The Inoperability I/O model

A risk-based approach for identifying key economic and infrastructure systems in a Swedish context

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Abstract
In this thesis the inoperability I/O model has been used in a case study to evaluate if it is applicable to Swedish conditions and if it is a suitable approach of describing interdependencies. The inoperability I/O model can, given a perturbation from one or more sectors, estimate the ripple effects measured in terms of industry inoperability and economic losses. The model approximates physical interdependencies with economic dependencies. The inoperability I/O model could be a cost-effective efficient alternative for comprehensively accounting for physical linkage between national sectors, considering the lack of alternatives.

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Summary

Today's critical infrastructures become more and more massive and complex as well as dependent on other critical infrastructures. This increases the likelihood of a multiple infrastructural breakdown. The development towards a more complex society with an increasing degree of interdependencies implies that we need to understand why system complexity results in increasing vulnerability. To be able to predict any consequences of a multiple infrastructural breakdown we need to construct models of the systems being considered, potential sources of risk and the couplings to other systems that might provide insight into the dynamics of risk propagation. In particular there is a need for a modelling framework capable of describing the interdependencies between our critical infrastructures.

One way of describing interconnectedness and critical interdependencies is modelling the way "inoperability" propagates throughout our critical infrastructure systems or industry sectors. One way of modelling inoperability is the Inoperability Input/Output model, which is a tool that can be used in various aspects of the risk and vulnerability modelling, assessment and management of large-scale economic-based engineering systems. The inoperability I/O model is often based on economic transaction data, i.e. the level of economic dependency between various sectors is assumed to be the same as the level of physical dependency. The model can, given a perturbation from one or more sectors, estimate the ripple effects measured in terms of industry inoperability and economic losses.

The main objective of this thesis was to study the inoperability I/O model in a Swedish context and to analyse if the inoperability I/O model can be applied to Swedish conditions and if it is a suitable approach to study critical interdependencies in Sweden. In order to fulfil the main objective of the thesis a literature study was conducted with scenarios designed in a Swedish context. The main conclusions of the work were:

- Technically the inoperability I/O model can be applied to the original model without any difficulty since the data material from SCB is presented in a suitable way for inoperability I/O modelling. When considering validity and accuracy regarding Swedish conditions there are some questions about the model that have to be analysed in further detail. One of the main conclusions made in this thesis is the importance of foreign trade, i.e. import and export. To get adequate results import and export has to be included in the model in one way or another.

- The identified key sectors, i.e. sectors with a large degree of influence on other sectors, included: the sector for real estate, the sector for manufacture of basic metals, the sector for construction, and the sector for import. Most of the identified key economic sectors have logical connections to almost all other sectors, for example most other sectors need the services from the sector for real estate or construction.

- Some of the identified sectors most vulnerable to cascading effects are considered critical for the society by the Swedish Contingency Agency, e.g. the sector for collection, purification and distribution of water, the sector for sewage and refuse disposal and sanitation, the sector for electricity, gas, steam and hot water supply as well as the sector for land transportation. It is argued that the protection for these

sectors needs to be strengthened and that risk-reducing work should be focused on these sectors as well as sectors indicated as key sectors.

- A considerably large part of the total economic loss after a disturbance can come from cascading effects or higher-order effects and it is therefore of great importance to analyse interdependencies.

In conclusion, to answer the main research question regarding whether the inoperability I/O model can be applied to study Swedish critical dependencies and if the model is suitable for a Swedish context, the inoperability I/O model is a cost-effective and efficient alternative for comprehensively accounting for physical linkage between national sectors. Otherwise a similar or even greater special data collection effort would be required. To get any adequate result for Swedish conditions the effects of import has to be included in the model in one way or another. But the model is still only an approximation of physical interdependencies with economic dependencies and should be used with caution and with an overall perspective where the details are not emphasised. Further evaluation is needed to be able to add more confidence to the results and the model's suitability for Swedish conditions.

Contents

Chapter 1 - Introduction

This master thesis is written as a part of the Fire Safety Engineering (B.Sc.) programme and Risk Management and Safety Engineering (M.Sc.) programme within the Department of Fire Safety Engineering and Systems Safety at the Faculty of Engineering at Lund University (LTH), Sweden.

1.1 Motivation

Risk, hazards and disasters have been a part of the society since people started living in groups. Throughout the centuries, new hazards and risks have emerged that have increased the possibility that new disasters and crises will occur. The character of today's hazards and risks are changing that increases the complexity of contemporary disasters (Quarantelli, Lagadec, & Boin, 2007). One significant trend is the increasing dependence on the service of infrastructure systems, i.e. critical infrastructures. We are getting more and more dependent on goods and services that these complex infrastructures provide us with. This development affects our society's ability to manage accidents, crises and disasters. The complexity per se leads to a lot of positive effects; we can all see the advantages with an automatized subway and to be able to pay your bills over the Internet. But the increased complexity also leads to an increased vulnerability for society.

There is a long list of recent events that substantiate this claim, such as the Hurricane Katrina in New Orleans 2007 that wiped out most of the critical infrastructure in the New Orleans area for a considerably amount of time and severely crippled recovery operations (Boin & Mcconnell, 2007), the Storm Gudrun in Sweden that rendered some 650 000 customers without electrical power supply and severely damaged the function of telecommunication systems and roads (Johansson, Lindahl, Samuelsson, & Ottosson, 2006), the terrorist attacks in New York (Kendra & Wachtendorf, 2003) and London (Hughes, 2006) and many more.

Today's critical infrastructures become more and more massive and complex as well as dependent on other critical infrastructures. This increases the likelihood of a multiple infrastructural breakdown (Boin & Mcconnell, 2007). The development towards a more complex society with an increasing degree of interdependencies implies that we need to understand why system complexity in results in increasing vulnerability. To be able to predict any consequences of a multiple infrastructural breakdown we need to construct models of the systems being considered, potential sources of risk and the couplings to other systems that might provide insight into the dynamics of risk propagation.

As described above, there is a need for a modelling framework capable of describing the interdependencies between our critical infrastructures. Rinaldi, Peerenboom & Kelly (2001) for example describes the critical need to develop methods and procedures to model and quantify interdependencies. One way of describing interconnectedness and critical interdependences is modelling the way "inoperability" propagates throughout our critical infrastructure systems or industry sectors. The inoperability Input-output model can model the propagation of inoperability, the model studies economic couplings and is based on input-output models. The inoperability I/O model is a tool that can be used in various aspects of the risk and vulnerability modelling, assessment and management of large-scale economic-based engineering systems. Its initial and most fundamental purpose is to measure the propagation of perturbations or disturbances throughout a system of interconnected and interdependent infrastructure and economic sectors. The inoperability I/O model is often based on economic transaction data, i.e. the level of economic dependency between various sectors is assumed to be the same as the level of physical dependency. The model can, given a perturbation from one or more sectors, estimate the ripple effects measured in terms of industry inoperability and economic losses (Crowther & Haimes, 2005). There have been several studies of the inoperability I/O model in the US (Haimes et al., 2005a; Santos & Haimes, 2004) and in Italy (Roberto Setola, De Porcellinis, & Sforna, 2009) but no Swedish studies about the inoperability I/O model, applied to Swedish data material in the area of risk management has been found.

1.2 Objectives and Research questions

The main objective of this thesis is to study the inoperability I/O model in a Swedish context and to analyse if the inoperability I/O model is a suitable approach to study critical dependencies in Sweden.

- Can the inoperability I/O model be applied to study critical dependencies and is the model suitable for a Swedish context?

To facilitate the work, the main research question is divided into four sub-research questions:

- Is it possible to apply Swedish data material to the inoperability I/O model in a suitable way?
- Which economic sectors in Sweden are most vulnerable and most resilient to ripple effects and are some of these sectors deemed to be critical for the society?
- Which economic sectors can be considered key sectors, i.e. have considerably large influence on other economic sectors?
- Can we see any increasing/decreasing trend in the extent of interdependencies from the year 2000 to 2008?

1.3 Limitations

The case studies presented in this thesis are limited to a Swedish context, i.e. only Swedish data material is used and only data material from the year 2000 to 2008 is used in this thesis.

In this thesis only economic dependencies are studied. This means that if there are no economic transactions between sectors there is no interdependence. This is a basic assumption in inoperability I/O analysis.

Also the calculations are limited to stationary conditions, i.e. no dynamic conditions are considered. This means that the results cannot be applied to the acute response phase, but rather to the long-term consequences.

1.4 Research process

A flow chart over the overall research process can be seen below in Figure 1. Objectives and research questions were discussed in Chapter 1.2.

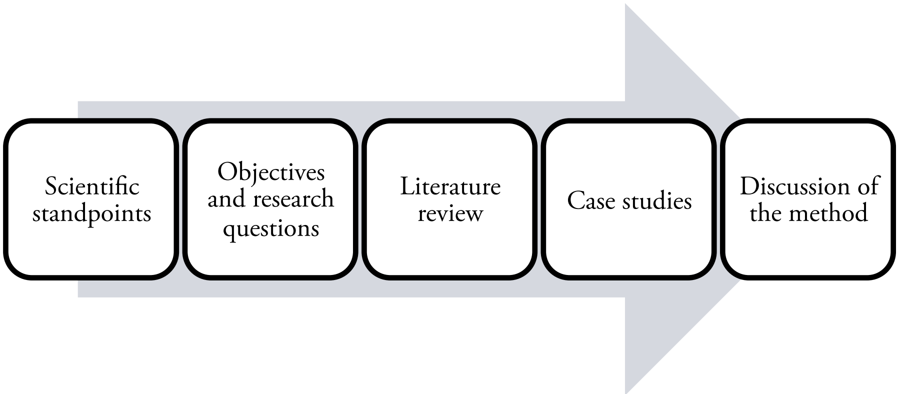

Figure 1: The overall research process

1.4.1 Scientific standpoints

This thesis aims towards a scientific approach, which is characterised by objectivity, correctitude and balance where objectivity means that in controversial subjects always retail all stands in the matter and to always explicitly specify if an argument is your own personal opinion, correctitude means that the given information is accurate and true, and that all information given in the thesis should come from the original sources, and balance means that the correct scope is given to the main subject and that minor details are not given to much space in comparison to important arguments, judgements and conclusions (Ejvegård, 2003).

1.4.2 Literature review

The aim of the literature review was to get an insight into relevant international research and to get a fundamental understanding of societal safety, risk and vulnerability analysis, critical infrastructure and inoperability input/output models.

The literature review consisted of a literature search in electronic databases such as SUMMON (Lund University, 2011) provided by Lund University and search engines such as Google Scholar. Cross-references and literature search on home pages of government agencies such as MSB (Swedish Civil Contingencies Agency) have also been used. The literature review can be divided into three sections: introduction to the area of societal safety and critical infrastructure, the background, structure, assumptions and equations of the original inoperability I/O model and a review of previous relevant case studies and applications in the area of inoperability I/O modelling. The results from the literature review are presented in Chapter 3 - Theoretical framework.

1.4.3 Case study design

The aim of the case studies was to apply the inoperability I/O model in a Swedish context, with Swedish data material and scenarios. More specifically, the objective of the case studies was to study if the inoperability I/O model is a suitable approach for Swedish interdependency analysis. The work in this section has proceeded according to the flow chart in Figure 2 below. For a more detailed description of the case study design see Chapter 3.

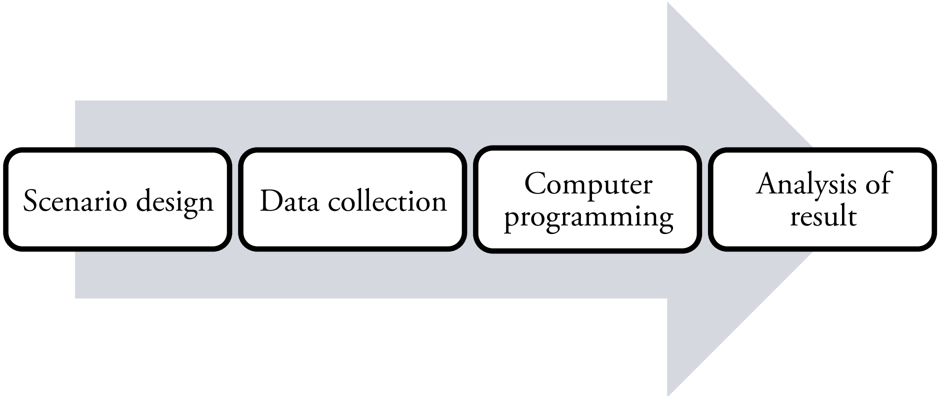

Figure 2: The case study design process

Scenario design

The first step in the case study process was to design scenarios based on the objectives and research questions established in Chapter 1.2. The developed scenarios can be divided into three different approaches: In the first approach all data material (from year 2000 - 2008) were used to see if any increasing or decreasing trend could be identified. In the second approach only the latest data from 2008 were used and the focus in these scenarios was to identify key sectors and sectors vulnerable to ripple effects. The third approach highlights two scenarios or crises that are high on the political agenda: Perturbations in the sector for Air transport and the sector for Agriculture and Forestry.

Data collection

The data material used in this thesis is provided by SCB (Swedish statistics) and covers the year 2000 to 2008. Statistics Sweden (SCB) publishes every year the national economic input-output accounts, which is the foundation for the inoperability I/O model (SCB, 2011). The SCB database, that provides an overview of the national economic I-O accounts, is a series of tables depicting the production and consumption of commodities (i.e., goods and services) by various sectors in the Swedish economy.

Computer programming

The next step in the case study process was to programme the code used in the computer calculations in R. In this thesis the computer software R has been used. The use of this computer software for the calculations was necessary since the amount of data handled has been vast, both in terms of input to the analysis and in terms of the output from it.

R is a free software environment for statistical computing and graphics and is an integrated suite of software facilities for data manipulation, calculation and graphical display. It includes

- An effective data handling and storage facility,
- A suite of operators for calculations on arrays, in particular matrices,
- A large, coherent, integrated collection of intermediate tools for data analysis,
- Graphical facilities for data analysis and display either on-screen or on hardcopy
- A well-developed, simple and effective programming language, which includes conditionals, loops, user-defined recursive functions and input and output facilities. (R Foundation, 2012)

Analysis of results

After the extraction of the results from R, the different case studies were analysed with respect to vulnerability, resilience and influence. These concepts as well as different techniques of presenting the results are defined in Chapter 3.4.

1.4.4 Discussion of method

In this section, Chapter 6, each step of the research process is evaluated and discussed with respect to the scientific standpoints, source of error and alternative methods.

The inoperability input/output model is also discussed in terms of reliability and validity. Reliability describes the accuracy and repeatability of a model and the extent to which a model gives results that are consistent. If the results are affected by chance the model cannot be seen as reliable. Validity of a model is the degree to which it measures what it is supposed to measure (Nationalencyklopedin, 2012b).

Chapter 2 - Theoretical framework

This chapter presents an overview of the research in the area of societal safety, critical infrastructure, complexity and interdependencies and how they are related. This chapter also provides a theoretical framework for the inoperability input/output model.

This chapter consists of three parts: background and motives for the study, description of the inoperability input/output model and some of the case study conducted with the inoperability I/O model. The first part of this chapter describes the background and motives for the study, why there is a need for a model that can describe the dependencies in a complex infrastructure. The second part of this chapter describes the inoperability input/output model, which assumptions the model is based on, the parts of model and some possible methods for validation. The third part of this chapter briefly describes some of the case studies conducted in this area and which are deemed to be relevant for this study.

2.1 Background

To understand the motives for the study this section briefly presents the research on the area of societal safety, critical infrastructure, complexity and interdependencies and how they interconnect.

2.1.1 Societal safety

The new era of risks and hazards, i.e. a more complex infrastructure, has led to a change in focus in most industrialized countries when it comes to the safety of the citizens. The end of the Cold war marked a change from preparedness for war to an increasing focus on civil society's own vulnerability.

Some of the changes that can adversely affect the vulnerability of society are: Globalisation, changes in demography, terms of trade, concentration in economic resources, complex and interlinked global technologies and infrastructures, increased mobility due to wars, crises, disasters or just tourism, environmental changes, responses to pandemic diseases, uncontrolled spread of weapons of mass destruction and global networks organizing terrorism or criminal activities. To be able to handle these new hazards and risks we need to develop new strategies. We can do this by developing new perspectives, including new approaches and new methods for identifying and analysing new threats as well as for prevention and management of occurring crisis. Since the late 1990s the term *Societal Safety* has been gradually incorporated into the Scandinavian safety vocabulary. The concept *Societal Safety* may be defined as:

'The society's ability to maintain critical social functions, to protect the life and health of the citizens and to meet the citizens' basic requirements in a variety of stress situations' (Olsen, Kruke, & Hovden, 2007).

The symbolic and political power of words is not to underestimate. Terms like terrorism, sustainable development and disaster can often be used to mobilize resources because they have heavy symbolic and political power. Maybe the term *Societal Safety* will have the same power.

2.1.2 Critical infrastructure - Definitions

An important part of the concept *Societal Safety* concerns protection of critical infrastructure. In 2011 the Swedish Civil Contingencies Agency presented, on behalf of the Swedish government, an overall national strategy for protection of vital societal functions[1] – *A functioning society in a changing world* (MSB, 2011). The National strategy for protection of vital societal functions aims to create a more resilient society with an enhanced capability to resist and recover from severe disturbances in vital societal functions. The strategy also aims to create better conditions so that the society will operate at an acceptable level during severe events and disturbances. *Vital societal function* is the Swedish nomenclature of the international concept critical infrastructure. The report defines the Swedish fundamental concept of *vital societal functions* and *critical infrastructure*.

Vital societal functions are defined as: *A societal function of such importance that a loss or a disturbance in the function would cause substantial risk or danger for the citizens' life and health, the society's functionality or the society's fundamental values.*

Critical infrastructures are defined as: *Physical infrastructures whose functionality contributes to secure the maintaining of vital societal functions.*

As noticed in the report, the Swedish definition of critical infrastructures does not correspond to the international (in particular the European Union) definition of the concept. This might cause some problems when relating to international literature and the European Critical Infrastructure directive (Council Directive 2008/114/EC) from 2008.The international definition does not only cover the supporting physical structures but also the functions and activities that would be defined as vital societal functions by the Swedish definitions. In this study the International definition of critical infrastructures was used. In some cases the Swedish concept vital societal functions were used for clarity.

The Swedish Civil Contingencies Agency (MSB) has given some examples of what type of functions that are considered to be vital or critical for the society (MSB, 2009a). These include:

- Supply of energy
- Financial services
- Retail and industry
- Health and social care
- Information and communications
- Supply of food
- Public administration, protection and security
- Transports
- Water distribution

2.1.3 Critical infrastructure breakdowns

As described in an earlier part of this chapter, modern society relies more and more on the effective functioning of critical infrastructure networks to provide public services, enhance

[1] Samhällsviktig verksamhet

quality of life, sustain private profits and spur economic growth. This means that the critical infrastructures become more and more massive and complex. At the same time, society also become more aware of our vulnerability to new and future threats such as terrorism and climate change (OECD, 2003).

The most complicating factor when it comes to critical infrastructure breakdown is that we cannot predict with any degree of precision the potential consequences of infrastructural failure. If we cannot predict what is going to happen then how can we prepare ourselves and reduce our vulnerability? In the western societies we have experienced relatively few major infrastructural failures and most of these have been breakdowns in one single infrastructure. One exception is when the Hurricane Katrina wiped out most if not all critical infrastructures for a considerable amount of time in New Orleans. The chaos and disorder that overtook New Orleans can provide us with some ideas of what a worst-case scenario for a critical infrastructure breakdown may look like (Boin & Mcconnell, 2007). But the chaos and disorder in New Orleans were initially caused by a Hurricane and not an infrastructural breakdown, event though the hurricane caused a multiple infrastructural breakdown that worsened the situation. So catastrophes caused by infrastructural breakdowns are yet to emerge. They fall in the category of "future crises" (Rosenthal, Boin, & Comfort, 2001) and these "future crises" can, as pictured by Hurricane Katrina, also fall in the category of "worst cases" (Clarke, 2006).

2.1.4 Risk and Vulnerability

To handle the possibility of a "worst case" scenario we need tools like risk assessment and risk management. The risk management standard ISO 3100 (ISO, 2009) defines risk management according to Figure 3.

