.7.4).

In Table 3.9 the different levels of the System Impact Level are described. As was the case for Dependency Impact Levels, this measure should be judged and interpreted with reference to the spatial and system extent that has been stated previously in the System consequence characteristics. See Chapter 3.3.7.4 for further discussion.

Table 3.9. System Impact Levels and description of each level.

Level	Description
3	Major System Impact
2	Moderate System Impact
1	Minor System Impact
0	No System Impact

3.4 Analysis of the cascading effects

The various characteristics described in the three steps of the method (Chapter 3.3.6-3.3.8), are extracted from the written accounts of the studied incidents. Based on these, the cascading effects that have occurred and the potential cascading effects that could have occurred can be analysed in detail. Such information in turn would be a very valuable input to an Incident Evolution Tool and to emergency responders, who need to consider how to prioritise different lines of action.

How to analyse this information is not part of D2.1 but Table 3.10 provides a number of examples of metrics than can be used to describe the cascading effects and which would be possible to calculate/measure based on the information extracted by the method described in this report. Some of those are metrics expressed for the incident as a whole, some are expressed for individual systems and some express relations between systems.

Table 3.10. Metrics that can be calculated/measured based on the information extracted using the method described in this report.

Metrics	Description
Total duration	Time duration of the event considering all its impacts
Total spatial extent	Spatial extent of the event considering all its impacts
Total cascade order	Total number of sequences of cascading effects in the event
Total consequences	Aggregation of consequences for all impacted systems in the event
Cascade rapidity	How quickly a failure in the originating system(-s) spread to the dependent system
Relative duration	Duration of the failure of the dependent system in relation to the duration of the failure in the originating system
Spatial proximity	Geographical closeness between originating system and dependent system
Relative spatial extent	Spatial extent of the impact on the dependent system in relation to the impact on the originating system
Duration	How long the dependent system is affected due to a failure in the originating system(-s)
Relative duration	The duration of the failure of the dependent system in relation to the duration of the failure in the originating system
Avoided consequences	Aggregation of the consequences that would be avoided if no impact would propagate further[1]
Cascade order	The number of stages in a propagation from a directly impacted system to a particular system that is impacted indirectly

[1] Could be a good metric to identify chain breakers – see the DoW for further details on this concept.

By performing systematic analysis for several events, conclusions regarding general patterns will be possible to make. But again, since this is not part of D2.1 it will not be addressed in further detail here.

3.5 Summary

In this chapter the method for describing past events has been presented. This is the result of concurrent, iterative applications of the method in a number of pilot case studies which will be further described in the next chapter. A large variety of characteristics, measures and metrics that are interesting to describe when it comes to past events have been included in the proposed method. Of course, this does not mean that all this information about these events is easily retrievable from written material. In fact, this will vary from case to case as will be discussed further in the next chapter.

4 Discussion

As was described in the introduction, an iterative process for developing the method has been used, where pilot cases have been analysed in parallel to the development and refinements of the method. This chapter presents and discusses experiences and challenges from these applications.

4.1 Overview of the studied cases

A number of past incidents were chosen rather early in the method development process. The choice of incidents was made in order to obtain the greatest variety of incidents to for testing and developing the method with reference to. The underlying motivation for this was to ensure that the method is not only applicable to specific types of incidents, e.g. by only capturing some specific types of dependencies and cascading effects; but rather is applicable as broadly as possible. When choosing cases the focus was to cover diverse aspects across the following characteristics:

1. Types of initiating events (Natural, Accidental, Intentional)
2. Spatial extent of Initiating Event (Local, Regional, National, International)
3. Spatial extent of cascading effects (Local, Regional, National, International)
4. Duration (Days, Weeks, Months, Years)
5. Impacted systems (see Table 3.1).
6. Dependency types involved (Functional (F)/Geographical(G)/Logical (L))

In Table 4.1 an overview of the chosen cases is presented. As can be seen, together they cover a rather large variety of different types of incidents, which has been positive from the perspective of the method development.

Table 4.1. Overview of the pilot cases and their key characteristics.

Case	IE type	Spatial extent IE	Spatial extent CE	Duration	Impacted Systems[1]	Dependency types
Hurricane Katrina	Natural	Regional	National	Months	1, 2, 3, 4, 5, 7, 9, 11, 13, 14, 18, 19, 22	Functional, Geographical
Ejafjällajökull Volcano	Natural	International	International	Weeks	7, 9, 11, 13, 14, 19	Functional Logical
Mont Blanc tunnel fire	Accidental	Local	Regional	Months	9, 14, 19	Functional
Enschede fireworks explosion	Accidental	Local	Local	Weeks	2,7,8,18,19	Functional Logical
Auckland power outage	Accidental	Local	Regional	Months	1,2,3,5,9,10,14,15, 16,18,19	Functional Logical
Tieto IT incident	Accidental	Local	National	Days	2,7,8,14,16,17,18,1 9	Functional
UK Floods 2007	Natural	National	National	Weeks	1,2,3,4,5,8,9,10,13, 14,17,18,19,22	Functional, Geographical
London Bombings	Intentional	Local	Regional	Days	2,10,16,19,21	Functional , Logical

[1] See Table 3.1 for description of the various impacted systems.

4.2 Challenges for method application

In the applications various challenges were encountered. These challenges related both to how to apply the method so that this is done in a consistent way across different users of the method, but also when it comes to finding relevant information about the chosen incidents. These two main challenges will be described below.

4.2.1 Consistent application of the method

One challenge in applying the method is that different analysts apply it consistently. This can be related to using and interpreting the system categories in a similar way but also applying the method with a similar level of detail. The approach chosen here has been to arrange meetings on a regular basis to discuss the considerations and assumptions made by the analysts so that the applications of the method are harmonised. In addition, the method is applied in a transparent way where the basis for judgements and characterisations are tracked and detailed references are provided. In that way fine-tuning can be made retrospectively.

4.2.2 Finding relevant information about the incidents

The main source of information for the analyses of cascading effects, in the pilot case studies, was official reports as these were regarded to have the highest degree of validity. However, it became obvious that many of these official reports do not focus on cascading effects in detail. Often the main focus is on describing the initiating event and its direct consequences. For example, in the case of Eyjafjallajökull volcano eruption, the main official report (Torkelsson, 2012) gave a great deal of attention to the volcanic phenomena and the direct effects of the eruption, e.g. for flight safety. However, but much less focus was placed on the higher-order consequences of the eruptions, e.g. what cascading effects the air travel restrictions gave rise to. Sometimes, the cascading effects are summarised in the label "socio-economic impact", such as in the case of the Mont Blanc tunnel investigation (Promat, 2008), but that does not provide enough detail for the purpose of the present project. Furthermore, in many cases concrete cascading effects are described but there are not enough details provided in the report in order to be able to describe all characteristics that are specified in the method proposed in this report. This means that it is likely that some data points will be missing in the collected material which of course needs to be addressed when e.g. trying to find general patterns in the data.

A possible reason for the fact that information about cascading effects sometimes is missing in official reports is that existing accident models typically focus on describing the causes for accidents. In Appendix 1, a review of a number of common accident investigation methods is performed, and from this review it is clear that most of the methods mainly address events and conditions preceding the initiating event rather than how the negative consequences of the accident cascade across systems and sectors.

Something that also has been difficult to find information about from official reports is how various conditions affect the cascading effects. Sometimes conditions are listed or can be extracted from the reports but it might be unclear if or to what extent they affected the cascading effects. Of course, by listing conditions for the studied incidents statistical analyses could be made to draw conclusions of the effects of various conditions. However, that would require analysis of a very large number of incidents – more than would be possible in the frame of this project.

4.3 Complementing with additional data collection

As described previously the written material does not always provide the details necessary to be able to characterise and subsequently analyse cascading effects. Hence, sometimes there seems to be a need to complement the data collection based on written material with additional methods in order to increase the knowledge that can be gained from past events. Here we will briefly present possibilities of complementing the current method with additional data collection methods. In essence, we propose that two additional types of methods could complement the one proposed in this report, which are: 1) In-depth case studies and 2) Counterfactual scenario reasoning (which will be discussed in what follows). There is an ambition to develop our thoughts on these methods during the course of the CascEff-project and also test them to see in what way they complement the method proposed here. However, due to time constraints, exhaustive analyses of the cases reviewed using the method proposed in Chapter 3 will not be possible.