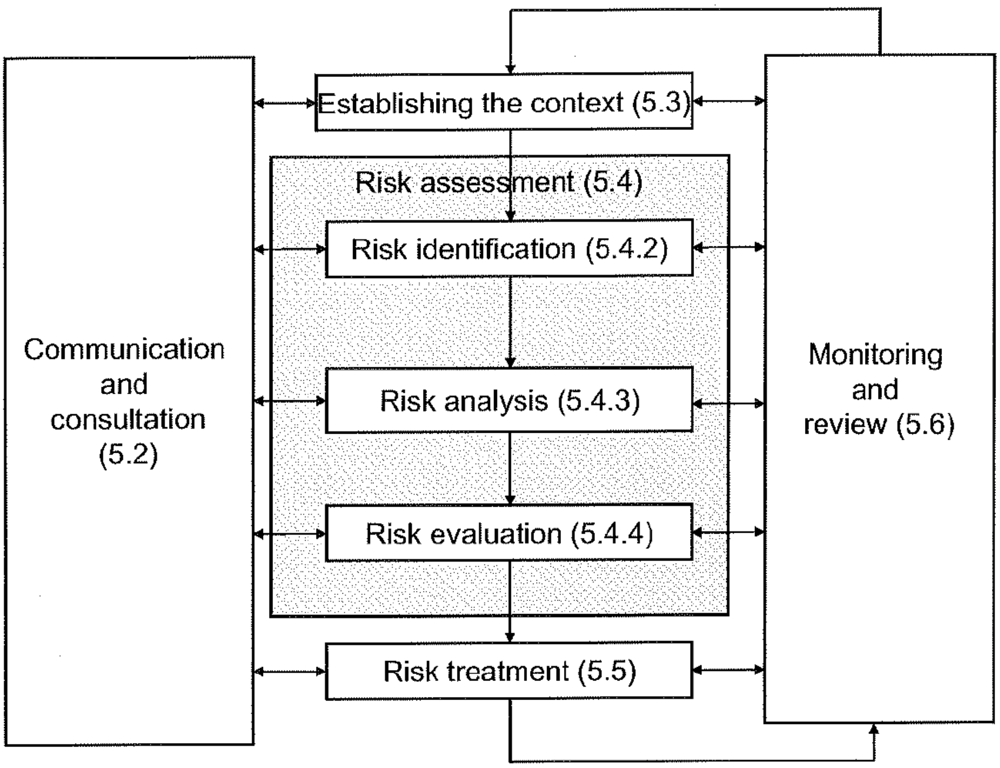

Figure 3: The risk management process (ISO, 2009)

One part of the risk management process is risk assessment, which consists of risk analysis and risk evaluation. Risk assessment is a process for understanding the result of destructive events acting on something human value in terms of potential adverse consequences and their likelihoods. Kaplan and Garrick (1981) suggested defining risk as a triplet of questions.

- What can go wrong?
- What is the likelihood?
- What are the consequences?

Ideally, the process of risk assessment fully develops answers to this triplet of questions and therefore captures all the sources of risk and assesses their associated likelihoods and consequences. According to Haimes et al. (2007) current assessment methodologies that decompose systems into isolated subsystems for analysis is inadequate for analysing complex, interdependent systems of systems. Rinaldi et al. (2001) points out the importance of interdependency analysis when assessing the risks to infrastructures. They describe the importance of considering multiple interconnected infrastructures and their interdependences in a holistic manner.

Various methodologies that seek to answer the first triplet of questions have led to the development of theories and methodologies for risk management and control (treatment). Haimes (1991) presents a second triplet of questions that outline the fundamental tasks of quantitative risk management.

- What can be done and what options are available?
- What are the trade-offs in terms of costs, benefits and risks?
- What are the impacts of current decisions and future options?

When considering and working with the risks to our nation's critical infrastructure it is important to not only consider the risk but also the systems' vulnerability. There is a fundamental difference between the definitions of vulnerability and risk. Johansson & Jönsson (2007) defines vulnerability as the answer to the following triplet of questions.

- What can happen, given the perturbation?
- How likely is it, given the perturbation?
- If it does happen, what are the consequences?

Johansson & Jönsson (2007) makes the point that in order to assess the vulnerability to a system, according to this definition, the main task is to estimate the consequences that arise given a certain perturbation i.e. in contrast to risk where the quantification of the probability of the perturbation is of equal importance. In this thesis the main interest is the consequences of a given perturbation and not the probability. According to above definitions of risk and vulnerability, the methods of interest is applicable in the context of vulnerability analysis and since vulnerability analysis can be seen as a part of the risk analysis the methods are also applicable in the context of risk analysis.

Figure 4 and 5 below describes some of the questions that we need to work with when assessing and managing the vulnerability to the nation's Critical Infrastructures. Phase I is defined as risk- and vulnerability analysis and phase II as risk treatment according to ISO 3100.

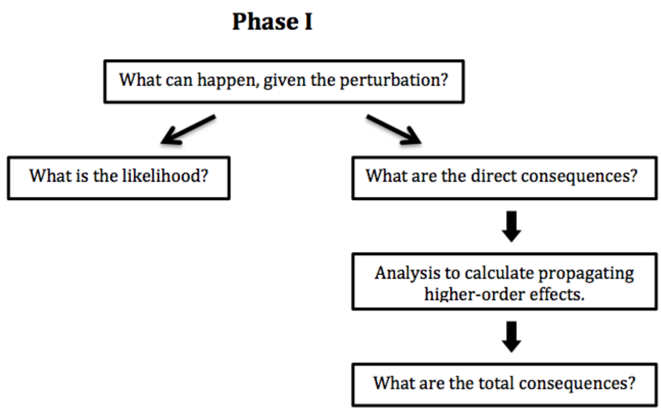

Figure 4: Risk- and vulnerability analysis

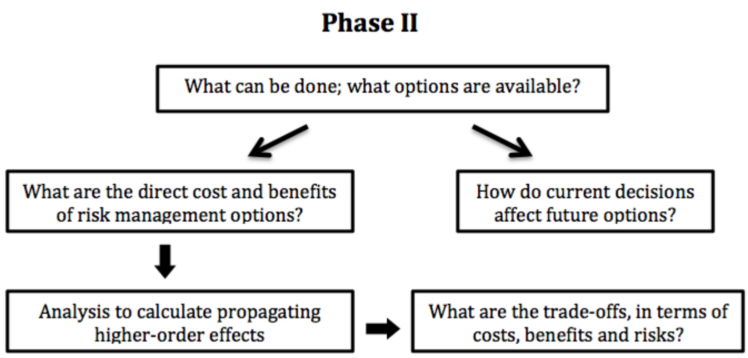

Figure 5: Risk treatment process

As previously mentioned, a full-scale critical infrastructure breakdown falls in the category of “Worst cases”. The question "what can go wrong" is all about imagination when it comes to this category. To be able to prepare ourselves, to reduce the risks we need to imagine the worst thing that can happen. It is very hard to predict the consequences of an infrastructural breakdown, but is it impossible? To respond to this question we need to look into some trends that affect the societies’ critical infrastructures.

2.1.4 Increased complexity, coupling, creeping dependencies and other trends

As mentioned in earlier sections, today’s critical infrastructures become more and more massive and complex as well as dependent on other critical infrastructures. This increases the likelihood of a multiple infrastructural breakdown (Boin & Mcconnell, 2007). The development towards a more complex society with an increasing degree of interdependencies implies that we need to understand why complexity in systems results in increasing vulnerability.

Perrow (1999) describes how accidents are naturally associated with complexity and tight coupling, and that complex interactions in technical systems inevitable can lead to accidents (which can be considered normal or natural). This discussion can to some extent be transferred to describe the political, institutional, technological and economic interdependency and complexity at a societal level. So complex and tight-coupled systems are characterized by the fact that they will fail but in an unpredictable way, i.e. there will be an incident but it is difficult or impossible to know where in the system or how the events will unfold. Another characteristic for these systems is that a relatively small incident may rapidly escalate and spread to other parts of the system. All this reasoning about complexity and coupling is important to understand if you are to understand the mechanisms behind an infrastructural breakdown, because as earlier mentioned, the modern critical infrastructure consists of complex and tight coupled systems (Perrow, 1999).

There is another important factor that has to be considered when discussing the vulnerability of the society. It revolves around incremental or evolving changes that accumulate over time and may result in latent conditions (Reason, 1997) or creeping dependencies (Hills, 2005), which makes society more vulnerable. Creeping dependencies may be explained as the effect of incremental or evolving changes in complex systems. This is a slow development that may lead to a cumulative risk of failure in critical infrastructure. As mentioned in an earlier section, incidents in technological and social systems can rapidly spread to other sectors and systems, which mean that a small failure in a single system may rapidly develop into a threat to the societal safety. Small incidents may also, just as latent conditions for accident in technological systems, trigger tensions in social systems and rapidly turn smaller events into serious crises (Hills, 2005).

Other trends that affect the vulnerability of society are privatization and outsourcing. Critical infrastructures have traditionally been the responsibility of various public organisations and institutions. These institutions and organisations are now increasingly being outsourced to both domestic and international private corporations. This means that societal safety now will compete with other goals like efficiency or profitability. The task of providing infrastructure that will serve the best interest of the public at large, regardless of whether these have been profitable in an economic point of view, are increasingly being provided on the basis of competitive tenders. Consequently, this means that safety considerations and robustness within our critical infrastructures may come in conflict with goals related to economic profitability and competitiveness. So the improved efficiency through competitive tenders may increase the vulnerability of society and reduce our ability to manage critical situations (Olsen et al., 2007).

Globalisation and internationalisation are also trends that can affect society's vulnerability. For example, an increased mobility between continents can lead to faster spreading of diseases from one continent to another. Additionally globalisation often means that a country's all interdependencies rarely are found only within the country's own borders; a nation is often dependent on goods and services from a large part of the world (Clarke, 2006; Quarantelli et al., 2007). One example of how we can be affected by an incident far from our own country's boundaries is the volcano eruption at Iceland during spring 2011 when all air traffic in northern Europe was disrupted.

McConnell and Drennan (2006) describes another trend that affect the work with risk and vulnerability, namely the difficulty to get enough resources. In a world of tight public expenditure constraints and extensive state intervention in areas such as health, education, transport and defence, low likelihood scenarios is low on the list of political priorities compared to the front-line every-day delivery of public services. Low likelihood scenarios are highly unlikely and risk management demands recourses for events that may never occur.

2.1.5 Managing interdependencies

Previous sections made it clear that risk assessment and management in large-scale systems require an understanding of how and to what degree the systems are interdependent. This section reviews several fundamental types of coupling and dependencies.

Physical interdependencies Physical coupling between components exists when energy or matter is physically transferred from one component to another. In the case of interdependent infrastructures, physical interdependencies can be transmission of electricity, water, and materials from one process to another or from one facility to another (Haimes et al., 2007).

Logical and information interdependencies Information couplings or cyber couplings between components exists if the commodity information is transferred through the information infrastructure. An infrastructure has cyber interdependency if its state depends on information transmitted through the information infrastructure. Many infrastructure sectors have become extremely dependent on networked information systems for efficient operations and timely delivery of products and services.

Two infrastructures are logically interdependent if the state of each depends on the state of the other via a mechanism that is not a physical, cyber, or geographic connection (Rinaldi et al., 2001). One example of a logical interdependence is the coupling between mobile and fixed telephone. The use of mobile telephone is likely to increase if the fixed phone line breaks down.

Inter-sector economic interdependencies

This type of coupling yield insight into how disruptions in one sector will affect economic dependent sectors. These interdependencies can be based on the economic transactions between sectors; the strength of the interdependence is correlated with the size of the economic transaction. Furthermore, as production is driven by demand, disruptions in the marketplace, where commodities are consumed by households, will propagate back to the producers that supply the end products as well as constituent ingredients and other support commodities (Haimes et al., 2007).

2.1.6 Modelling critical interdependencies – different approaches

To model the consequences of an infrastructural breakdown we need to assess all of these different interdependencies between our nation's critical infrastructures. But as pictured above there are several trends that make this very difficult. To be able to predict any consequences we need to construct models of the systems being considered, potential sources of risk and the couplings to other systems that might provide insight into the dynamics of risk propagation. One approach might be to use expert input models that consider different types of interdependencies. Another approach is network analysis that models physical interdependencies.

Expert input models: One example of an expert input approach in Sweden is the works that lead to the report *Faller en faller alla* by the Swedish Civil Contingencies Agency

(MSB, 2009b). In this report the interdependencies between sectors considered critical for the society were assessed by experts from the different sectors. The interdependencies were quantified on a scale from 1 to 3. Another approach to use expert inputs was made by Setola (2009) using the framework of input-output modelling. There are several difficulties with this type of expert input models, the first issue considers reliability. How reliable are the inputs form the expert and how do we handle uncertainties? The second issue considers resources since this type of study requires a massive amount of resources.

Network analysis This modelling approach is based on the field of network theory. In this approach a detailed computer model of a physical, technical system is constructed with all its basic components and then a disturbance in one part of the system and the way it propagates through the system is simulated. For a more detailed description of this type of approach see Johansson & Hassel (2010). The disadvantage of this approach is the level of details and available resources; it is not possible to build a model with this level of details of all the infrastructures in Sweden.

So in earlier sections of this chapter it was established that we need models to describe and quantify the interdependencies between critical sectors. Above a few approaches to model interdependencies were described but also the difficulties that this bring and that makes them unsuitable for the modelling that need to be done.

2.2 The Inoperability Input-Output model

There is a need for a modelling framework capable of describing the interdependencies between our critical infrastructures. Rinaldi et al. (2001) for example describes the critical need to develop methods and procedures to model and quantify interdependencies. One way of describing interconnectedness and critical interdependences is modelling the way *inoperability* propagates throughout our critical infrastructure systems or industry sectors. The term *inoperability* is defined as "*the inability of the system to perform its intended natural or engineered functions"* (Haimes & Jiang, 2001). The term can denote the level of the system's dysfunction, expressed as a percentage of the system's "as-planned" level of operation. The term inoperability can alternatively be interpreted as a degradation of a system's capacity to deliver its intended output (or supply) due to internal failures or external perturbations.

The inoperability caused by wilful attacks, accidental events or natural causes can set off a complex chain of cascading impacts on other interconnected systems. One way of modelling inoperability is the Inoperability Input-output model (IIOM), which is a model that study economic couplings and is based on Leontief's input-output model. The IIOM is a tool that can be used in various aspects of the risk and vulnerability modelling, assessment and management of large-scale economic-based engineering systems. Its initial and most fundamental purpose is to measure the propagation of perturbations or disturbances throughout a system of interconnected and interdependent infrastructure and economic sectors. The IIOM can, given a perturbation from one or more sectors, estimate the ripple effects measured in terms of industry inoperability and economic losses (Crowther & Haimes, 2005).

2.2.1 The Inoperability I/O model

The IIOM can be seen as a mapping of sector interdependencies. In Figure 6, S_i, $i = 1, 2, \ldots, 6$ represents a sector with financial, physical and commercial linkages to other sectors (depicted by dotted lines). The model then translates these linkages to a series of linear equations whose parameters a_{ij} that populate the matrix quantify the linkages between sectors i and j based on the inter-sector transaction data collected and processed by SCB. Because it is based on transaction data that is already being collected by SCB, the IIOM is an inexpensive, holistic method for estimating economic impacts and sector interdependencies (Haimes et al., 2007).

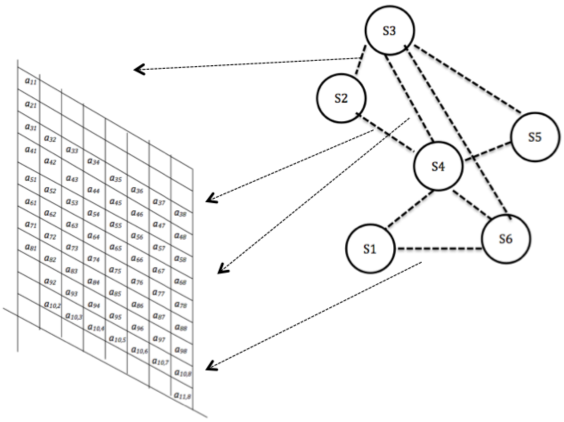

Figure 6: IIOM modelling principle as a snapshot of interdependencies, adapted from Haimes et al. (2007)

2.2.2 Background: Leontief Input-Output Model

In 1973 Wassily Leontief was awarded a Nobel Prize in Economics for the input-output (I-O) model for economy (Leontief, 1951). Leontief's I-O model describes the equilibrium behaviour of both regional and national economies. The model presents a framework capable of describing the interactive nature among various economic sectors. For a comprehensive introduction of the model and its applications see Miller and Blair (1985). In short terms, an input-output model divides the national or regional economy into various industrial sectors and tracks how much each industry must purchase from every other industry to produce one unit of output (Bezdek & Wendling, 2005).

The original formulation of the Leontief I-O model is shown in Eq. (1).

$$x = Ax + c \Leftrightarrow \{x_i = \sum_j a_{ij}x_j + c_j\} \forall\, i \qquad (1)$$

The notation x_i refers to the total production output of industry i. The notion a_{ij} is called Leontief technical coefficient and indicates the ratio of the input of industry i to industry j, with respect to the total production requirements of industry j. Thus, given n industries, a_{ij} can tell the distribution of inputs contributed by various industries i = 1, 2, . . ., n to the total inputs required by industry j. The notation c_j refers to the final demand for the i^{th} industry, which is the portion of industry i's total output for final consumption by end-users (i.e., the excess of all intermediate consumptions by various industries j = 1, 2, . . ., n) (Haimes et al., 2005a).

2.2.3 Physical based IIOM

Haimes and Jiang (2001) developed the first generation of the inoperability I-O model of interconnected systems that was grounded on Leontief's work. This model is called the physical-based IIOM and its desired output is the inoperability that can be triggered by one or multiple failures due to their inherent complexity or external perturbations (e.g., natural hazards, accidents or terrorism). The primary purpose of the model is to improve understanding of the impact of complexity on the continued and sustained operability of these systems under adverse conditions.

The model considers a system consisting of *n* critical interconnected sectors. The output of the model is as previously mentioned and defined the sectors inoperability, which can be triggered by the input of one or multiple failures, accidents or terrorism. The inoperability is assumed to be a continuous variable with a value between 0 and 1, where 0 corresponds to a flawless system state and 1 corresponds to the system being completely inoperable. Depending upon the nature of the problem and the type of system, inoperability can take different forms. In situations where the major concern is the production level, inoperability may be defined as unrealized production (i.e. the actual production level subtracted from the desired production level). For a power plant it may be suitable to define inoperability as the ratio of the actual amount of power produced to the desired production level (in an appropriate unit).

The formulation of the physical-based model is shown in Eq. (2):

$$x_i^P = \sum_j a_{ij}^P x_j^P + c^P \Leftrightarrow \boldsymbol{x}^P = \boldsymbol{A}^P \boldsymbol{x}^P + \boldsymbol{c}^P \tag{2}$$

Haimes and Jiang (2001) added the superscript P in Eq. (2) to the original formulation to distinguish it from Leontief's model. When comparing Eq (1) and Eq (2) the mathematical construct of the two models is similar but the interpretation of the model parameters is fundamentally different. In Leontief's model both $\boldsymbol{c}$ and $\boldsymbol{x}$ represents commodities typically measured in production or monetary units. But in the physical-based model the vector $\boldsymbol{c}^P$ represents the *input* to the interconnected infrastructure-perturbations in the form of natural events, accidents or terrorism. So $\boldsymbol{c}^P$ is some form of perturbation caused by external events. The model's output is the vector $\boldsymbol{x}^P$ and is defined as the resulting vector of inoperability of the different infrastructures due to their connections to the perturbed infrastructure and to one another. By using Eq. (2) the long-run intolerabilities of the interconnected infrastructures following an attack, accident or natural event can be calculated. The vector $\boldsymbol{x}^P$ can be called the inoperability vector and as mentioned before, it describes the degree of functionality of interconnected infrastructures. Thus it can take the values between 0 and 1, where flawless operation corresponds to $\boldsymbol{x}^P = 0$ or $x_1^P = x_2^P = \cdots = x_n^P = 0$ for $\boldsymbol{n}$ interconnected infrastructures. A perturbation input $\boldsymbol{c}^P$ will cause a departure from this condition (the infrastructures are said to be at their as-planned or ground state) as well as set off a chain of effects leading to higher-order inoperability.

For example, if the power infrastructure (the kth infrastructure) would initially lose 10% of its functionality due to an attack that delivers a perturbation of $c_k^P = 0.1$ this would mean that the perturbation can be interpreted as the resulting inoperability of the power infrastructure right after an attack. The inoperability will then propagate to other power-dependent infrastructures and will in turn cause more inoperability and ultimately may cause additional inoperability in the power infrastructure itself.

The biggest disadvantage with the physical-based IIOM is that it suffers from the expense of gathering large amounts of data in order to detail inter-sector connectivity. This data can for example be collected by expert input (Setola, 2007).The next generation of IIOM is the demand-based IIOM, which are derived by combining the physical-based IIOM with already collected databases from Statistics Sweden (SCB).

2.2.4 Demand-reduction based IIOM

By combining the insight and intuition gained from the physical IIOM with the rigor and proven SCB databases that accompany the original Leontief model the demand-reduction IIOM is derived. While the physical-based model quantifies inoperability in terms of degraded capacity to deliver the intended outputs, the demand-based model quantifies the inoperability as the reduced production resulting from perturbations to the demand. Logically the demand reduction of a perturbed sector produced further adverse impacts on the operation of other dependent sectors. For example, the demand reduction of the airline industry after the 9/11 terrorism attack caused the demand for other dependent industries to decline as well (e.g., travel and hotel industries). By integrating the concept of inoperability into Leontief's economic I/O model makes it possible to analyse how demand-reduction inoperability affects other interdependent infrastructures (Haimes et al., 2005). The input-output data from SCB is a record of the physical exchange of commodities between various interconnected industrial sectors of the economy that have been scaled by producers' prices into one common unit of Swedish kronor. As such, the economic transactions are used as an approximation of the interdependencies between sectors.

By using the definition of normalized production loss we can derive the demand-based model on the basis of the Leontief model. The first step is to define Normalized Production Loss as a percentage of its "as-planned capacity". Haimes and Jiang (2001) defined Normalized Production Loss according to Eq. (3).

$$Normalized\ Production\ Loss\ = \frac{As\ planned\ Production - Degraded\ Production}{Nominal\ Production} \tag{3}$$

All of the remaining derivation of the demand-based IIOM is carried out according to Haimes et al. (2005). The second step is to define an as-planned production scenario based on the Leontief balance:

$$\hat{\mathbf{x}} = \mathbf{A}\hat{\mathbf{x}} + \hat{\mathbf{c}} \tag{4}$$

The variables in Eq. (4) are defined as follows: $\hat{\mathbf{x}}$ = as-planned total production vector; $\mathbf{A}$ = Leontief coefficient matrix; and $\hat{\mathbf{c}}$ = as-planned final demand vector.

The next step is to define a degraded production scenario based on the Leontief balance equation:

$$\tilde{\mathbf{x}} = \mathbf{A}\tilde{\mathbf{x}} + \tilde{\mathbf{c}} \tag{5}$$

The variables in Eq. (5) are defined as follows: $\tilde{\mathbf{x}}$ = degraded total production vector; $\mathbf{A}$ = Leontief coefficient matrix; and $\tilde{\mathbf{c}}$ = degraded final demand vector.

By using Equation (1) we can define inoperability, $\mathbf{q_i}$ as the normalized production loss between the "as-planned" production, $\hat{\mathbf{x}}$ and the degraded production, $\tilde{\mathbf{x}}$ as shown below.

$$\mathbf{q_i} = \frac{\hat{x}_i - \tilde{x}_i}{\hat{x}_i} \tag{6}$$

A reduction in the final demand (denoted by $\boldsymbol{\delta}\mathbf{c}$ in Eq. (8)) is defined to be the difference between the as-planned and degraded final demands. This reduction in final demand consequently triggers reduction in production (denoted by $\boldsymbol{\delta}\mathbf{x}$ in Eq. (7)), which is defined to be the difference between the as-planned and degraded productions.

$$\boldsymbol{\delta}\mathbf{x} = \hat{\mathbf{x}} - \tilde{\mathbf{x}} \tag{7}$$

$$\boldsymbol{\delta}\mathbf{c} = \hat{\mathbf{c}} - \tilde{\mathbf{c}} \tag{8}$$

Subtracting Eq. (5) from Eq. (4) will result in in the following relationship between $\boldsymbol{\delta}\mathbf{x}$ and $\boldsymbol{\delta}\mathbf{c}$:

$$(\hat{\mathbf{x}} - \tilde{\mathbf{x}}) = \mathbf{A}(\hat{\mathbf{x}} - \tilde{\mathbf{x}}) + (\hat{\mathbf{c}} - \tilde{\mathbf{c}}) \Leftrightarrow \boldsymbol{\delta}\mathbf{x} = \mathbf{A}\boldsymbol{\delta}\mathbf{x} + \boldsymbol{\delta}\mathbf{c} \tag{9}$$

The transformations in Eqs. (10) - (12) are needed to derive the demand-based model in a form analogous to the balance equation of the Leontief model.

$$\mathbf{c}^* = \left[\left(\mathrm{diag}(\hat{\mathbf{x}})\right)^{-1}\boldsymbol{\delta}\mathbf{c}\right] \tag{10}$$

$$\mathbf{A}^* = \left[\left(\mathrm{diag}(\hat{\mathbf{x}})\right)^{-1}\mathbf{A}\left(\mathrm{diag}(\hat{\mathbf{x}})\right)\right] \tag{11}$$

$$\mathbf{q} = \left[\left(\mathrm{diag}(\hat{\mathbf{x}})\right)^{-1}\boldsymbol{\delta}\mathbf{x}\right] = \frac{\hat{x}_i - \tilde{x}_i}{\hat{x}_i} \tag{12}$$

Define the transformation matrix:

$$\mathbf{P} = \left[\left(\mathrm{diag}(\hat{\mathbf{x}})\right)^{-1}\right] \tag{13}$$

Using the transformation matrix in Eq. (14), Eq. (9) becomes Eq. (15) by the transformation defined in Eq. (12):

$$[\mathbf{P}\boldsymbol{\delta}\mathbf{x}] = [\mathbf{P}\mathbf{A}\mathbf{P}^{-1}][\mathbf{P}\boldsymbol{\delta}\mathbf{x}] + [\mathbf{P}\boldsymbol{\delta}\mathbf{c}] \tag{14}$$

$$\mathbf{q} = \mathbf{A}^*\mathbf{q} + \mathbf{c}^* \tag{15}$$

Assuming that the demand-based interdependency matrix $\mathbf{A}^*$ is nonsingular and stable, the demand-based inoperability $\boldsymbol{q}$ can be calculated as follows:

$$\mathbf{q} = [\mathbf{I} - \mathbf{A}^*]^{-1}\mathbf{c}^* \tag{16}$$

The variables in Eq. (16) are defined and interpreted as follows:

$\mathbf{c}^*$ = A perturbation vector expressed in terms of normalized degraded final demand (i.e. "as-planned" final demand minus actual final demand, divided by the "as-planned" production level). Since $\mathbf{c}^*$ is demand-based, a supply-based reduction is treated as a forced-demand reduction.

$\mathbf{A}^*$ = The demand-reduction based interdependency matrix, which indicates the degree of coupling of the industry sectors. The elements in a particular row of this matrix can tell how much additional inoperability is contributed by a column industry to a row industry.

$\mathbf{q}$ = The inoperability vector expressed in terms of normalized economic loss (inoperability).

The demand-based economic loss can be calculated as follows:

$$\mathbf{E} = \mathbf{q}\hat{\mathbf{x}} \tag{17}$$

The variables in Eq. (17) are defined and interpreted as follows:

$\mathbf{q}$ = The inoperability vector expressed in terms of normalized economic loss (inoperability).

$\mathbf{E}$ = The inoperability vector expressed in terms of Economic loss.

$\hat{\mathbf{x}}$ = As-planned total production vector.

2.2.6 Economic I/O accounts

Table 1 below are adopted from Santos & Haimes (2004) and shows a summary of the economic I/O accounts and the different variables that that make up the input to the inoperability I/O model.

Table 1: Economic I/O accounts

	Commodity	**Industry**		
Commodity		Use Matrix (U)	Exogenous Demand (e)	Total Commodity Output (y)
Industry	Make Matrix			Total Industry Output (x)
		Value Added (Z^T)		
	Total Commodity Input (Y^T)	Total Industry Input (X^T)		

- The make matrix (V) shows the amount of the different column commodities produced by the row industries.
- The use matrix (U) shows the amount of the different row commodities consumed by the column industries.
- The exogenous demand vector (e) shows the amount of commodity used other than those intermediate consumptions by industries in the use matrix.
- The value-added vector (z) shows the amounts of industry inputs other than commodities.
- The total industry output (x) corresponds to the value of all commodities produced by a particular industry (i.e., the sum along a row of the make matrix).
- The total commodity output (y) corresponds to the value of all the intermediate industry consumptions and exogenous demands for a particular commodity (i.e. the sum along a row of the matrix added to the corresponding element of the exogenous demand vector (Santos & Haimes, 2004)).

Santos (2006) describes that the make matrix is an industry-by-commodity matrix, which means that it shows the monetary values of different column commodities produced by the different row industries. Table 2 shows a part of the make matrix data for the 2008 Swedish economy. The table can be read according to the following example, the agriculture and hunting industry (AGRI) produced 49 664 millions of Swedish kronor (m SEK) worth of agriculture and hunting (AGRI) commodity and 51 m SEK worth of food and beverages (FOOD) commodity.

Table 2: Make matrix in millions of Swedish kronor.

Code	Description	AGRI	FRST	FISH	MINE	FOOD	WOOD
AGRI	Agriculture and hunting	49 664	0	0	105	0	0
FRST	Forestry and logging	0	37 256	0	0	0	1 025
FISH	Fishing	0	0	1 557	0	0	0
MINE	Mining of coal	0	0	0	970	0	80
FOOD	Manufacture of food and beverages	51	0	1	0	137 407	0
WOOD	Manufacture of wood	0	669	0	268	0	81 032

The use matrix is a commodity-by-industry matrix that shows the monetary values of the different row commodities consumed by the different column industries. Table 3 shows a part of the use matrix data for the 2008 Swedish economy. For example, the agriculture and fishing commodity was in 2008 used of: 9 090 m SEK by the agriculture and hunting (AGRI) industry, 72 m SEK by the Forestry and logging industry (FRST), 35 002 m SEK by the manufacture of food and beverages industry (FOOD) and 9 m SEK by the manufacture of wood (WOOD) industry.

Table 3: Use matrix

Code	Description	AGRI	FRST	FISH	MINE	FOOD	WOOD
AGRI	Agriculture and hunting	9 090	72	0	0	35 002	9
FRST	Forestry and logging	17	1 334	0	0	9	17 880
FISH	Fishing	10	0	0	0	693	0
MINE	Mining of coal	480	0	0	218	0	88
FOOD	Manufacture of food and beverages	7 412	0	0	0	31 793	0
WOOD	Manufacture of wood	139	233	78	143	158	15 800

To be able to use the make (V) and use (U) matrices in the inoperability I/O model they need to be normalized according to their respective column sum. The normalized make matrix is denoted $\widehat{\mathrm{V}}$ and the normalized use matrix is denoted $\widehat{\mathrm{U}}$.

2.2.7 Interdependency matrix

The Leontief technical coefficient matrix, denoted by **A**, is a matrix with industries along the rows, and the industries along the columns. It can be shown that **A** is the product of the normalized make and the normalized use matrices, for details about these operations see Santos & Haimes (2004).

In the inoperability I/O model the demand-side interdependency matrix **A*** is used and it can be shown to be related to the Leontief technical coefficient matrix **A** and the vector of industry "as-planned" productions $\hat{\mathrm{x}}$ in the following way:

$$\mathbf{A}^* = [(\mathrm{diag}\ (\hat{\mathbf{x}}))^{-1}][\mathbf{A}][\mathrm{diag}(\hat{\mathbf{x}})] \quad (18)$$

Each elements of the demand-side interdependency matrix ($\mathrm{a}^*_{\mathrm{ij}}$) represents the fraction of inoperability transmitted by the *j*th infrastructure to the *i*th infrastructure, i.e. how much the inoperability of the *j*th infrastructure influences the *i*th infrastructure.

Setola (2009) introduced two indices to better understand the role played by each infrastructure. The dependency index δ_i is defined as the sum of the coefficient along a row of the interdependency matrix **A***:

$$\delta_i = \frac{1}{n-1} \sum_{j \neq i}^{n} a_{ij} \text{ (Row summation)} \quad (19)$$

The influence index ρ_j is defined as the column sum of the coefficients in the interdependency matrix:

$$\rho_j = \frac{1}{n-1} \sum_{i \neq j}^{n} a_{ij} \text{ (Column summation)} \quad (20)$$

The dependency index δ_i is the mean value of the coefficients used to propagate inoperability from all the infrastructures to the *i*th infrastructure. Thus it expresses the exposure of the *i*th infrastructure to failures in other infrastructures. Similarly, since the influence gain ρ_j is the mean value of the coefficients used to propagate inoperability from the *j*th infrastructure to other infrastructures, it expresses the overall influence exercised by the *j*th infrastructure. This indices expresses only the direct influences exerted or suffered by infrastructures and do not take into account the consequences of second- or higher-order dependencies. To be able to take into account these affects we can use the row summation and column summation of the overall interdependency matrix S that is defined according to Eq. (21).

$$S = (I - A^*) \qquad (21)$$

Each elements of the overall interdependency matrix (s^*_{ij}) represents the overall transmission of inoperability from the *j*th infrastructure to the *i*th infrastructure taking into account first-, second- and higher-order dependencies.

Thus the overall dependency index is defined according to Eq. (22).

$$\overline{\delta_i} = \frac{1}{n-1} \sum_{j \neq i}^{n} s_{ij} \text{ (Row summation)} \qquad (22)$$

The influence index ρ_j is defined according to Eq. (23).

$$\overline{\rho}_j = \frac{1}{n-1} \sum_{i \neq j}^{n} s_{ij} \text{ (Column summation)} \qquad (23)$$

These indices express the resilience of the corresponding infrastructure and the influence that an infrastructure exercises on the entire system considering first-order and higher-order dependency phenomena.

2.2.8 Practical applications

Considering the theory behind the inoperability I/O model there are several possible practical applications the model. The model can be used to:

- Guide policymaking activities for mitigating the highly uncertain outcome of disruptive events and develop risk management policies that focus on the most-affected sectors.
- Compute various perspectives of impact, which yield insight into societal consequences and provide a quantitative method for resource allocation.
- Calculate total inoperability and economic loss for affected sectors.
- Decision-making and trade-offs between possible reduction in economic losses and the corresponding cost of investment required for carrying out various equipment recovery/resource allocation options.

All these possible alternatives mean that the inoperability I/O model might be useful in various phases of the risk assessment and management process. In Figure 7 the models place in a risk assessment is highlighted.

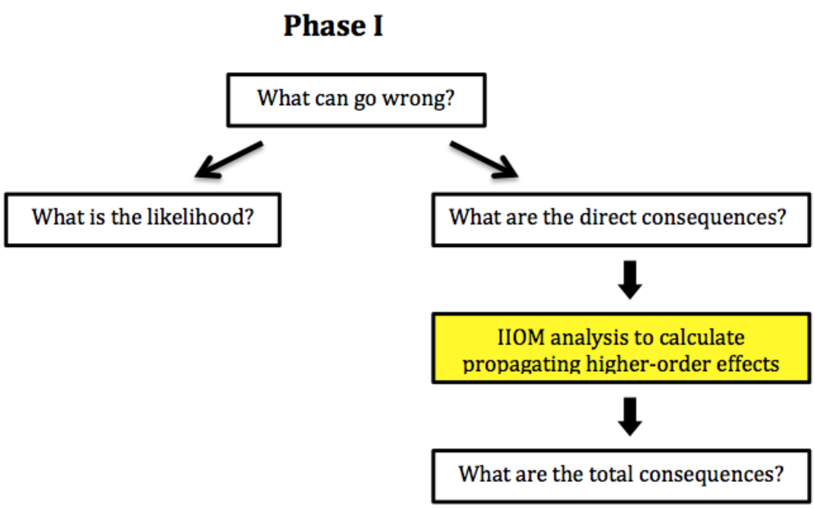

Figure 7: Example of Inoperability I/O analysis in risk- and vulnerability analysis, adapted from Crowther and Haimes (2005)

In Figure 8 the models place in a risk treatment process is highlighted.

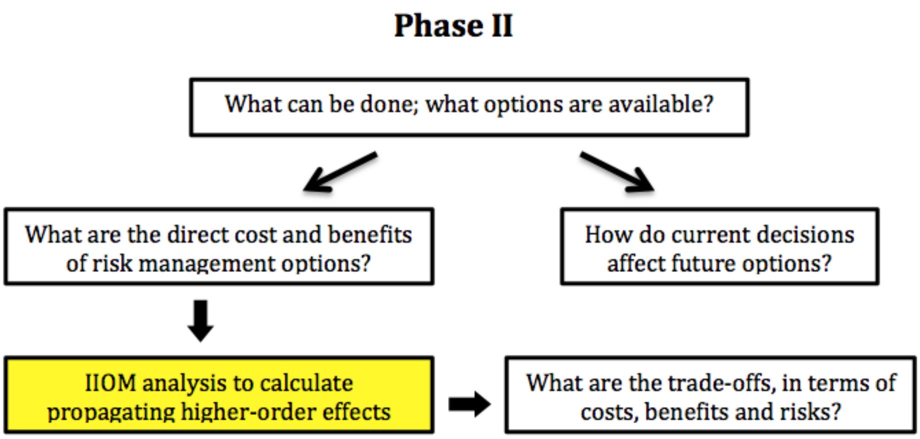

Figure 8: Example of IIOM analysis in risk management process, adapted from Crowther and Haimes (2005)

The different ways of practical applications and the suitability of them are discussed in Chapter 6.

2.2.9 Assumptions

Several of the assumptions made in the original Leontief structure are retained in the inoperability I/O model. The most fundamental assumptions are presented below and are quoted from Santos (2005).

- **Equilibrium Assumption** This assumption means that the industry inputs and outputs will balance with the final consumption of the sectors' output, i.e. the interactions between sectors are at a state of equilibrium. In the long run such a condition will eventually be true. However during the transient times following a harmful event that causes large and widespread demand perturbations, non-equilibrium conditions will probably dominate. In these cases the results from the inoperability I/O model would not accurate reflect the real economic effects.

Therefore, it is necessary to consider a substantially long period of time to satisfy the equilibrium assumption.

- **Deterministic Assumption:** The foundation of Leontief's model and the inoperability I/O model is the technical coefficient matrix **A**, which is derived from economic input-output data. These data is based on assumptions of constant technology and economic structure, i.e. there is no change in the technological and economic structure. Hence, the constant values that define the relationships between sectors do not change in time and are deterministic.

- **Linear Assumption:** The economic input-output data material exists of a number of sectors whose output contributes to the inputs required by other sectors. Each element in this matrix gives a constant, linear value that represents the contributions to one sector, say *j*, from any other sector, say *i*, which is proportional to the output of sector *j*. There are several examples where this assumption is valid. For example, if sector *i* is produces tire and sector *j* produces cars, then the value of tires used by sector *j* would naturally increase linearly with the value of cars produced by sector *i*. On the other hand there are also examples where the linearity assumption may not be valid. As production increases proportionally, producers seek to increase efficiency through for example resource-sharing to consume fewer production requirements.

2.2.10 Other extensions of the Inoperability I/O model

The above-described version of the inoperability I/O model is the static and demand-reduction based inoperability I/O model. There are several other versions or extensions of the inoperability I/O model and below a few of these are briefly described.

- **The dynamic inoperability I/O model:** This extension of the original inoperability I/O model was developed to more accuracy handle the temporal dynamic behaviour of industry recoveries and can be viewed as a general extension of the static inoperability I/O model. The static model can be viewed as a description of the dynamic model at its equilibrium conditions since in this state the dynamic inoperability I/O model reduces to the form of the static model (Haimes et al., 2005a).

- **Supply-reduction based and output-reduction based inoperability I/O model:** In the demand-reduction based model described in Chapter 2.2.4 the initiating events are considered to be perturbations to the final demand levels. The demand-reduction model addresses inoperability due to degraded levels of final demand, where a sector reduces output in response to this reduction in demand. The supply reduction based and the output-reduction based inoperability I/O model addresses inoperability in terms of degraded production capacity and efficiency. For example can damage to facilities and equipment, inability of the workforce to work, or shortage of materials results in lower production output and thereby limiting the supplies available to other sectors and to the final consumer, i.e. cause inoperability.

  In the output-reduction based model the initial event is the impact of direct perturbation on the output of a sector. This perturbation may have resulted from capacity loss, facility closure, or supply flow disruption, among others. These disruptions can be translated into a direct reduction in the output value of the sectors affected. For instance, if a major industry were made inoperable by for example a terrorist attack or a natural event, there would be a direct and significant reduction in the output of that particular sector.

The supply-reduction based model considers perturbation to the value added levels of the inoperability I/O model in contrast to the demand-reduction based model that are considering perturbations to the final demand. For example can an event that initializes higher wages because of for example overtime and longer working hours to maintain a normal level of operations cause a supply-reduction perturbation. The increase in wages in an industry is considered an increase in its value-added component. An increase in the cost of wages in a specific sector can cascades to the other sectors, and result in an increase in their output prices (Leung, Haimes, & Santos, 2007). The supply-reduction based model can also be considered to be a way of describing forward linage instead of backward linkage as for the demand-reduction based.

2.3 Previous case studies

This section contains a brief description of a few case studies conducted with the inoperability I/O model. The described case studies are in some way or another related to the case study designed in this thesis in Chapter 3. Some of the presented case studies have been inspiring the design of the case studies conducted in this thesis and different ways of analysing the results.

2.3.1 The United States

The original inoperability I/O model was developed by Haimes and Jiang (2001) with data from the BEA (The Bureau of Economic Analysis). Several case studies have since been conducted in the US. Haimes et al. (2005b) conducted a case study that focused on HEMP (High-altitude electromagnetic pulse) attack where sectors susceptible to a HEMP attack were identified as well as the cascading effect of such attack. Crowther and Haimes (2005) demonstrated how the inoperability I/O model could be used in various phases of risk assessment and risk management with several different case studies. Santos (2005) conducted an ex post analysis of the September 11 attack, that resulted in a demand-reduction perturbation for the air transport sector and the hotel sector due to mostly physiological effects. The study is particular interesting since Santos also presented a visualisation tool for conducting multi-criteria ranking of the most-affected systems using both economic loss and inoperability metrics. Finally Barker & Santos (2010) presented case study aiming to identify key economic and infrastructure systems that were of interest since one of the objectives of this thesis was to identify Swedish key sectors.

2.3.2 Italy

Setola (2008) and Santos et al. (2009) used the Inoperability I/O model to analyse the interdependencies between Italy's economic sectors. By using economic data from 1995 to 2003 provided by the Italian National Institute of Statistics, the study demonstrated that interdependencies between economic sectors have an overall increasing trend. This case study is of interest since there are thoughts that the interdependencies in Sweden also have an overall increasing trend and it is of interest to study if this trend can be identified in the economic data material from SCB. A few of the indices described by Setola (2009) will be used to analyse the results obtained from the case study conducted in this thesis.