4.3.1 In-depth case studies

By doing in-depth case studies additional information about the incidents can be extracted, corresponding to the information sought by the proposed method. The structure of these in-depth studies can be inspired from the existing accident investigation methods reviewed in Appendix A. Here, it is suggested that the in-depth case studies should make use of semi-structured interviews with key persons representing affected systems. Semi-structured interviews are useful for gathering information when the information needed is not clearly defined. They are also flexible enough to be adapted during the interview, so that an opportunity to gather vital information about the system is not lost.

In order to be able to perform interviews, it is first necessary to identify one or several affected systems. An ideal situation is if a study of existing written material has already taken place, then the different actors mentioned in that study can be used to conduct the first series of interviews. Alternatively or additionally, media articles can be used to provide an idea of which systems are involved, for example if a spokesperson from an agency is mentioned in an article, their organisation is most likely involved in some way.

The goal of the interviews is to extract the necessary information as described in the proposed method in Chapter 3; i.e. this includes Dependency Impacts, System Impacts and conditions that may mitigate or aggravate these impacts. Sometimes the previous study of existing written material may already have extracted some information of relevance; then the interviews will focus on validating this information and complementing it with the information that is missing.

By also asking the interviewees how other systems were dependent on them and affected by impacts on their own system, a snowballing process can be initiated that where additional affected systems emerge during the interview process. The process can continue until no new systems are found or until the investigator is satisfied, depending on the purpose of the study.

4.3.2 Counterfactual scenario

Something that is difficult to extract from the analysis of single incidents is the effect of various conditions. Sometimes relevant conditions can be concluded as important based on e.g. previous experiences of those involved. But in order to make such inferences it is typically necessary to have similar incidents to compare with, which often is not the case. An alternative approach would be to apply some hypothetical/counterfactual reasoning where one assumes that some other conditions would prevail and then reason about how that would have changed the impacts and the cascading effects. In that way, conclusions regarding the effects of various conditions can be drawn. Of course, these conclusions will be strongly dependent on the knowledge of those persons making the judgements.

Counterfactual thinking is something most people do; most of us have had thoughts of the following kind: “If I had done this instead of that, then this would have happened instead”. A counterfactual thought is often defined as mental representations that are explicitly contrary to facts or beliefs and are often formulated as conditional statements (Roese & Morrison, 2009). These statements are usually divided into an antecedent (“If I had done this”) and a consequent (“then this would have happened”).

The more formal analytical method referred to as Counterfactual reasoning is closely related to counterfactual thinking, which constructs alternative scenarios using counterfactual events, usually in order to provide input to decision making. It can be used both retroactively, thus changing historical facts or adding new ones, or proactively, making an assessment of the future. In Abrahamsson et al. (2010), counterfactual reasoning is used to study the effects of changing conditions and system states in the emergency response to a past event. This is done with the purpose of broadening the learning potential from past events. The purpose in applying counterfactual reasoning in the CascEff-project would be similar, but with the focus on better understanding ways that changing conditions would alter the cascading effects.

According to Hendrickson (2008), all counterfactual reasoning should start with creating an *antecedent scenario*, which he describes as a precisely formulated series of events that makes the antecedent true. Using the example “If the green party wins the election, the coal power plants would be forced to close”, an antecedent scenario consists of all the events and circumstances leading up to the green party winning the election (such as a skilled party leader, effective campaigning or a political scandal amongst competitors). The general principles when choosing an antecedent scenario is to choose the one that preserves history best (in the case of retroactive reasoning), have the highest probability and has the fewest amount of deviations from reality (Hendrickson, 2012).

Hendrickson (2008) further explains the next step, which is to create the *intermediate scenario*, the series of events from the antecedent being true until the consequent scenario, as well as the likelihood of the events. In the example above, from the election being won until the plants are forced to close (this could include events like propositions in parliament, increased taxes on carbon emissions etc.).

The final step is the *consequent scenario*, where the consequence and the aftermath of it are described. Here basically every nonzero probability scenario, which is not in contradiction to previously described events, is allowed, but they should also be of strategic importance for the purpose of the analysis (Hendrickson, 2008).