Chapter 3 - Case study design

This chapter describe the case study design and consists of four sections, one for each part of the case study design process from Chapter 1.4.3. The four sections include: Scenario design, Data collection, Computer programing, and Analysis of results. The part considering Computer programing shows a fictional 4-sector system to better illustrate how the data is used in the calculations.

3.1 Scenario design

The first step in the case study process was to design scenarios based on the objectives and research questions established in Chapter 1.2. The developed scenarios can be divided into three different approaches: In the first approach the whole data material (from year 2000 - 2008) was used to see if any increasing or decreasing trend could be identified. In the second approach only the latest data from 2008 were used and the focus in these scenarios was to identify key sectors and sectors that are vulnerable and resilient to ripple effects. The aim of the third approach was to illustrate how the inoperability input/output model could be used in the context of a vulnerability analysis and highlights two scenarios or crises that are high on today's political agenda: Perturbations in the sector for Air transport and the sector for Agriculture and Forestry. Demand-reduction based perturbations for the air transport sector is political interesting because of the fairly recent terrorist attacks on the sector, i.e. the terrorist attacks in New York (Kendra & Wachtendorf, 2003). Similarly the sector for Agriculture and Forestry is high on the political agenda because of the fairly recent BSE outburst in Europe (OECD, 2003).

3.1.1 Trends

In the approach were the main focus was to identify any increasing or decreasing couplings between interdependent sectors, 52 scenarios for each year were constructed. In each scenario a 10 % demand-reduction perturbation were induced to one sector at a time, i.e. in the first scenario a 10 %-perturbation for sector 1 was induced, in the second scenario a 10 %-perturbation for sector 2 was induced and so on.

The code that was used for the calculations in R for these scenarios can be seen in Appendix B.1. A list of all sectors and their respective sector number can be seen in Appendix A.

3.1.2 Dependency and key sector analysis

In this section the focus were dependency and key sectors. 52 scenarios with the demand-reduction based model were constructed and for each scenario a 10 % demand-reduction perturbation was induced to one sector at a time, i.e. in the first scenario a 10 % perturbation for sector 1 was induced, in the second scenario a 10 %-perturbation for sector 2 was induced and so on.

The code that was used for the calculations in R for these scenarios can be seen in Appendix B.2.

3.1.3 Air transport and agriculture disturbances

In this section the focus was, as previously mentioned, on two scenarios that are high on the political agenda, namely a perturbation to the air transport sector and a perturbation to the sector for agriculture and forestry.

In the air transport case, two types of perturbations were considered, the demand reduction and the supply reduction. Psychological effects after a terrorist attack on the air transport sector can cause the demand-reduction perturbation, for example attacks like the terrorist attack in New York 2001(Santos, 2006; Santos & Haimes, 2004), i.e. the demand for air travel goes down and can cause rippling effects all over the economy.

In the agriculture and forestry case the demand-based reduction can be caused by an outburst of some kind of zoonosis, which is an infection that can be transmitted from animals to humans by for example food. BSE (Bovin spongiform encefalopati or the mad cow decease) and salmonella is two examples of zoonosis that have caused and can cause a reduction in the demand for some kind of foods (in this case meat from cows and chicken). (Nationalencyklopedin, 2012)

For both scenarios a 10 % perturbation was induced and the total economic loss and the total inoperability were calculated. The code that was used for the calculations in R for these scenarios can be seen in Appendices B.3 and B.4.

3.2 Data collection

The data material used in this thesis is provided by SCB (Statistics Sweden) and covers the year 2000 to 2008. Every year SCB publishes the national economic input-output accounts, which is the foundation for the inoperability I/O model. The SCB database, that provides an overview of the national economic I-O accounts, is a series of tables depicting the production and consumption of commodities (i.e., goods and services) by various sectors in the Swedish economy. The SCB consumption and production tables are combined to calculate the interdependence matrix for 52 industry sectors of the Swedish economy. The detailed national tables are organized according to the European System of National Accounts (ESA95) and fully consistent with the worldwide guidelines on national accounting (System of National Accounts, SNA93). The industries are organized and classified according to the SNI 2002. The data is available at the webpage of SCB in Microsoft Excel documents (SCB, 2012).

3.3 Computer programming

The next step in the case study design process was to programme the code that was used in the calculations in R. The chosen version of the inoperability I/O model was the demand-reduction based model, this model was chosen because of the rigid literature foundation and the many conducted case studies. For more details about the demand-reduction based model see Chapter 2.2.4.

3.3.1 Model modification

When writing the code and assessing the data material collected in the previous step a slight modification of the original inoperability I/O model had to be done. This modification was necessary to get accurate and useful results for Swedish conditions.

The original model was developed for conditions in the US, which is a much larger country than Sweden, and it is unclear if this model includes import and export. To exclude the effects of import and export may be an accurate assumption when considering the US with a GDP at $15.094 trillion compared to Sweden's GDP at $381.719 billion (International Monetary Fund, 2012). But Sweden heavily depends on the foreign trade, i.e. import and export, so the assumption that import and export will not affect the results to a large extent is not a valid one for Swedish conditions. For some sectors the imported quantity of the main commodity is several times bigger than the domestic produced quantity. In the demand-based model the perturbation is caused by a reduction in the final demand and because export by definition means that a sector only can give input to the export sector but not use anything from the export sector, the export sector can be treated as an exogenous demand or final demand in this analysis. However the import sector cannot be treated and included in the model in the same way. So in the analyses conducted in this thesis a sector for import were included in the analyses.

The codes used for the calculations for all scenarios with the slight modification can be seen in Appendix B.

3.3.2 Fictional 4-sector system

For illustrative purposes lets consider a hypothetical four-sector economy comprised of (1) transportation; (2) paper industry; (3) electricity; (4) metal industry. The scenario considered is the following:

A bomb was found during a security check in a major airport. The event was followed by many cancellations in air travel bookings, and a notable decrease in air travel overall, estimated at 20 % of the total final output of the transport sector, i.e. a decrease in the total final demand for the transportation industry.

The aim with the calculations is to calculate the ripple effects of this demand-reduction for all four sectors.

The interdependency matrix

The foundation of the inoperability I/O model is the interdependency matrix, which can be seen as a mapping of sector interdependencies. All sectors have financial, physical and commercial linkages to other sectors. In the inoperability I/O model these linkages are quantified based on the inter-sector economic transaction data and transformed to a series of linear equations whose parameters x_{ij} populate the interdependency matrix. The transaction data used in this fictional example can be seen in table 4 below.

Table 3: Economic transaction data used in the fictional 4-sector system

	j=1	*j=2*	*j=3*	*J=4*	Demand **c**	Total output **x**
i=1, Transportation	x_{11}=500	800	800	400	1 000	3 500
i=2, Paper industry	400	900	1 000	800	1 500	4 600
i=3, Electricity	700	400	800	400	800	3 100
i=4, Metal industry	500	800	300	800	500	2 900

By using normalization and matrix transformations described by for example Santos & Haimes (2004) the interdependency matrix in Eq. (24) below can be obtained.

$$\mathbf{q} = (\mathbf{I} - \mathbf{A}^{*})^{-1}\mathbf{c}^{*} = \begin{pmatrix} 1.57 & 0.77 & 0.79 & 0.57 \\ 0.49 & 1.72 & 0.74 & 0.62 \\ 0.68 & 0.69 & 1.84 & 0.60 \\ 0.66 & 0.94 & 0.73 & 1.84 \end{pmatrix} \begin{pmatrix} 0.2 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0.32 \\ 0.099 \\ 0.14 \\ 0.13 \end{pmatrix} \quad (24)$$

Interdependency matrix Disturbance Resulting Inoperability

Eq. (24) shows the inoperability equation where:

q = The resulting inoperability
c* = Perturbation or disturbance
$(\mathbf{I} - \mathbf{A}^*)^{-1}$ = The interdependency matrix

3.4 Analysis of results

For each case study approach the results from R were extracted and presented in the report according to the following:

3.4.1 Trends

For each scenario the inoperability and the economic loss were calculated according to Eq. (16) and Eq. (17). For each year the overall inoperability, the total economic loss and the weighted overall inoperability were calculated according to Eq. (25), Eq. (26) and Eq. (27) below.

Total Economic loss = $\sum_{i=1}^{52} \hat{x}_i \bar{q}_i$ (25)

The overall inoperability = $\sum_{i=1}^{52} \bar{q}_i$ (26)

Weighted overall inoperability = $\frac{1}{\sum_{i=1}^{n} \hat{x}_i} \sum_{i=1}^{52} \hat{x}_i \bar{q}_i$ (27)

3.4.2 Dependency and key sector analyses

For all sectors the dependency and the influence indices as well as the overall dependency and influence indices were calculated according to Eq. (28), (29), (30) and Eq. (31) below. For each sectors the total and average inoperability and economic loss for all perturbations were calculated according to Eq. (32), (33), (34) and (35) below. Furthermore, for each scenario the total and average inoperability and economic loss were calculated according to Eq. (36), (37), (38) and (39) below.

Dependency index, $\delta_i = \frac{1}{n-1}\sum_{j\neq i}^{n} a_{ij}$ (Row summation) (28)

Influence index, $\rho_j = \frac{1}{n-1}\sum_{i\neq j}^{n} a_{ij}$ (Column summation) (29)

Overall dependency index, $\overline{\delta_i} = \frac{1}{n-1}\sum_{j\neq i}^{n} s_{ij}$ (Row summation) (30)

Overall influence index, $\bar{\rho}_j = \frac{1}{n-1}\sum_{i\neq j}^{n} s_{ij}$ (Column summation) (31)

Total sector (i) inoperability (q) for all scenarios (s) = $\sum_{S=1}^{52}(q_i)_s$ (32)

Average sector (i) inoperability (q) for all scenarios (s) = $\frac{1}{52}\sum_{S=1}^{52}(q_i)_s$ (33)

Total sector (i) economic loss (E) for all scenarios (s) = $\sum_{S=1}^{52}(E_i)_s$ (34)

Average sector (i) economic loss (E) for all scenarios (s) = $\frac{1}{52}\sum_{S=1}^{52}(E_i)_s$ (35)

Total scenario (s) inoperability (q) for all sectors (i) = $\sum_{i=1}^{52}(q_s)_i$ (36)

Average scenario (s) inoperability (q) for all sectors (i) = $\frac{1}{52}\sum_{i=1}^{52}(q_s)_i$ (37)

Total scenario (s) economic loss (E) for all sectors (i) = $\sum_{i=1}^{52}(E_s)_i$ (38)

Average scenario (s) economic loss (E) for all sectors (i) = $\frac{1}{52}\sum_{i=1}^{52}(E_s)_i$ (39)

3.4.3 Air transport and agriculture case studies

The total inoperability and economic loss for the 10 % perturbation for each scenario were calculated according to Eq. (25) and (26) above.

3.4.4 Analysis

After the extraction and presentation of the results, the different case studies were analysed with respect to vulnerability, resilience and influence. In this thesis, these concepts are defined according to:

- A key sector has a strong influence on other sectors' operability.
- A resilient sector is not sensitive to cascading effects.
- A vulnerable sector is sensitive to cascading effects i.e. is dependent on many other sectors.

To be able to handle cases with several different result metrics a method for multi-criteria evaluation was constructed in the form of a two dimensional matrix inspired by Santos (2006) Two different approaches for illustrating the two dimensional perspective was used The first approach showed the results in a matrix with the sector ranking on the horizontal and vertical scales whilst the second approach showed the sectors in a scatter plot with the inoperability metric on the vertical scale and the economic loss on the horizontal scale.

These illustrations may allow policy-makers to view the effects of a harmful scenario in different perspectives. Such visual aids as the constructed multi-criteria evaluation matrices can help decision-making by giving information of which sector is most-likely to suffer largest effects (i.e. economic loss and inoperability). In the analysis some special interest has been given to sectors that can be considered vital for the society, i.e. critical infrastructure.

Chapter 4 - Results

This chapter presents the results from the case studies along with short analyses of the results with respect to the research questions in Chapter 1.2. The chapter consists of five parts, divided according to the case study approaches described in Chapter 3.1: Trends, dependency and key sector analysis, and Air transport and agriculture case studies.

4.1 Trends

This section for trends includes analyses regarding the resulting overall inoperability, total economic loss and weighted overall inoperability of 10 % perturbations for each sector at a time. For a detailed definition of these concepts see Chapter 3.4.1 and for a detailed description of the case study see Chapter 3.1.1. This section also includes a short discussion regarding the importance of the initial perturbation that is not connected to the other parts of this section.

4.1.1 Overall inoperability

The overall inoperability was calculated according to Chapter 3.4.1. In Figure 9 below the overall inoperability for the 10 sectors with the largest change over the year 2000 to 2008 is presented. For the complete results, i.e. sector 1 to 52, see Figure C-1 to C-5 in Appendix C. As is evident by the complete results there is no overall increasing or decreasing trend in the overall inoperability. Although it is worth noticing that all the trend analyses are being conducted with the key sector point of view. But in some sectors, as can be seen in Figure 9 below, there are some significant changes. The sector for food products and beverages and manufacture of tobacco products (Sector 6) has experienced a slightly decreasing trend as well as the sector for manufacture of furniture (Sector 25) and the sector for public administration and defence (Sector 44). The sector for manufacture of basic metals (Sector 17) has experienced a fairly large increasing trend from the year 2003 to 2007. This might be an effect of the international political climate, i.e. the Iraq war that increased the demand for weapon, vehicles among others that use basic metals in the manufacture process. Other sectors that have experienced a slight increase are the sector for wholesale and retail (Sector 30), the sector for manufacture of machinery and equipment (Sector 19), and the sector for research and development (Sector 43). The sector for pulp, paper and paper products experienced a quick increase followed by quick decrease (a bump) during the years 2005 to 2006, which is probably an effect of the Storm Gudrun (Johansson et al., 2006) that hit Sweden early in 2006 and severely damage Swedish forests, i.e. there was an overload of timber needed to be taken care of. The sector for electrical machinery and apparatus (Sector 21) experienced a dramatic drop from the year 2001 to 2004. The most likely explanation for this dramatic drop is the burst of the Information Technology Bubble in the year 2000.

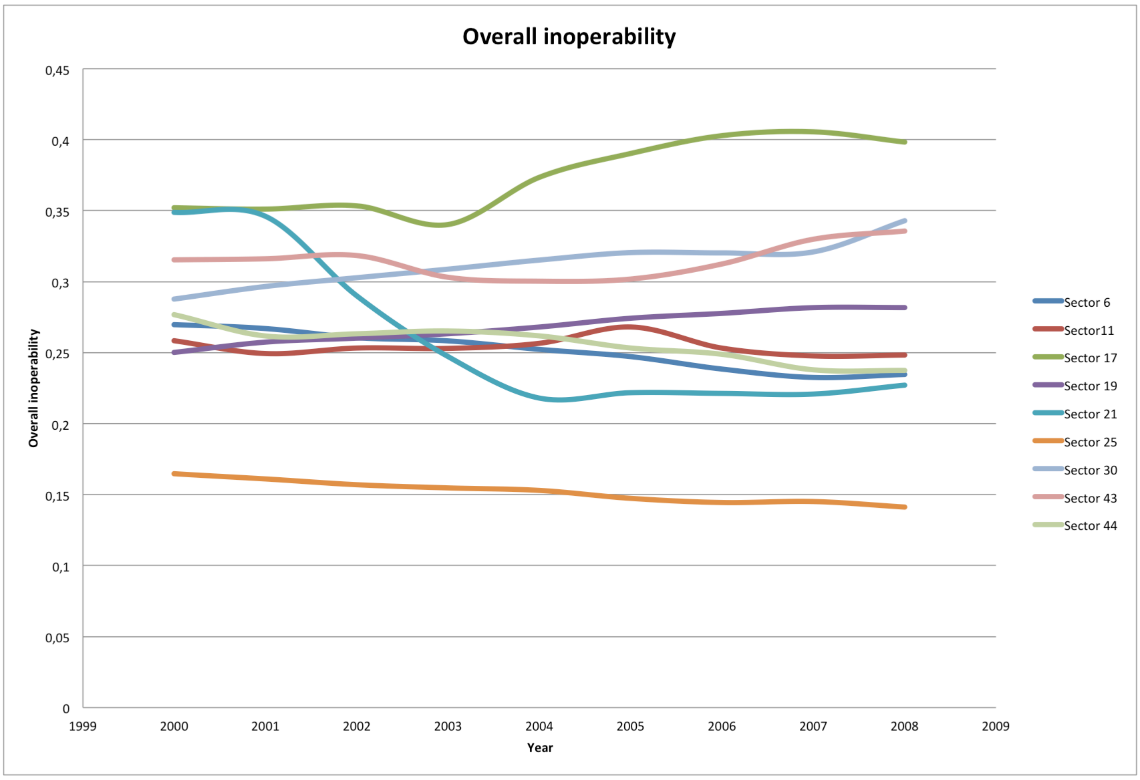

Figure 9: The overall inoperability caused by 10 % perturbation to each sector for the year 2000 to 2008 for the 10 sectors showing a significant change

The metric overall inoperability does not take into account the size of each economic sector; instead it gives the same weight to all sectors no matter the economic size. This might not be an accurate measurement in some applications.

4.1.2 Economic loss

In contrast to overall inoperability the metric economic loss weights each sector by its economic size. The total economic loss is calculated according to Chapter 3.4.1. In Figure 10 below the total economic loss for the 10 sectors with the largest change over the year 2000 to 2008 is presented. For the complete results, i.e. sector 1 to 52, see Figure C-6 to C-10 in Appendix C. The complete results show an overall increasing trend. This increase can however be explained by an increase in the economy, e.g. economic growth and inflation and not an increase in interdependencies.

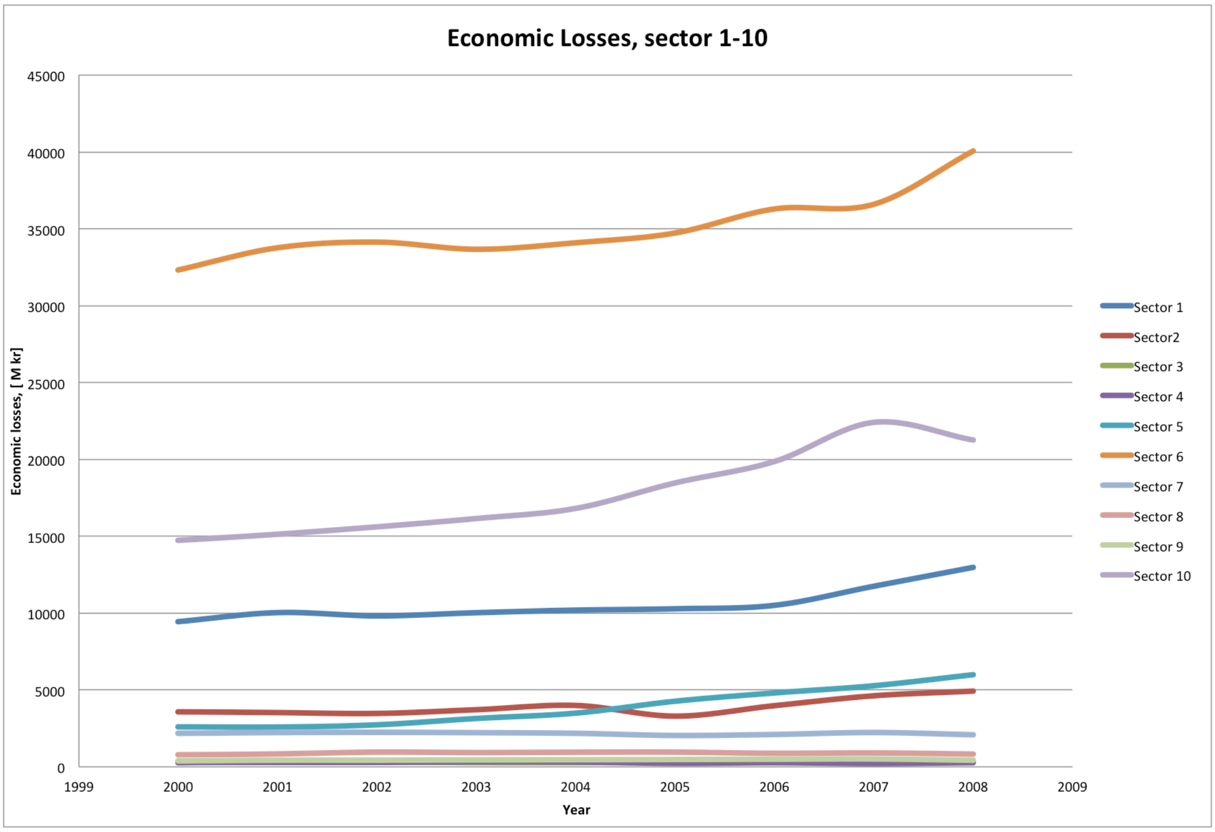

Figure 10: Total economic loss caused by a 10% perturbation to each sector from the year 2000 to 2008

4.1.3 Weighted overall inoperability

The metric weighted overall inoperability, in contrast to economic loss, takes into account the effect of economic growth and inflation and is a more accurate measurement when it comes to describing trends regarding interdependence. The weighted overall inoperability is calculated according to Chapter 3.4.1. In Figure 11 below the weighted overall inoperability for the 10 sectors with the largest change over the year 2000 to 2008 is presented. For the complete results, i.e. sector 1 to 52, see Figure C-11 to C-14 in Appendix C. When expressing the results in terms of weighted overall inoperability instead of economic loss the overall increasing trend that was evident in previous section is, as suggested, reduced to null. So the overall increase for the total economic loss can probably be explained by growth in economy and inflation.