Hendrickson’s guide to counterfactual reasoning is very rigorous and designed primarily for the intelligence community, where it is used as a supporting tool for making strategic decisions, which may have huge consequences (Hendrickson, 2008). The trade-off is the time required to make such detailed scenarios, a reasonable trade for an organisation with a lot of resources and the need of the best possible assessments. However, the main purpose of counterfactual reasoning for the CascEff-project is to evaluate which conditions will affect cascading effects and how. Potentially there would be a large array of conditions that could be addressed which means the reasoning around each condition needs to be limited. Therefore, instead of working with several consequent scenarios, it is more reasonable to only work and end up with one consequent scenario – the most likely one.

Applying the structure provided by Hendrickson in the CascEff-project would include defining the antecedent scenario which in this case simply would be in terms of the scenario that actually did occur, e.g. the UK floods 2007. In the intermediate scenario, the condition/conditions that will be altered are chosen and the ways in which they are altered are specified. Finally, in the consequent scenario the changed character and extent of the cascading effects are determined. Since it requires a lot of knowledge to be able to credibly reason and make predictions regarding the effects of changed conditions, counterfactual reasoning in the CascEff-project has to be performed in a workshop setting where participants representing the different systems involved in the incidents are included. As such, this is a rather time-consuming data collection process.

5 Conclusions

This report has presented a method to describe and characterise cascading effects in past events. The method has been developed through an iterative process where successive applications in pilot case studies have been used to further develop and refine it. In the method a broad range of cascading effect characteristics is included. The purpose of this is to enable the extraction of as much relevant information as possible from the written accounts and by doing so enable a large array of subsequent ways to analyse the data. Of course, even though a broad range of characteristics is included in the method, it does not mean that all these characteristics must be described for all incidents since the necessary information may be difficult to retrieve. However, that also means that subsequent analysis of the nature, processes and patterns of cascading effects must be able to account for data gaps. In fact, based on the pilot case studies performed in this project it is clear that written accounts often do not focus on cascading effects and often there are not enough details provided. Additional data collection methods, such as in-depth case studies using interviews and counterfactual reasoning in a workshop setting, would therefore be a good way of complementing the knowledge gained based on written accounts. However, due to time limitations in the CascEff-project these methods will not be possible to apply in full scale.

The main conclusion of the report is that by using the method for studying past events that has included cascading effects, a basis for gaining knowledge about the nature, processes and patterns of cascading effects can be developed. The next step in the project will be to apply this method in full scale case studies. These applications are likely to give rise to further refinements of the method, such as refining and adding consequence measures, refining and adding system categories, etc.

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Appendix 1 - Existing incident investigation methods

This appendix presents a review of existing accident investigation methods.

Events and causal factor charting and analysis (ECFC/A)

The method is developed by the U.S. Department of Energy (DOE) and is the foundation of the investigations conducted by the department (DOE, 2012). The charting is conducted throughout the whole investigation process, continuously updating a timeline of events on the x-axis (from left to right), with their respective causal factors (i.e. contextual factors) on the y-axis. The analysis uses deductive reasoning in order to determine which events and causal factors that actually contributed to the accident, removing the ones that did not. The aim is to map all the contributing events up until the accident.

Barrier analysis, change analysis and root cause analysis are also vital parts of the DOE investigation process, used as support to the charting of events (DOE, 2012).

Barrier Analysis

The foundation of the barrier analysis is Haddon's energy model. The main principle is that an excess of energy from a hazard which a target then absorbs causes an accident (Haddon, 1980; Kjellén, 2000). Barriers are means to control, prevent or impede the energy from reaching the target (Sklet, 2004).

The basic steps according to the DOE manual are (DOE, 2012):

- Identify the hazard and the target.
- Identify each barrier.
- Identify how the barrier performed.
- Identify and consider probable causes of the barrier failure.
- Evaluate the consequences of the failure in the accident.

The barrier analysis is incorporated in many accident investigation methods, such as the MORT, TRIPOD, MTO-analysis and the AEB presented later.