But in some cases, as can be seen in Figure 11 below, there are some significant changes. Some changes were evident in the overall inoperability analysis, for example the sector for food products and beverages and manufacture of tobacco products (Sector 6), the sector for manufacture of basic metals (Sector 17), the sector for manufacture of machinery and equipment (Sector 19), the sector for pulp, paper and paper products, and the sector for wholesale and retail (Sector 30).

Other changes that are being highlighted in Figure 11, with a slight decrease in the sector for publishing, printing and reproduction of recorded media. This is probably a reaction to the fact that electronic music and books gets more and more popular as well as illegal downloading of the same. The sector for manufacture of coke, refined petroleum products and nuclear fuels experienced a slight increase as well as the sector for manufacture of motor vehicles, trailers and semi-trailers, the sector for construction and the sector for import. In the case of the import the explanation might be an overall economic boom in Sweden or an increase in the demand for imported products.

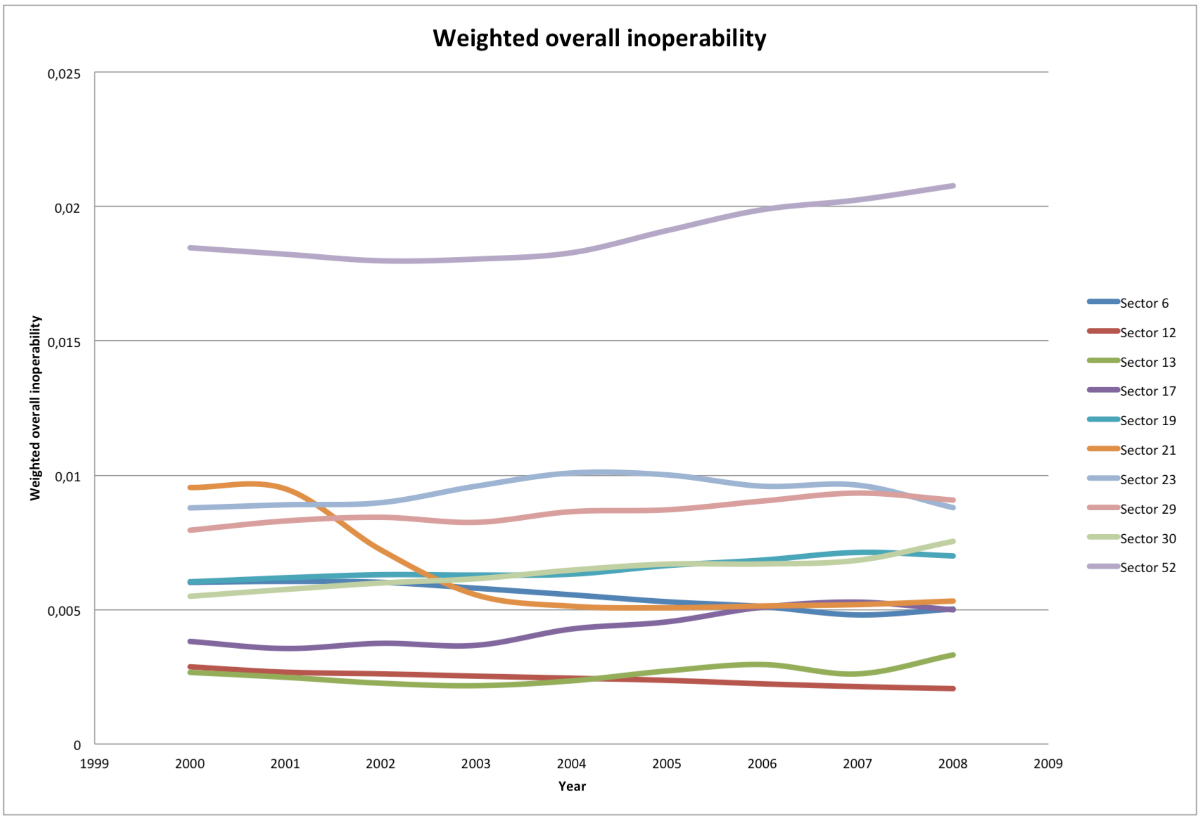

Figure 11: The weighted overall inoperability caused by a 10% perturbation to each sector for the year 2000 to 2008 for the 10 sectors showing a significant change

4.1.4 Initial perturbation

The importance of the initial perturbation is shown in Figure 12 below for sector 1-10, for complete results se Appendix C.4. As can be seen in the figures the size of the initial perturbation does not change the ranking of the sectors. In fact the size of the total perturbation (inoperability and economic losses) increases linear with the size of the initial perturbation, i.e. if the initial perturbation increases by 2 the total perturbation increases by 2. This means that if one calculates the economic loss or inoperability for 1 perturbation (for example 10 %) one can easily extrapolate this to the economic loss or inoperability for other perturbations (for example 5 % or 15 %). This also means that the size of the initial perturbation is not of importance if one is just interested in the ranking, which sectors are most dependent and which ones are not. This scalability or linearity can be traced back to the linear assumption described in Chapter 2.2.10 (Santos, 2006). For complete results see Appendix C-4.

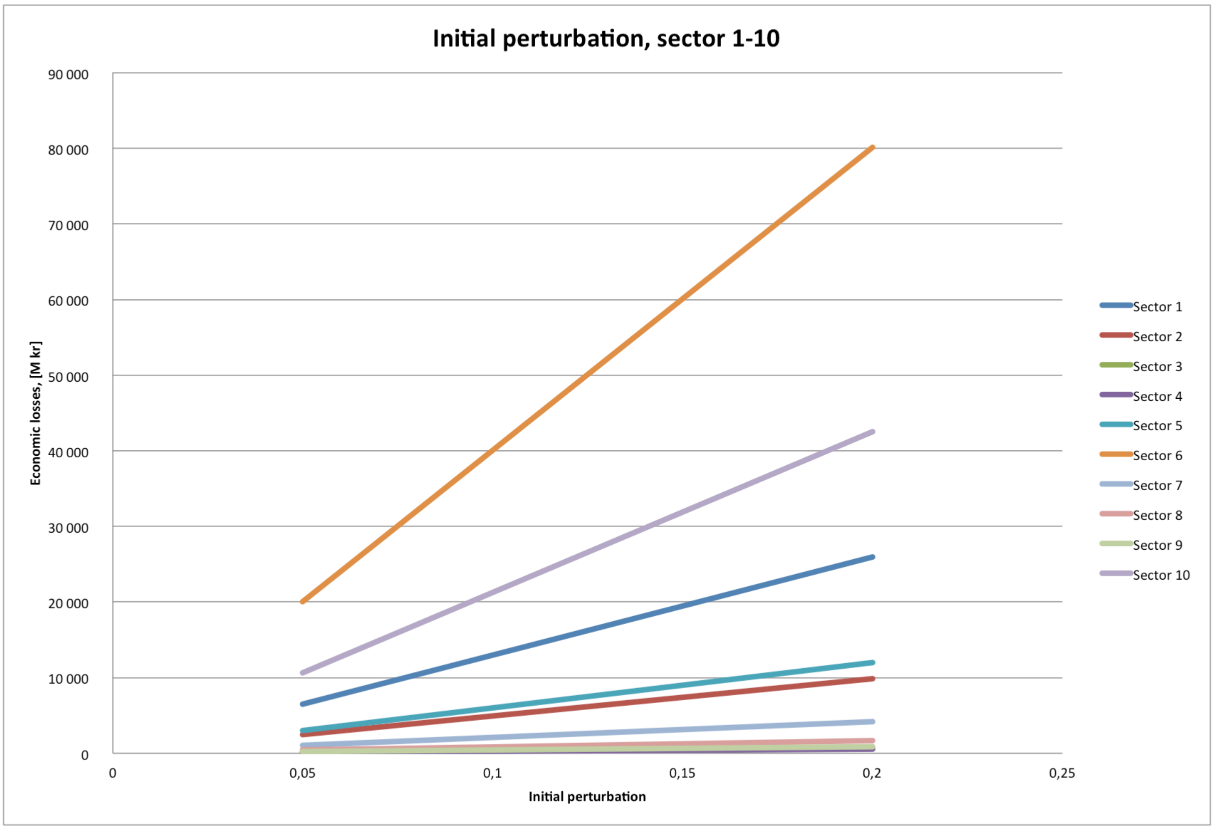

Figure 12: Resulting total economic loss for each sector for an initial perturbation ranging from 5% to 20%

4.1.5 Summary

The results from the calculations show no overall increasing or decreasing trend in either overall inoperability or weighted overall inoperability. Thus when using calculations from the inoperability I/O model no specific overall trend can be identified. According to the results the economic interdependencies between sectors have not increased from 2000 to 2008. This is a surprising result considering the growing interdependencies described by several authors mentioned in Chapter 2 (Boin & Mcconnell, 2007; Hills, 2005; Quarantelli et al., 2007). This result can be explained by the fact that it is only economic interdependencies that are described and that in this model the economic interdependencies substitutes physical, logical and other interdependencies described in Chapter 2.1.5. This approach might not be the most accurate way to describe how the interdependencies increase. The results from this analysis also differ from the results from a similar Italian study that found a significant increase in interdependencies between Italy's economic sectors (Setola, 2008.). However, it is unclear if the same type of data and method was used. It is also possible that they have not compensated for inflation and economic growth in their calculations and in that case their results (i.e. the large increase in economic loss) just show inflation or economic growth.

4.2 Dependency and Key sector analysis

There are several ways of analysing the inoperability I/O results with respect to vulnerability, resilience and key sectors. The data can be analysed through dependency and influence indices taking into account just first-order dependencies or higher-order dependencies. The advantage of using these indices to describe interdependencies is that any advance calculations is not necessary. It can also be analysed with respect to total or average inoperability or economic loss, or both with a multi-criteria evaluation matrix. For a more detailed description of the scenario design see Chapter 3.1.2 and for a detailed description of the presentation of the results se Chapter 3.4.2.

4.2.1 Dependency and influence index

Figure 13 below shows the top 10 influence indices from the interdependency matrix A, just considering first-order dependencies and Figure 14 shows the top 10 overall influence indices from the interdependency matrix S, taking into account higher-order dependencies. For more about these indices see Chapter 3.4.2. For complete results see Appendix C-5 and C-6.

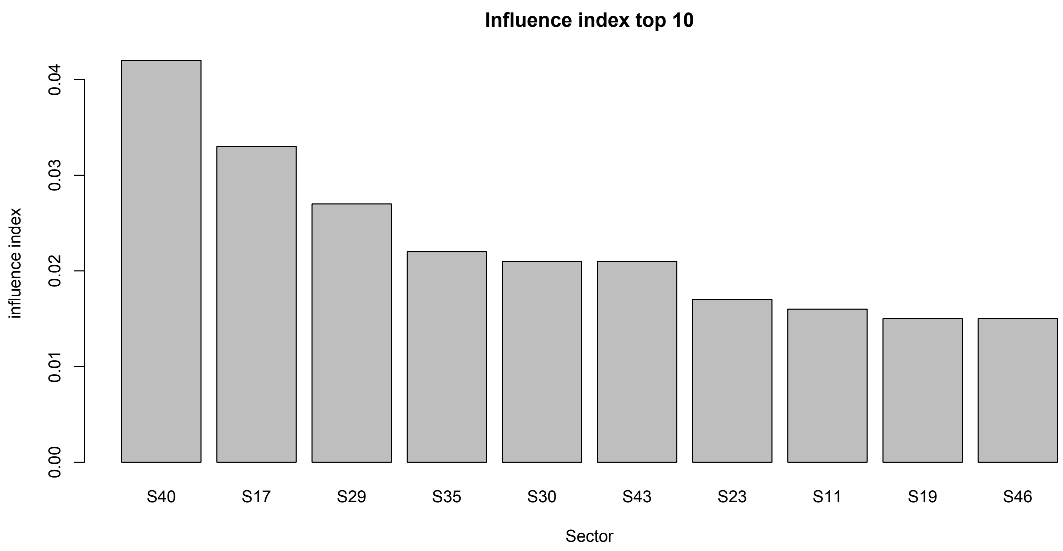

Figure 13: The top 10 sectors with the highest influence index

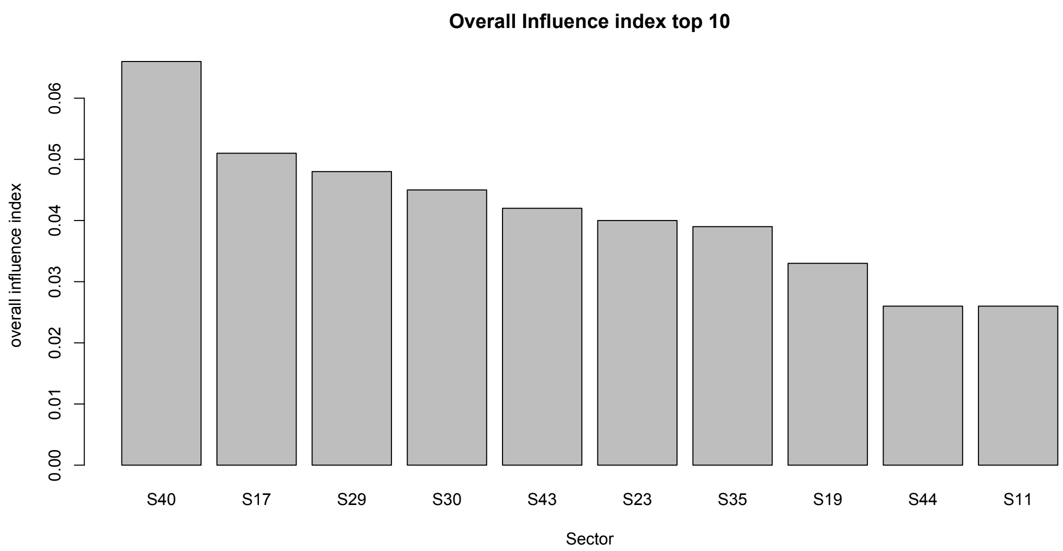

Figure 14: The top 10 sectors with the highest overall influence index

Figure 15 below shows the top 10 dependency indices from the interdependency matrix A, just considering first-order dependencies and Figure 16 shows the top 10 overall dependency indices from the interdependency matrix S, taking into account higher-order dependencies.

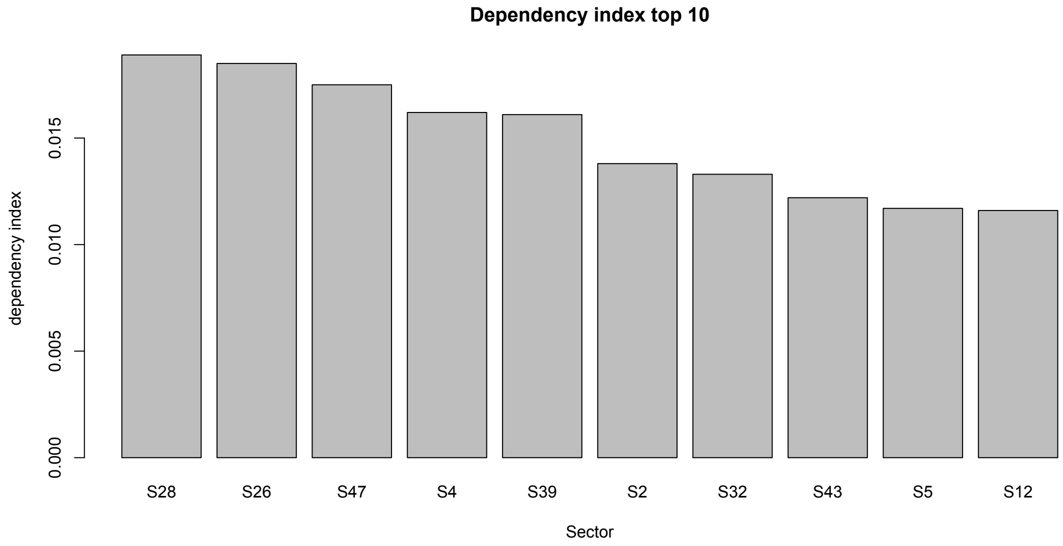

Figure 15: The top 10 sectors with the highest dependency index

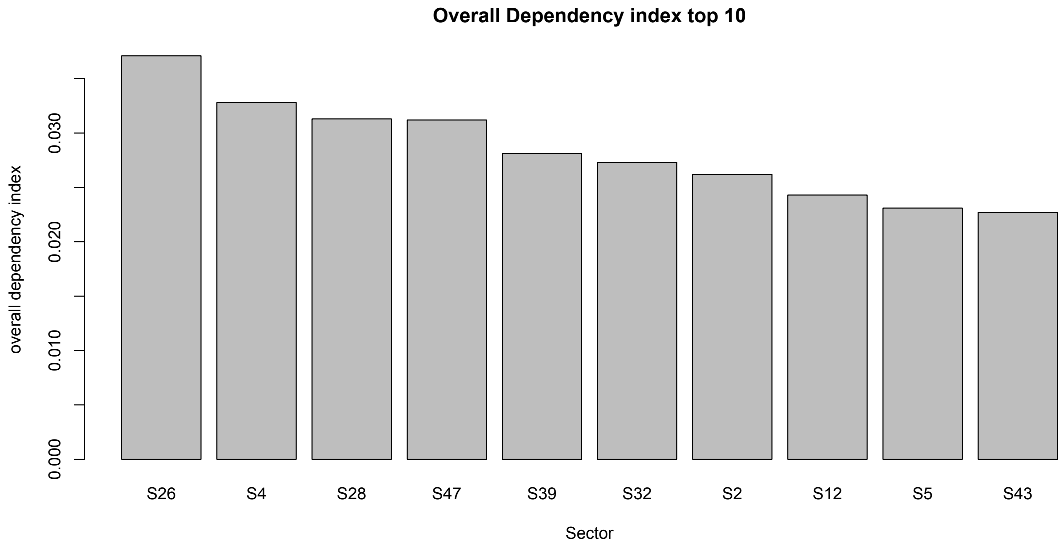

Figure 16: The top 10 sectors with the highest overall dependency index

Figure 17 below shows the 10 lowest dependency indices from the interdependency matrix A, just considering first-order dependencies and Figure 18 shows the 10 lowest overall dependency indices from the interdependency matrix S, taking into account higher-order dependencies.

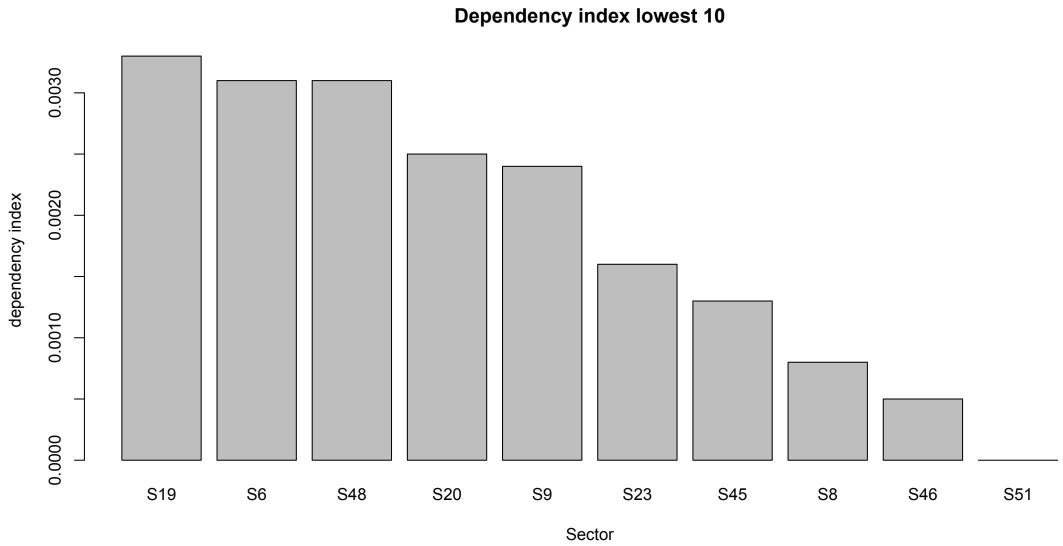

Figure 17: The 10 sectors with the lowest dependency index

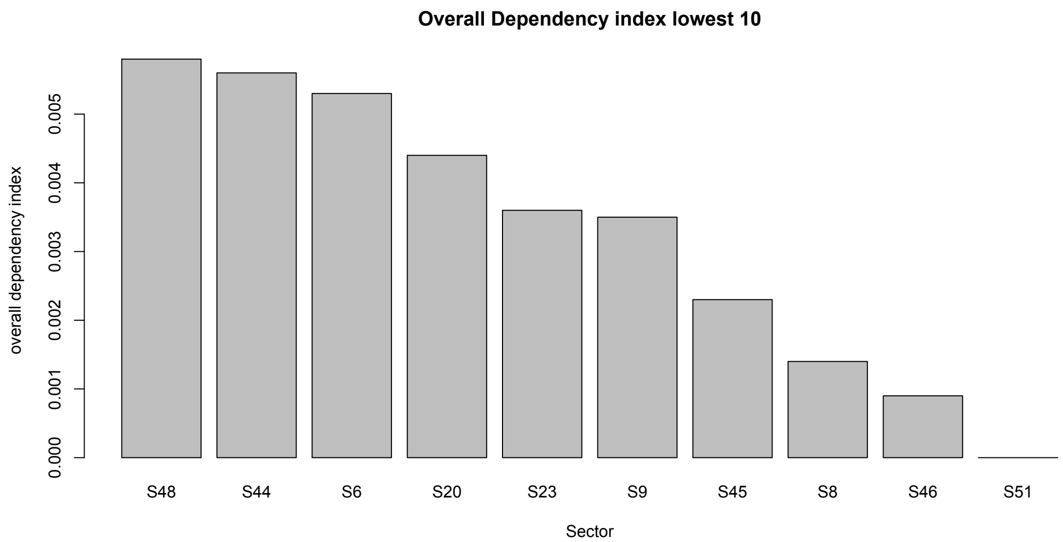

Figure 18: The 10 sectors with the lowest overall dependency index

When considering just first-order dependencies, the data in Figure 15 demonstrates that the sector for real estate activities (S40) exerts the highest influence on other sectors (i.e. identified key sectors), followed by the manufactures of basic metals (S17) and the sector for construction (S29). The most dependent sector in Figure 17, i.e. the sector that is most vulnerable to cascading effects, is the sector for collection, purification and distribution of water (S28), followed by the sector for recycling (S26) and the sector for sewage and refuse disposal, sanitation and similar activities (S47). The sector for private households (S51), the sector for health and social work (S46), the sector for manufacturing of wearing apparel (S8) and the sector for education (S45) are the most resilient sector, i.e. the sectors that are the least sensitive to cascading effects.

When considering higher-order dependencies, Figure 16 demonstrates that the sector for real estate (S40), manufacturer of basic metals (S17) and construction (S29) again are the sectors that exert the highest influence on other sectors with overall influence indices. Figure 18 demonstrates that de most dependent sector when considering higher-order dependencies is the sector for recycling (S26) followed by the sector for mining of coal and lignite (S4) and the sector for collection, purification and distribution of water (S28). The most resilient sectors are again the sector for private households (S51), the sector for health and social work (S46), the sector for manufacturing of wearing apparel (S8) and the sector for education (S45).

Figure 19 and 20 below shows a scatter plot with the First-order effects on the horizontal scale and all first-, second and higher-order effects on the vertical scale. Everything below the inserted line represents the first-order effects and everything above the higher-order effects. As is evident by the figures, the higher-order effects make up a considerably large part of the total effects.

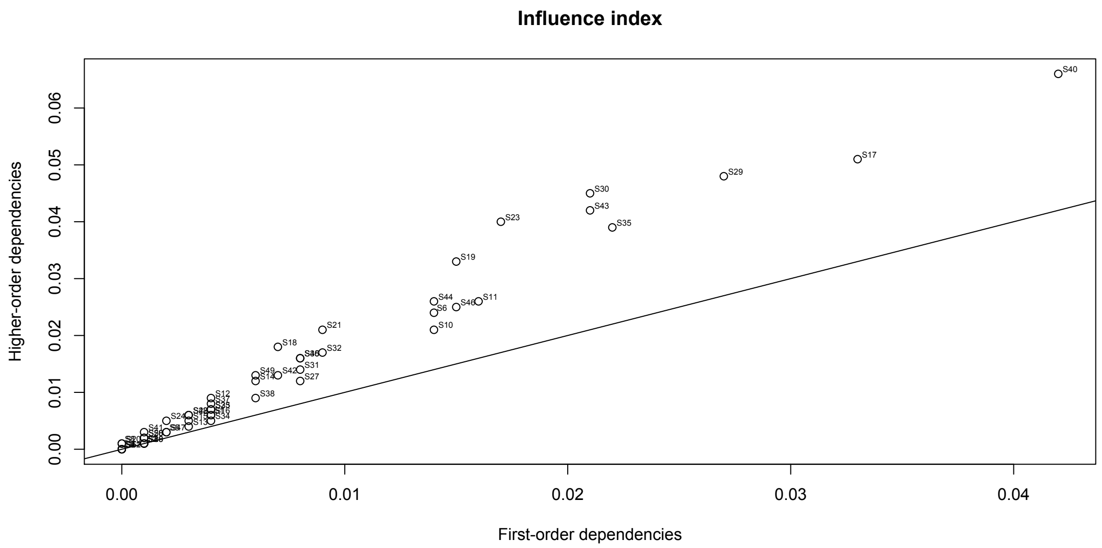

Figure 19: Scatterplot with the influence index on the horizontal scale and the overall influence index on the vertical scale

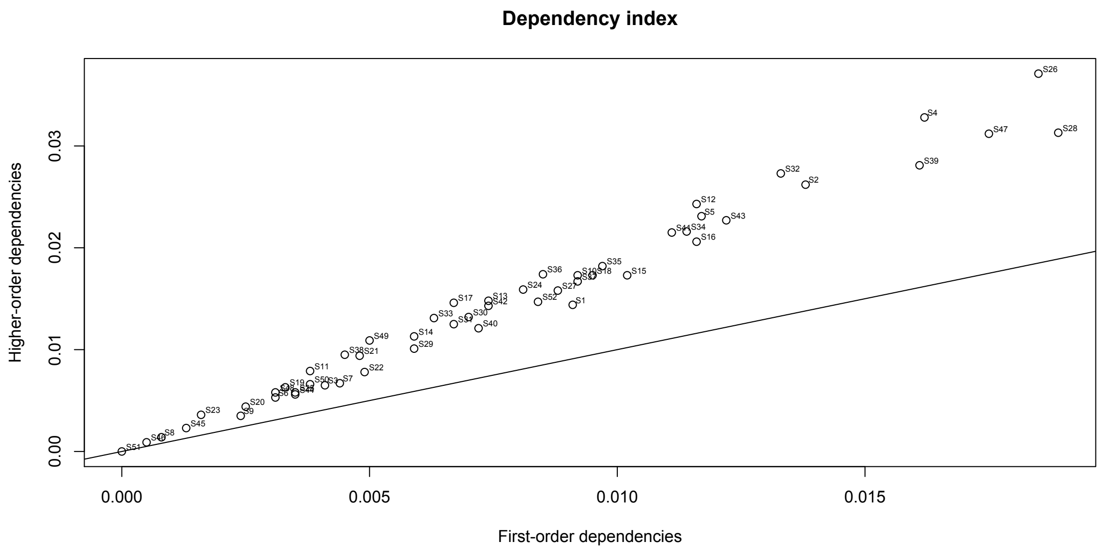

Figure 20: Scatterplot with the dependency index on the horizontal scale and the overall dependency index on the horizontal scale

4.2.2 Key sector analysis

The key sectors were identified according to Chapter 3.1.2. For complete results see Appendix C-7. The top 10 sectors that cause the highest total economic losses are shown in Figure 21 below. These sectors can be called key sectors since they have a strong influence on other sectors' operability. The sector for import (Sector 52) has the highest influence on other sectors, which is not surprising since Sweden is very dependent on foreign trade. Other sectors that cause high economic losses are the sector for real estate (S40) and the sector for research and development (S43). When just considering total inoperability, the top 10 sectors that cause the highest total inoperability are shown in Figure 22. The sector for real estate (S40) causes the highest total inoperability followed by the sector for manufacture of basic metals (S17) and the sector for construction (S43).

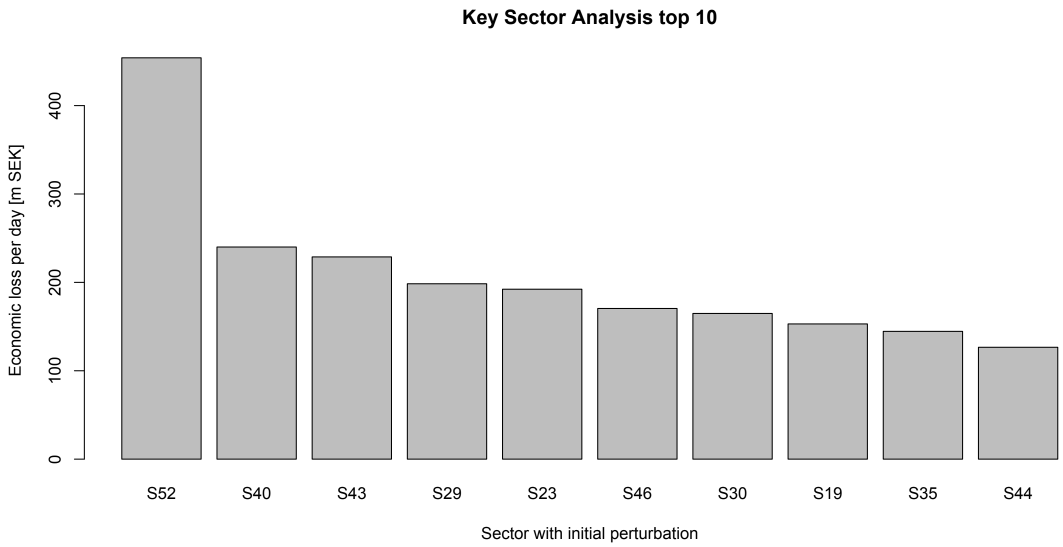

Figure 21: The top 10 sectors causing the highest economic loss

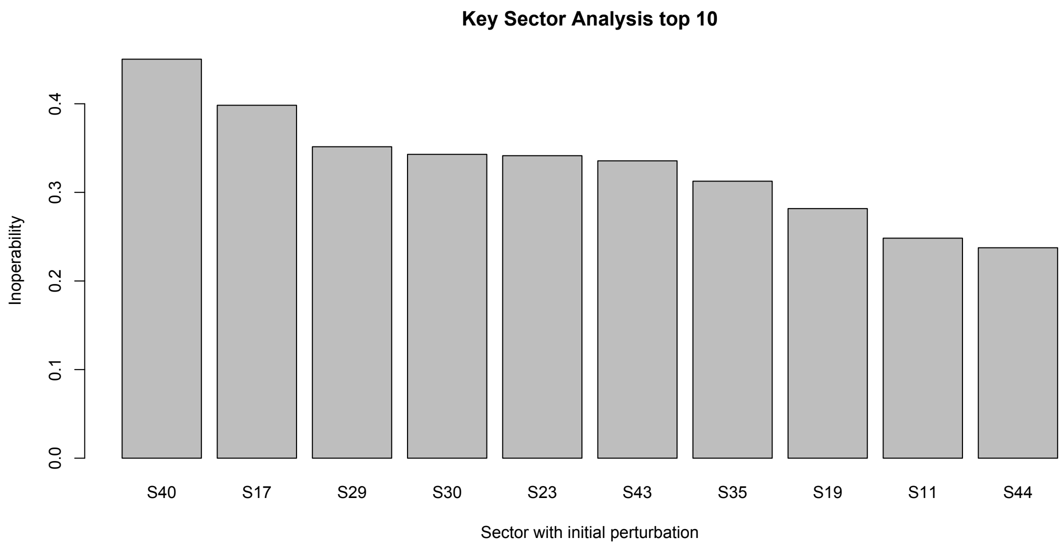

Figure 22: The top 10 sectors causing the highest inoperability

When conducting a risk assessment both the metric inoperability and economic loss need to be considered since they can yield different criticality ranking of sector effects. Both metrics can be of different interest. The economic size of a sector is not necessarily the same thing as social importance. The case study results above show that the inoperability and economic loss metrics yield different top 10 key sector ranking. The sector rankings can be integrated into a multi-criteria evaluation matrix that is capable of taking into account the results from both the inoperability and economic loss metrics. In Figure 23 below, the sector impacts are arranged according to three types of zones, namely the top 10, top 20 and top 30 zones. For example, the top 10 zone is generated by taking those sectors that belong to the top 10 rankings of both metrics. This includes: Real estate activities (S49), Construction (S29), Wholesale and retail trade (S30), Manufactures of motor vehicles (S23), Supporting and auxiliary transport activities (S35), Manufacture of machinery and equipment (S19), and Public administration and defence (S44).

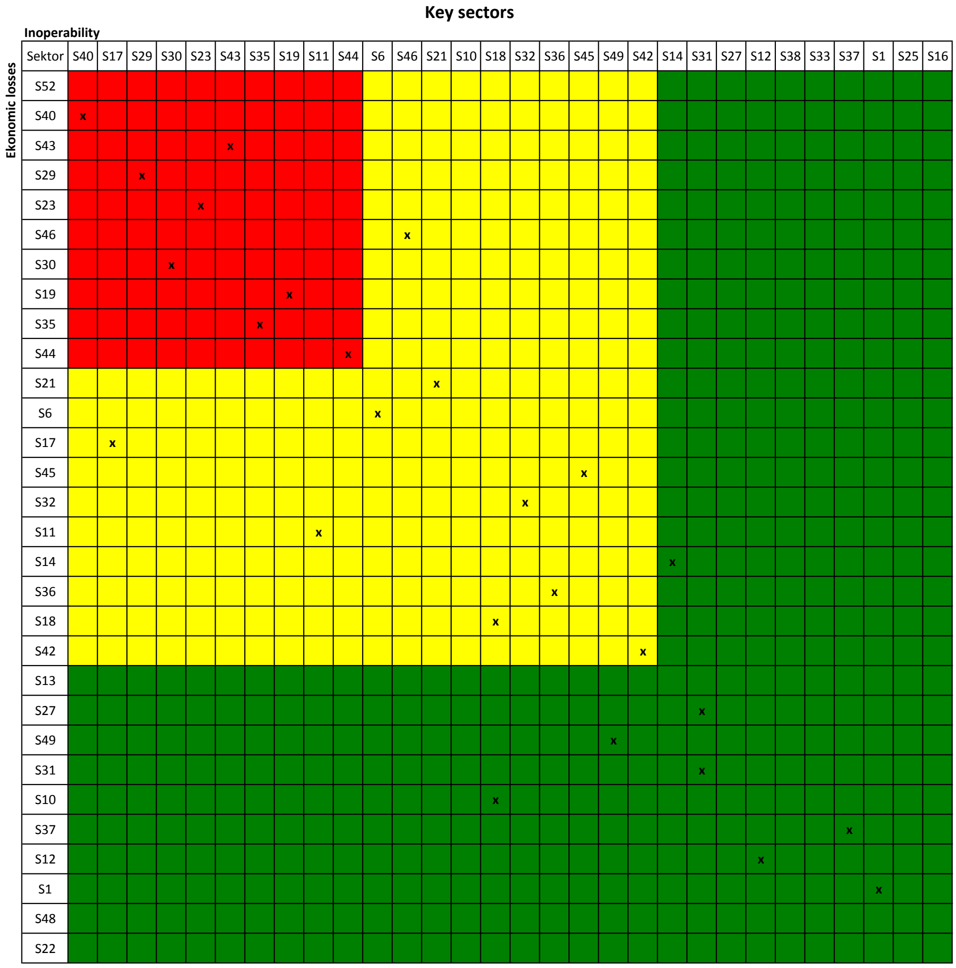

Figure 23: Multi-criteria evaluation chart for the key sectors

Another way of illustrating this multi-criteria evaluation is by a scatter plot with the economic loss on the horizontal scale and inoperability on the vertical scale. In Figure 24 below, all 52 sectors are represented in this type of a multi-criteria evaluation chart.

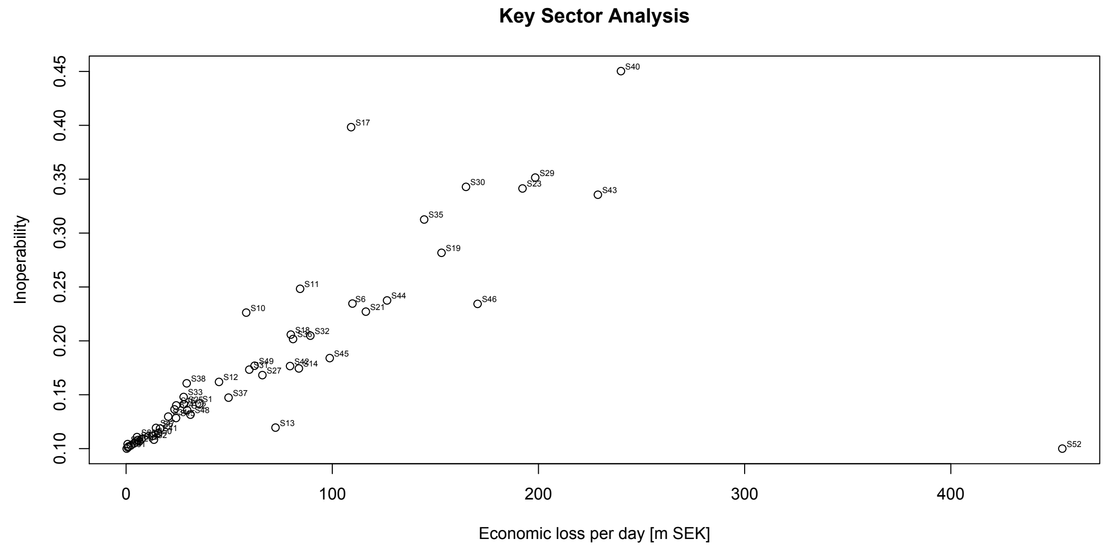

Figure 24: Multi-criteria evaluation scatter plot for the key sectors

4.2.3 Dependency analysis

In this analysis a 10 % perturbation for each sector, one at a time, was introduced and the total inoperability and the total economic loss for each sector for all perturbations were calculated. For complete results see Appendix C-8. The top 10 sectors with the highest economic losses are shown in Figure 25 below. The sector for import (S52) is the most dependent (most vulnerable to cascading effects) sector followed by the sector for research and development (S43) and the sector for real estate activities (S40). The 10 sectors with the lowest economic loss are shown in Figure 26 below. The most resilient sectors when considering economic loss are the sector for private households, the sector for fishing, operating of fish hatcheries and fish farms and the sector for mining of coal and lignite. Note that these three sectors belong to the smallest sectors of all, which contributes to the small magnitude of the economic loss. The fact that the size of the sector decides the ranking of the most resilient sectors implies that the metric inoperability might be a better way to rank sectors when it comes to resilience.

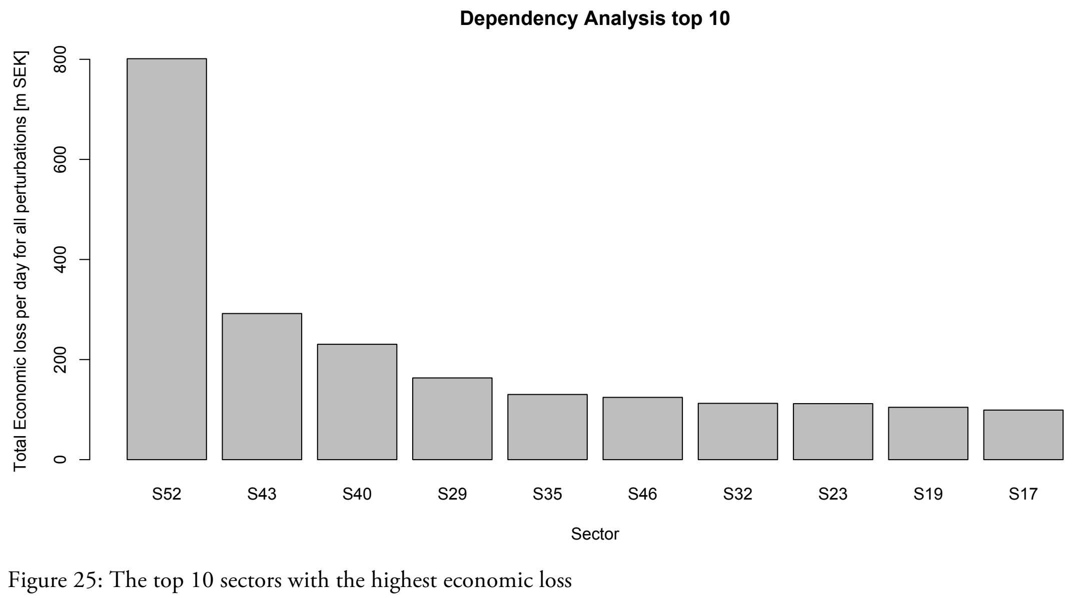

Figure 25: The top 10 sectors with the highest economic loss

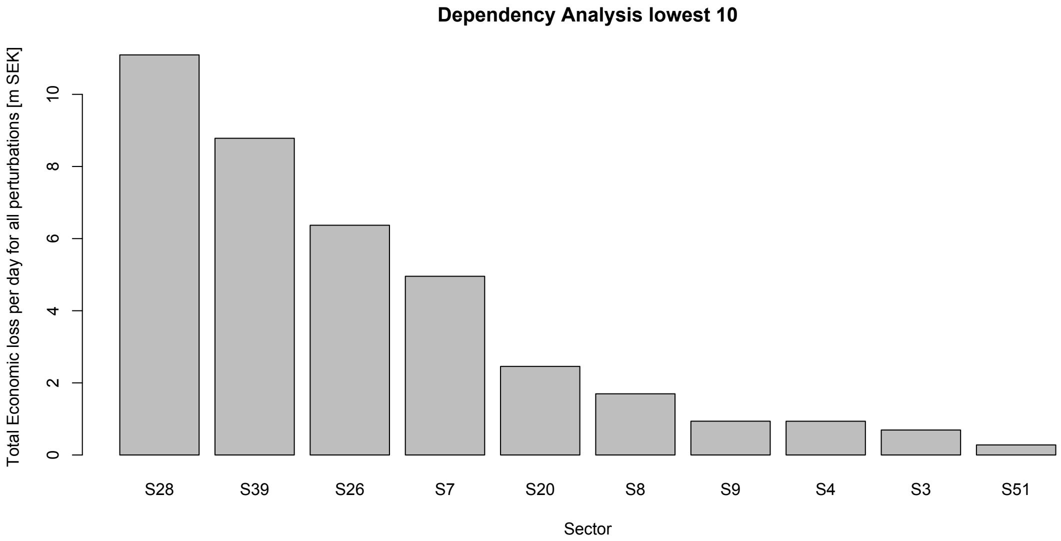

Figure 26: The 10 sectors with the lowest economic loss

The top 10 sectors with the highest and the lowest total inoperability are shown in Figure 27 and 28 below. The sector for recycling (S26) is the most affected sector followed by the sector for mining of coal and lignite (S4) and the sector for sewage and refuse disposal and sanitation (S47). The most resilient sectors are the sector for private households (S51), the sector for health and social work (S46), the sector for manufacture of wearing apparel (S8) and the sector for education (S45).