A problem with barrier analysis in this context is the very narrow perspective; the hazards and respective barrier(s) are studied one at a time with no regard to time. However, one could view the originating system as a hazard, the dependent system as the target and then try to find barriers that will stop the propagating effects. To successfully apply this perspective, the kinds of energy that is usually considered most likely have to be adapted.

This also questions the usefulness of the well-established prevention strategies that have been developed with this model (Haddon, 1980).

Change Analysis

The principle of change analysis is to compare the accident timeline with some kind of baseline when the system was operating under normal conditions, for example the week before or according to the design. The differences are analysed to determine what kind of impact they have on the outcome. This of course requires some kind of mapping of events before it can be conducted. In the DOE framework it is used to identify additional causal factors after a preliminary ECFC has been done (DOE, 2012).

Root Cause Analysis (RCA)

A root cause analysis aims to identify fundamental deficiencies in safety management systems that affect several causal factors and which would prevent similar accidents if corrected (DOE, 2012). There is no real agreement on what a root cause is amongst practitioners (Sutton, 2008) and performing an analysis forces the investigator to use their own judgements (DOE, 2012). Again, this requires some kind of charting and analysis of events before a root cause analysis can be performed.

Event Tree Analysis (ETA)

The event tree analysis is mainly used as a risk assessment method, where the focus is on event sequences after an initiating event (Kjellén, 2000). An event sequence is affected by whether safety functions and barriers are successful or not (Sklet, 2004). According to Sklet it can also used as an investigation method, through the identification and illustration of the accident path.

The method has some similarities to CascEff's way of charting cascade effects (i.e. start with an event and map a sequence of events (cascade effects) that follows it), but takes little consideration to contextual factors.

Acci-map

Like the ETA, the Acci-map is not a pure investigation method, but offers an interesting perspective (Sklet, 2004). It was developed by Rasmussen and the Swedish Rescue Services Agency and utilises an organisational perspective where the focus is on six levels of decision-making, from equipment and staff to regulatory and governmental level (Rasmussen & Svedung, 2000). The accident is mapped from left to right according to the levels, where arrows are used to indicate influences.

MTO-analysis

The MTO-analysis, developed for the Swedish nuclear industry, is based on the idea that human, technical and organisational factors should be regarded as equal and interlocking parts of system safety (Rollenhagen, 2003). This is done by a structured analysis with event-cause-diagrams, a change analysis and a barrier analysis, complemented by a checklist for common failure causes (Sklet, 2004). The diagram is drawn with the event chain in the middle, from left to right. The various conditions are plotted above, with a change analysis in the top. Below the event chain, the barrier analysis is presented.

TRIPOD

Accidents occur when active failures and latent conditions causes holes in the barriers protecting the systems, allowing the hazards to penetrate the defences and do damage (Reason, 1997). Furthermore, these active failures (i.e. errors or unsafe acts performed by workers) are a result of latent conditions (e.g. design flaws, working procedures and maintenance failures), which are the effect of decisions made by governments, designers, organisation management and more. An investigation should start with the accident and work backwards to identify these latent conditions (Sklet, 2004).

Accident Evaluation and Barrier Function (AEB)

AEB models an accident as a sequence of interactions between technical and human systems; to stop the accident from reoccurring the sequence must be broken through an adequate barrier (Katsakiori, Sakellaropoulos, & Manatakis, 2009; Svensson, 2000). This method focuses only on one chain and does not account for time. AEB does not try to find underlying causes, because the aim is to analyse why barrier functions failed and how to strengthen them (Katsakiori et al., 2009).

Sequential Timed Events Plotting (STEP)

STEP is more of a way to visualise an accident more than an analytical tool, the main feature is the use of a multi-linear event chain (Favarò, Jackson, Saleh, & Mavris, 2013; Sklet, 2004).

Agents, persons or objects involved in the accident and that can change states or interact to create events, are plotted on the y-axis of the diagram (Nano & Derudi, 2013). Further, the x-axis represents time and arrows leading from and to events represent the sequential order as well as dependencies. Events are plotted on the row of the agent it belongs to and at the time it took place.