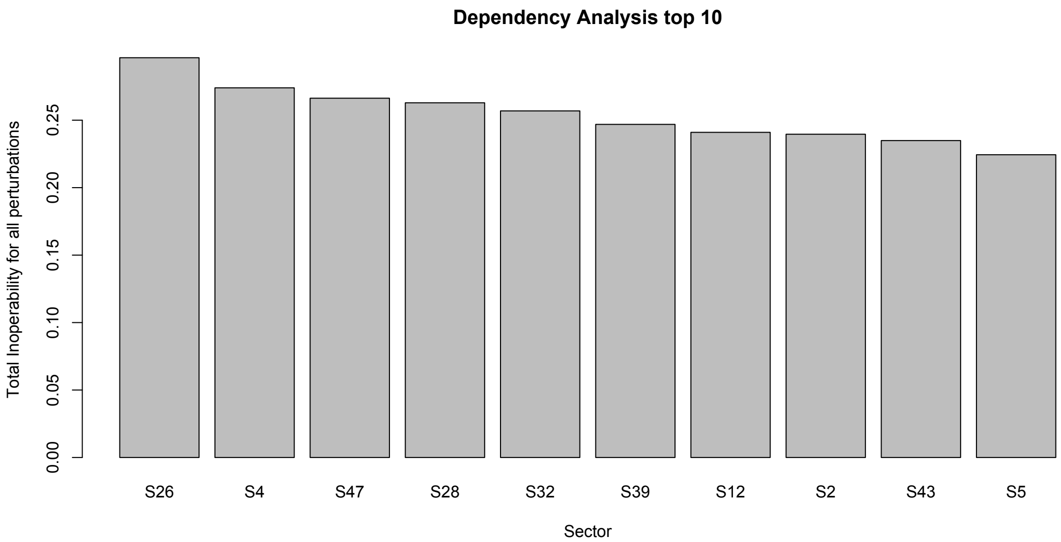

Figure 27: The top 10 sectors with the highest inoperability

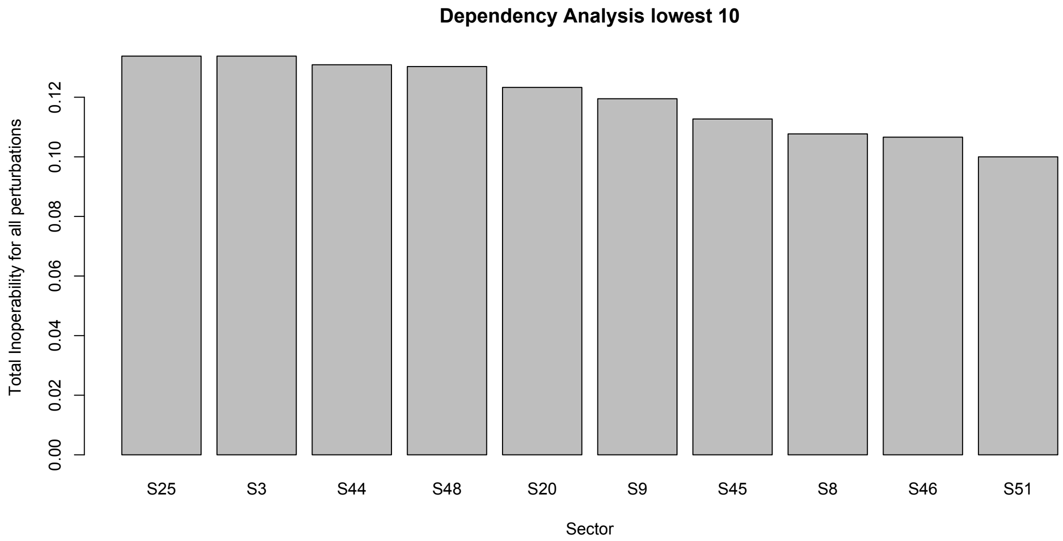

Figure 28: The 10 sectors with the lowest inoperability

Figure 29 below shows the multi-criteria evaluation matrix for vulnerability. The top 10 zone includes two sectors: the sector for land transport and the sector for research and development.

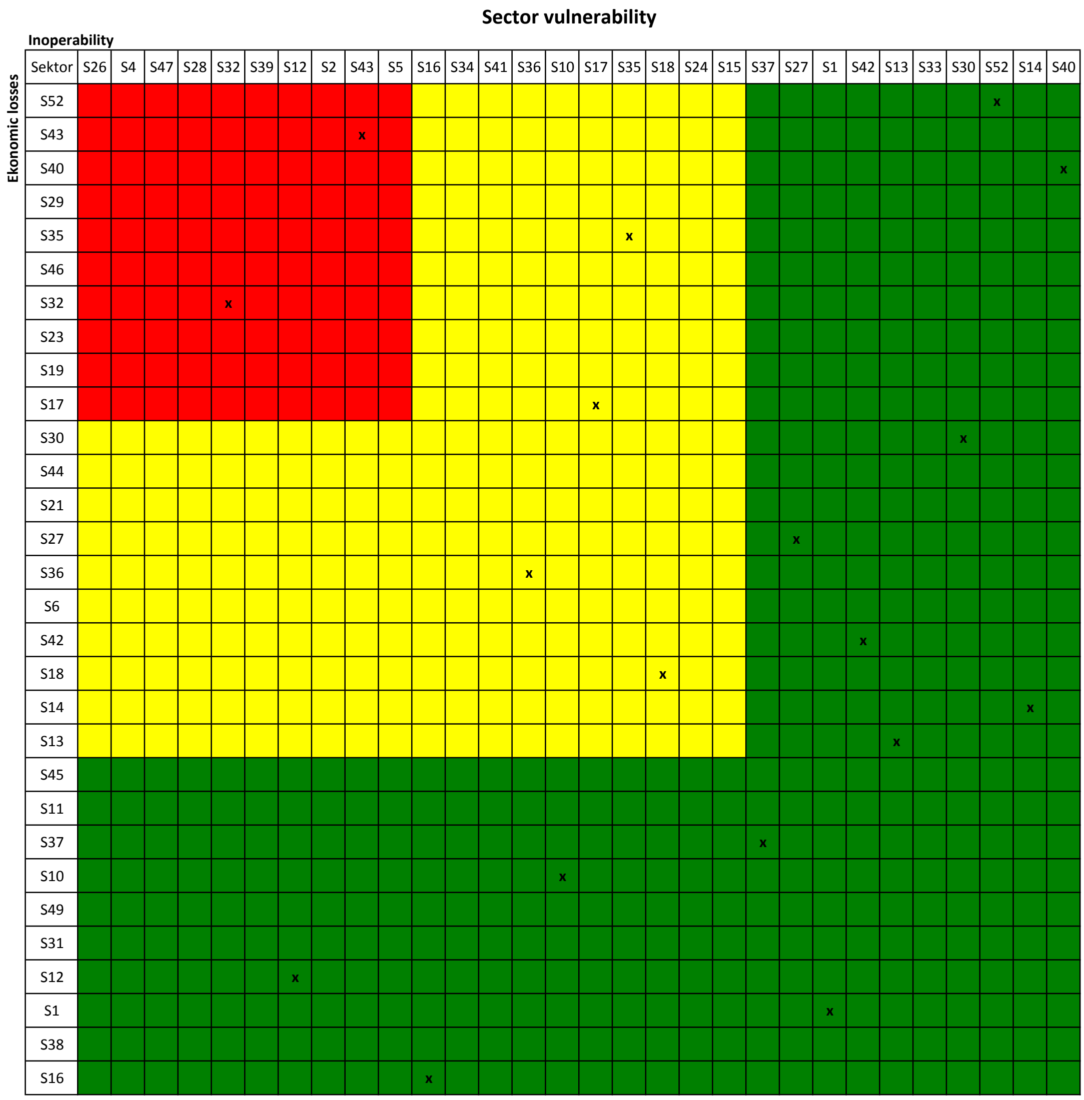

Figure 29: The multi-criteria evaluation chart for the dependency analysis

Figure 30 below shows the multi-criteria evaluation chart.

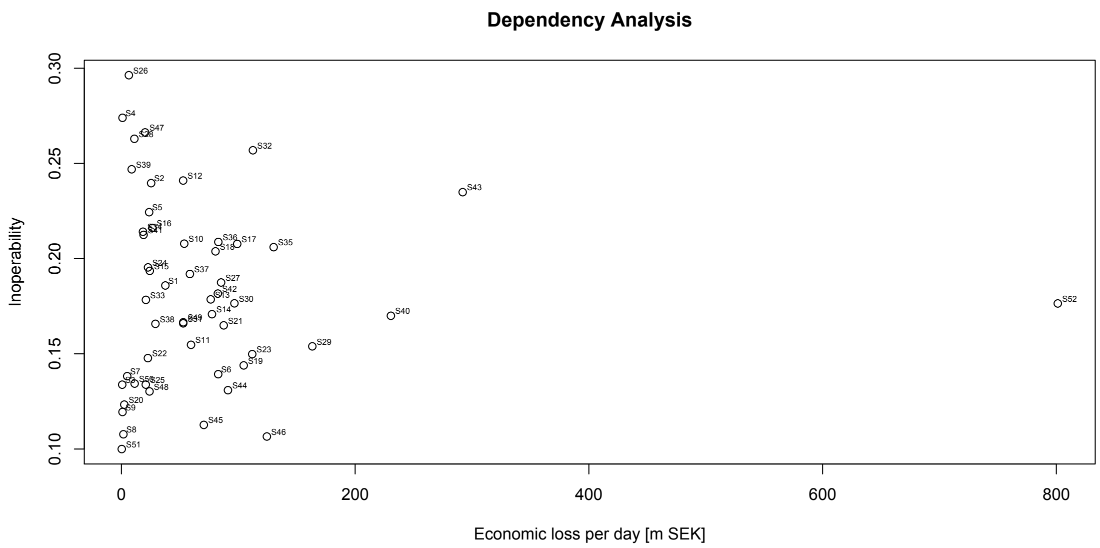

Figure 30: The multi-criteria evaluation scatterplot for the dependency analysis

4.2.4 Summary

Table 5 below summarize the results from the different methods of identifying key sectors. For all three methods the top three sectors are the same; namely, the sector for real estate (S40), the sector for manufacture of basic metals (S17) and the sector for construction (S29). These three sectors can be considered key sectors and have a strong influence on other sectors operability and their continued operability of these sectors can be seen as crucial for the overall national economy. When just considering economic loss the sector for import (S52) is the number one on the ranking, a matter that will be discussed in Chapter 6.

Table 5: Key sector analysis

Influence index	Overall influence index	Economic loss	Inoperability
S40	S40	S52	S40
S17	S17	S40	S17
S29	S29	S43	S29
S35	S30	S29	S30
S30	S43	S23	S23
S43	S23	S46	S43
S23	S35	S30	S35
S11	S19	S19	S19
S19	S44	S35	S11
S46	S11	S44	S44

Table 6 below summarize the results from the different methods of identifying vulnerable sectors.

Table 6: Dependency analysis

Dependency index	Overall dependency index	Total Economic loss	Total inoperability
28	26	S52	26
26	4	S43	4
47	28	S40	47
4	47	S29	28
39	39	S35	32
2	32	S46	39
32	2	S32	12
43	12	S23	2
5	5	S19	43
12	43	S17	5

There are a few sectors that are high on the ranking for several, although not all, of the methods. These include the sector for recycling (S26), the sector for collection, purification and distribution of water (28), the sector for sewage and refuse disposal and sanitation (S47), the sector for import (S52), and the sector for research and development (S43). The multi-criteria evaluation matrices contribute with two additional sectors, namely the sector for electricity, gas, steam and hot water supply (S27) and the sector for land transport (S32).

Table 7 below summarise the results from the different methods of identifying resilient sectors.

Table 7: Dependency analysis

Dependency index	Overall dependency index	Total Economic loss	Total inoperability
S19	S48	S28	25
S6	S44	S39	3
S48	S6	S26	44
S20	S20	S7	48
S9	S23	S20	20
S23	S9	S8	9
S45	S45	S9	45
S8	S8	S4	8
S46	S46	S3	46
S51	S51	S51	51

There are a few sectors that are high on the ranking for several, although not all, of the methods if we exclude the economic loss ranking according to a previous discussion. These include: the sector for public administration, defence and compulsory social security (sector 44), the sector for tanning and dressing of leather (sector 9), the sector for health and social work (sector 46) and the sector fore education (sector 45).

4.4 Air transport disturbance

In this case study a 10 % perturbation to the sector for air transport is studied. For a more detailed description of the scenario design see Chapter 3.1.3 and for a detailed description of the presentation of the results se Chapter 3.4.3.

The top 10 most affected sectors are shown in Figure 31 and 32 below. For complete results se Appendix C-10. The sector with the highest economic loss caused by cascading effects is the sector for import (S52) followed by the sector for supporting and auxiliary transport activities (S39) and the sector for manufacture of coke, refined petroleum products and nuclear fuel (S13). The sector with the highest inoperability is the sector for renting of machinery, equipment and personal and household goods (S41), followed by the sector for manufacturer of other transport equipment (S24) and the sector for manufacture of coke, refined petroleum products and nuclear fuel (S13).

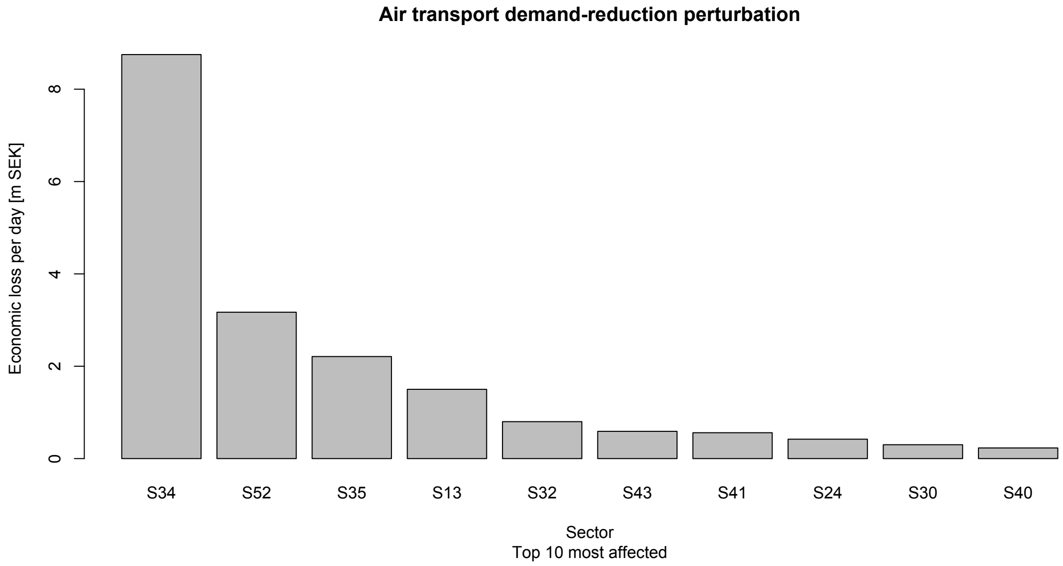

Figure 31: The top 10 most affected sectors when considering economic loss for the air transport disturbance

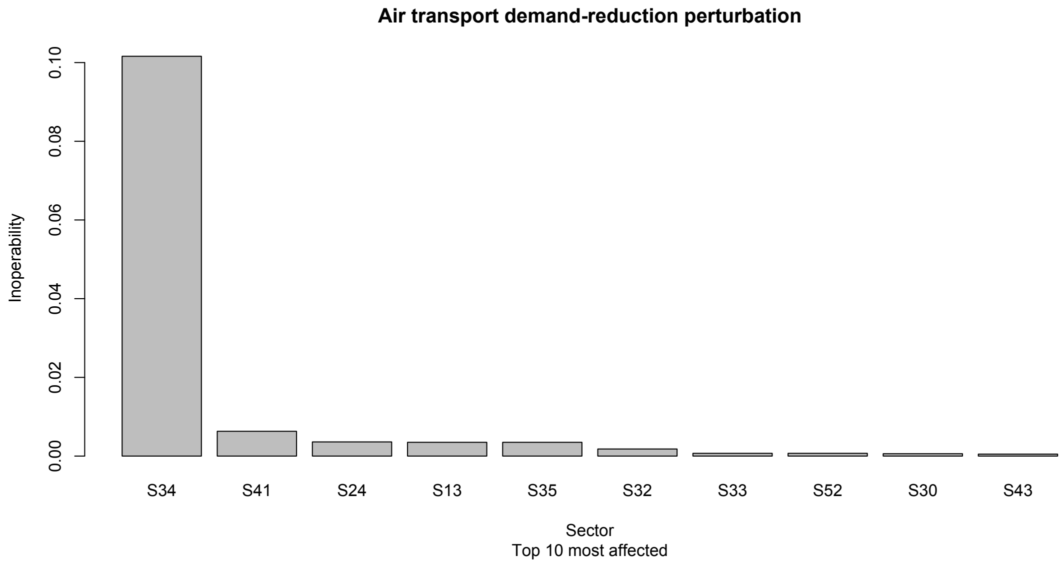

Figure 32: The top 10 most affected sectors when considering inoperability for the air transport disturbance

A multi-criteria evaluation matrix for both economic loss and inoperability is shown in Figure 33 below. The matrix shows that most of the sectors at the top 10 for inoperability are also ranked top 10 for economic loss.

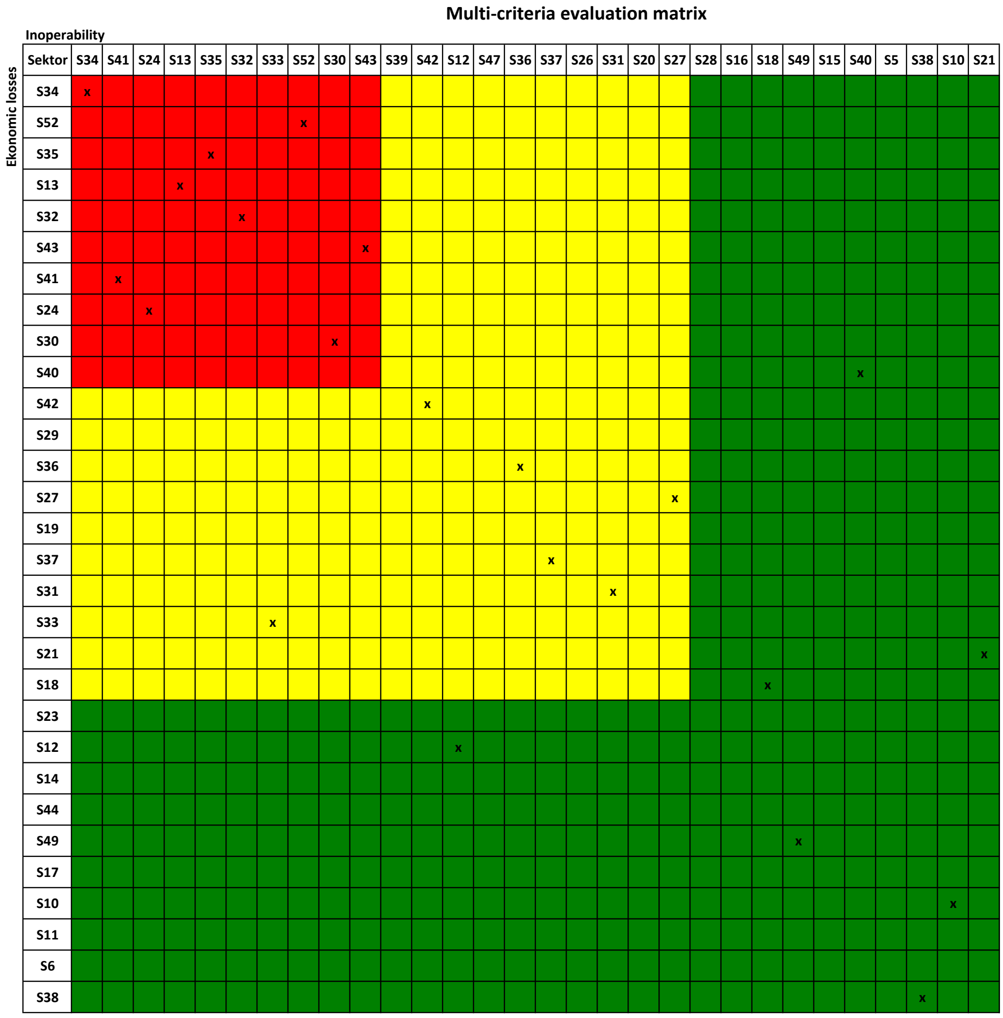

Figure 33: The multi-criteria evaluation chart for the air transport disturbance

Figure 34 below shows a multi-criteria evaluation chart with inoperability at the vertical scale and economic loss at the horizontal scale.