Systemic Cause Analysis Tree (SCAT)

SCAT is based on the ILCI accident model, which consists of five blocks, each representing a part of an accident (Katsakiori et al., 2009; Sklet, 2004). The five blocks in the model are: Lack of control (management level), Basic causes (job and personal factors), Immediate causes (substandard acts and conditions), Incident (contact with harmful energy/substances) and Loss (Kjellén, 2000). An accident is investigated in the reverse order, with supporting checklists in order to encourage an investigation that stretches deeper than operator error (Sklet, 2004).

Management Oversight and Risk Tree (MORT)

The MORT method makes use of the Haddon's energy model, thus defines an accident as a lack of or inadequate barriers or control functions (Katsakiori et al., 2009; Kjellén, 2000). MORT provides the analyst with a logical tree divided into three main branches, the S, R and M, each with a comprehensive set of questions (Katsakiori et al., 2009). The S-branch deals with oversight and omissions specific to the accident, the R-branch is known risk factors but for some reason not controlled and the M-branch investigates the management system (NRI, 2009). Before working with the questions in the tree, some kind of event sequencing (e.g. ECFA) and a barrier analysis should be performed (NRI, 2009).

A problem with MORT is that it requires a lot of resources and expertise and is best suited for big, bureaucratic organisations, such as the U.S. nuclear industry, where it is used (Katsakiori et al., 2009).

Fault Tree Analysis (FTA)

In a FTA, the analyst choses and defines an undesired event. All possible contributing events and factors are then diagrammed in a logical tree structure, using logical AND/OR gates to display relations between events (Katsakiori et al., 2009). The FTA gives little support to the investigating analyst, but a tool to visualise a logical representation of the accident (Katsakiori et al., 2009; Kjellén, 2000).

Influence Diagram

Paté-Cornell used an influence diagram as the basis of an investigation of the Piper Alpha accident, with a particular focus on three levels: basic events, decisions and actions and organisational (Pate-Cornell, 1993; Sklet, 2004). In order to draw a proper diagram, the basic events must be studied, and all actions and decisions related to that event are also mapped. Lastly, the actions and decisions are checked to see if they can be the cause of basic organisational factors (Sklet, 2004). The influence diagram should make a distinction between the different levels and show how each event, decision or organisational factors are related to each other, usually done by boxes and arrows (Pate-Cornell, 1993).

Summary

The methods used to gathering information about the event include interviews, workshops, physical evidence gathering, checklists, schematics, on-site inspections and more. Some methods do not provide any support for gathering data, thus are purely analytical (e.g. RCA, AEB, FTA). Interviews are mentioned or implied in many methods, for example the use of checklist usually involves talking to people in order to answer the questions in the list. The more comprehensive methods like MORT, STEP, TRIPOD, ECFC, Acci-mapping all requires interviewing persons involved.

The most common form of structuring the information gathered is some form of diagram, logical tree or a table. The biggest difference shows when it comes to analyse the data, where most methods use their own accident model or a variance of one. The principles of the energy-barrier model (Haddon, 1980) is trendsetting in models such as AEB, MORT, Barrier analysis, MTO-analysis and ETA.

What all these methods have in common is that they focus on the events leading up to the accident or incident (i.e. the initiating event), which means little attention is paid to the aftermath. This poses a problem for researchers interested in cascading effects, because they take place after the initiating event. The lack of details after an initiating event is also something the CascEff workgroup noticed while doing trial searches, which is not surprising if the investigation methods used do not pay attention to this matter.

A secondary problem, and also related to the first, is that many methods use a narrow system perspective. They either focus on a single event chain (AEB, FTA), or in other cases also organisational conditions are taken into consideration (MORT, MTO-analysis, SCAT) and some stretches even further to governmental level (Acci-map, TRIPOD, influence diagram, STEP), but they are still usually confined to a single company, system or sector. This might be due to the background of which most of these methods have emerged; many were developed to handle occupational hazards (e.g. SCAT, TRIPOD, MTO-analysis) or to investigate accidents within certain sectors (e.g. AEB, MORT for nuclear industry, ECFC for the U.S. Department of energy, FTA for the U.S. Department of Defence).

The effects on society are not mentioned explicitly in any of the studied methods and this is the level, which the CascEff project is interested in. However, most of the studied investigation methods do recognise that chain of event of an accident is affected by contextual factors (even though they have used other words, such as conditions or underlying causes).