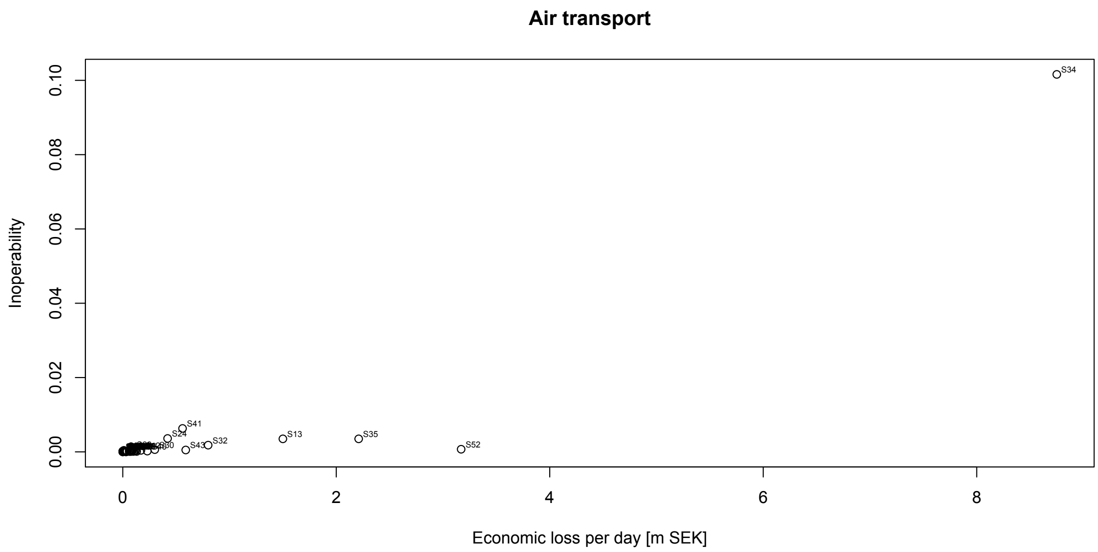

Figure 34: The multi-criteria evaluation scatter plot for the air transport disturbance

Summary
Total economic cost = 7500 m SEK
Total economic cost per day = 20 m SEK
Total economic cost excluding the sector for Air transport = 4000 m SEK
Total economic cost excluding the sector for Air transport per day = 12 m SEK

4.5 Agriculture disturbance

In this case study a 10 % perturbation to the sector for agriculture is studied. For a more detailed description of the scenario design see Chapter 3.1.3 and for a detailed description of the presentation of the results se Chapter 3.4.3.

The top 10 most affected sectors for the demand side model are shown in Figure 35 and 36 below. For complete results se Appendix C-9. The sector with the highest economic loss caused by cascading effects is the sector for import (S52) followed by the sector for manufacture of food products and beverages (S6) and the sector for manufacture of chemicals and chemical products (S14). The sector with the highest inoperability is the sector for mining of coal and lignite (S4) followed by the sector for manufacture of food products and beverages (S6) and the sector for manufacture of coke, refined petroleum products and nuclear fuel (S13).

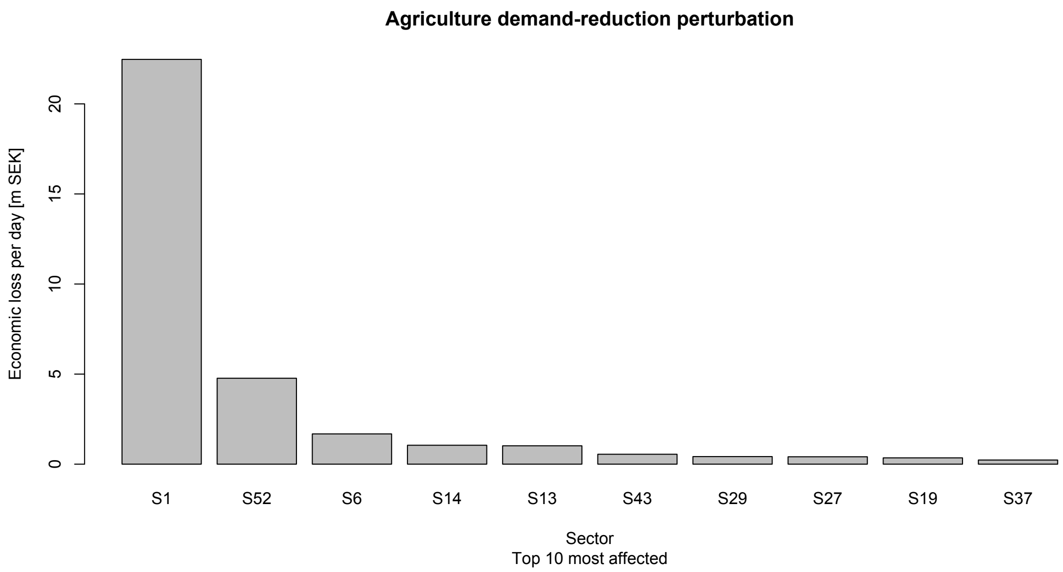

Figure 35: The top 10 most affected sectors when considering economic loss for the agriculture disturbance

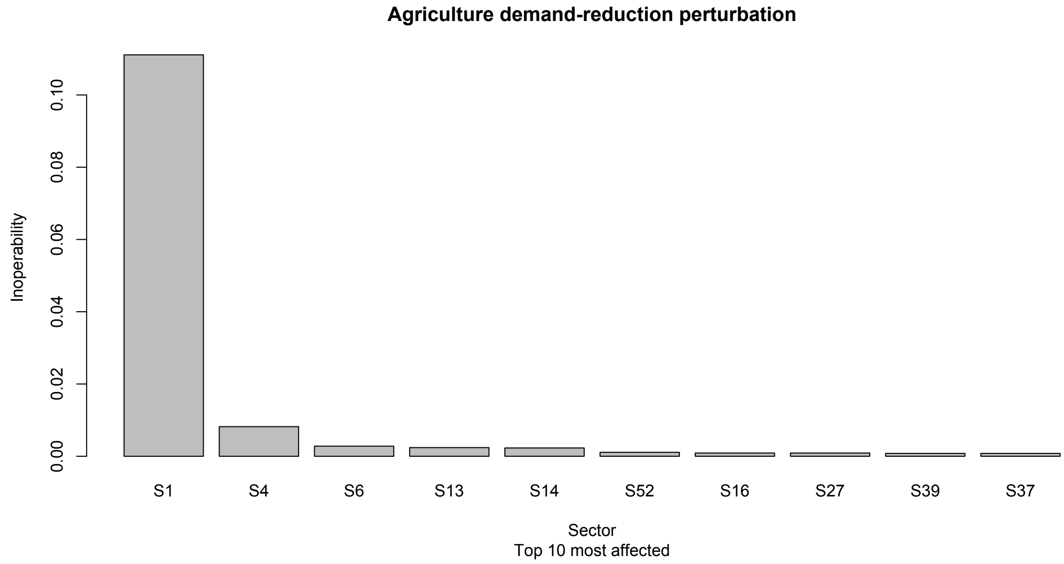

Figure 36: The top 10 most affected sectors when considering inoperability for the agriculture disturbance

A multi-criteria evaluation matrix for both economic loss and inoperability is shown in Figure 37 below. The top 10 zone includes: The sector for agriculture (S1), the sector for manufacture of food products and beverages (S6), the sector for manufacture of coke, refined petroleum products and nuclear fuel (S13), the sector for manufacture of chemicals and chemical products (S14), the sector for import (S52), the sector for electricity, gas, steam and hot water supply (S27) and the sector for financial intermediation (S37).

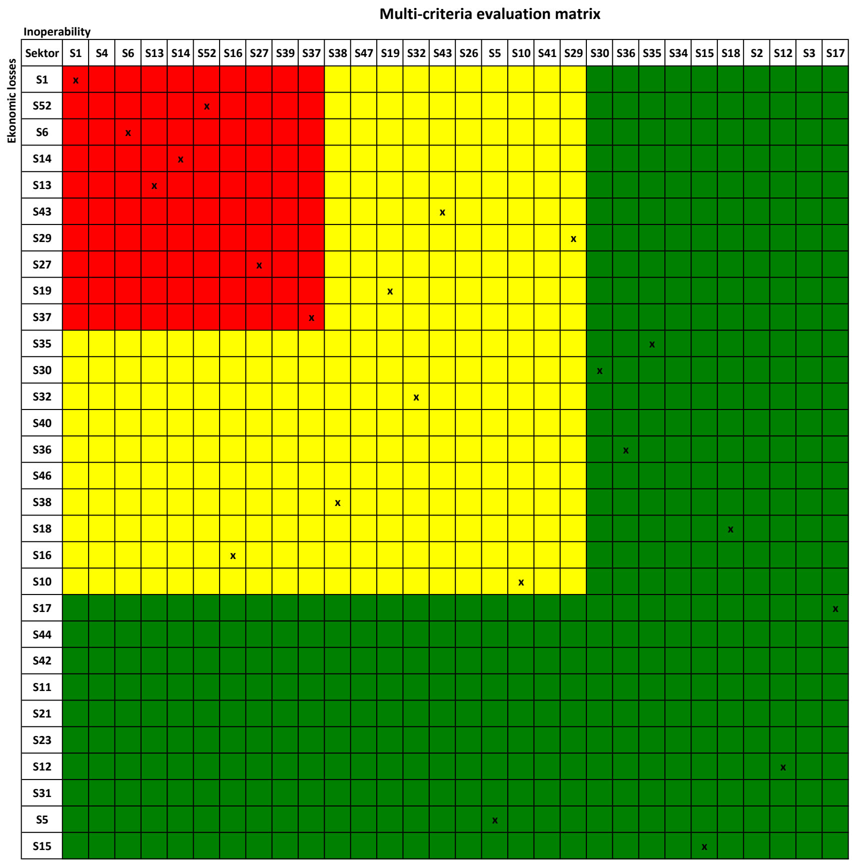

Figure 37: The multi-criteria evaluation chart for the agriculture disturbance

Figure 38 below shows a multi-criteria evaluation chart with inoperability at the vertical scale and economic loss at the horizontal scale.

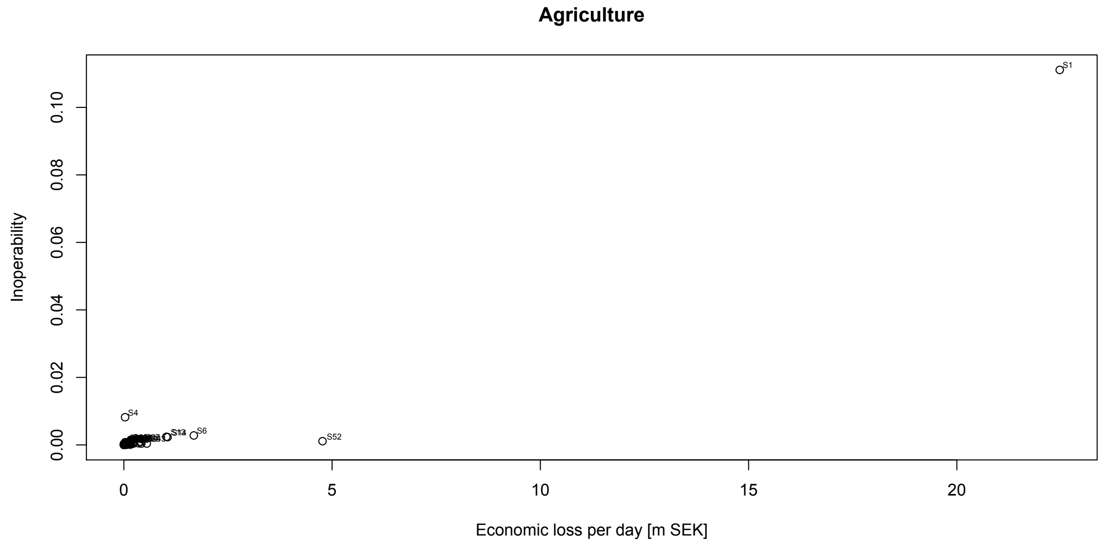

Figure 38: The multi-criteria evaluation scatter plot for the agriculture disturbance

Summary
The total economic cost = 13000 m SEK
The total economic cost per day = 35 m SEK
Total economic cost excluding the sector for Agriculture = 5000 m SEK
Total economic cost excluding the sector for Agriculture per day = 13 m SEK

4.6 Summary

The results from the case studies show no overall increasing or decreasing trend in either overall inoperability or weighted overall inoperability. Thus when using calculations from the inoperability I/O model no specific overall trend can be identified. According to the results the economic interdependencies between sectors have not increased from 2000 to 2008.

The key sector analyses showed that a few sectors can be considered key sectors, these included: the sector for real estate, the sector for manufacture of basic metals, the sector for construction, and the sector for import. Key sector analyses arising from scenario-specific assessments can provide practical insights on policy formulation. As discussed in Chapter 2.1.4 recourse allocation is a significant domain of interest by the authorities on different levels.

The demand side model case studies also identified a few sectors that are sensitive to cascading effects, i.e. vulnerable, these include; the sector for recycling, the sector for collection, purification and distribution of water, the sector for sewage and refuse disposal and sanitation, the sector for import, the sector for research and development, the sector for electricity, gas, steam and hot water supply and the sector for land transport

Chapter 5 - Analysis and implications

In this chapter the results are analysed with respect to keys sectors, vulnerability and resilience, and the risk management process described in Chapter 2.1.4.

5.1 Key sector analysis

In the literature there are many examples of risk analysis applications where researchers highlight the sectors most affected by disruptions resulting from one particular terrorist attack or event. Haimes et al. (2005b) examined the cascading effect of a high-altitude electromagnetic pulse attack on a few sector of the economy and in the previous section a scenario-based risk analysis was discussed and the results from the case studies regarding the sector for agriculture and the sector for air transport were used to illustrate how the inoperability I/O model can be used in this type of analyses.

In this thesis the key sector analysis were conducted with a different overall approach (see Chapter 3.1.2 for more details). Instead of just examining one perturbation to one or a few sectors, the approach in this thesis included perturbations to all sectors. By studying perturbations to all sectors the key sector analysis illustrated a more overall picture, an identified key sector is not just considered a key sector in a specific scenario, but an overall key sector for all scenarios. This approach is possible to conduct with the inoperability I/O model since the size of the initial perturbation does not affect the ranking (see Chapter 4.1.5 for more details) i.e. a sector that are considered top 3 for a 10 % perturbation will be top 3 for a 5 % or 20 % perturbation as well. This more general approach might be of interest if there are no or very little information about the likelihood of different scenarios, and there is a need to strengthen the general capability of the risk management system.

The results from the key sector analysis demonstrated that a few sectors can be deemed overall key sectors, these included: the sector for real estate, the sector for manufacture of basic metals, the sector for construction, and the sector for import. All of these sectors have couplings to a significant large part of the 52 sectors, which causes these sectors to be especially critical when it comes to cascading effects. If one of these sectors disturbed many other sectors will be affected as well. The result should not be surprising since all of these sectors belong to the largest economic sectors and all of them have logical connections to almost all other sectors, for example most other sectors need the services from the sector for real estate or construction. Similarly, many sectors are dependent on the goods and services from other countries since the Swedish economy is fairly small.

As discussed in previous section resource allocation is one of the main objectives of the risk management process. By identifying sectors that can be considered critical, i.e. key sectors, investments towards enhancing preparedness and resilience po licies for critical infrastructure and key resources can be made in the most cost-efficient way. By consider risk reduction options like inventories and redundancy for key sectors the overall resilience can be enhanced and the overall risk to the system can be reduced.

5.2 Dependency analysis

The aim of the dependency analysis was to identify the sectors that are considerably dependent on other sectors and those that are not, i.e. those who are vulnerable and those who are resilient to cascading effects. The dependency analysis was conducted with the same approach as the key sector analysis, i.e. not a scenario specific dependency analysis but an overall approach. An identified vulnerable or resilient sector is considered to be vulnerable and resilient in general and not for a specific scenario.

The results from the dependency analysis identified a few sectors that are sensitive to cascading effects and can therefore be considered vulnerable, these included; the sector for recycling, the sector for collection, purification and distribution of water, the sector for sewage and refuse disposal and sanitation, the sector for import, the sector for research and development, the sector for electricity, gas, steam and hot water supply and the sector for land transport. These sectors were the overall most affected sectors and they could be severely affected after a harmful event that causes cascading effects. The reason why these sectors are vulnerable is probably because they have close connection to some of the in the previous section identified key sectors or are highly dependent on goods and services from other sectors, i.e. they use goods and services from other sectors to a great extent.

Some of the identified sectors vulnerable to cascading effects are considered critical for the society (critical infrastructure, vital societal functions) by the Swedish Contingency Agency (MSB, 2009a) namely the sector for collection, purification and distribution of water, the sector for sewage and refuse disposal and sanitation, the sector for electricity, gas, steam and hot water supply as well as the sector for land transportation. If there would be a severe disturbance in these sectors the consequence could be very severe since the definition of a vital societal function states that a loss or a disturbance in the function would cause substantial risk or danger for humans life and health, the society's functionality or the society's fundamental values. The results from the dependency analysis show that it is of great importance to strengthen the protection of some of the sectors that are considered to be vulnerable. The report "*A working society in a changing world" (*MSB, 2011*)* is an overall national strategy for protection of vital societal functions, and the strategy described in this report should be applied to the sectors (considered vital for the society) identified in the dependency analysis as vulnerable.

The dependency analysis not only identified vulnerable sectors, it also identified resilient sectors, i.e. sectors that are not sensitive to cascading effects. The identified resilient sectors included: the sector for public administration, defence and compulsory social security, the sector for tanning and dressing of leather, the sector for health and social work and the sector for education. These sectors might have been identified as resilient since they use goods and services from their own sector to a great extent. But just because they have been identified as resilient in this dependency analysis it is important to remember that this analysis is just one part of the whole picture. Some of these sectors might not be economic dependent on other sectors included in this study to a great extent, but there is an important type of sector that is not included in this type of study, namely the factor of workforce. Some of these sectors might be very dependent on the availability of personnel and this type of dependency is not included in the chosen version of the inoperability I/O model. So the results about resilient sectors should be handled with caution, they might be very vulnerable to events that affect their personnel, e.g. a pandemic flu.

5.3 Risk management process

All risk assessment and management methodologies seek to find efficient assessments of risks. It is a challenge for policymakers to allocate resources in the most effective manner so as to mitigate the consequences of potential harmful events and prepare for future scenarios. As described in Chapter 2.2.7 the inoperability I/O model can be used in several phases of the risk assessment and management process. In a risk assessment the inoperability I/O model can be used to calculate propagating higher-order effects. In the risk management process the inoperability I/O model can quantify how risk management policies based on uncoupling the interdependencies will reduce the risk to all sectors and by reducing sector risk will cascade to a magnified reduction of system risk. In the risk management process the inoperability I/O model can also be used in the trade-off analysis of various risk management options.

The case studies for the sector for agriculture and the sector for air transport was an illustrative example of how the inoperability I/O model can be used in the risk assessment process. By using the results from these the propagating higher-order effects can be calculated and to answer the question "What are the consequences?" which is one of the risk triplet questions(Kaplan & Garrick, 1981). The inoperability I/O model also contributes with information of how the consequences are distributed among the sectors. If one is most interested in total consequences the metric economic loss might be most useful and if one is interested in the distribution of consequences and how each sector is affected the metric inoperability is probably the most useful.

In the case study focusing the sector for agriculture, the total economic cost for a 10 % demand-reduction perturbation to the sector for agriculture would be around 13 000 m SEK for a year which is around 35 m SEK per day and around 13 m SEK of these arises from cascading effects. In the case regarding the sector for air transport the total economic loss would be around 7500 m SEK for a year, which is around 20 m SEK per day and of these around 12 m SEK arises from cascading effects. These results show how a considerably large part of the total economic loss for a perturbation can come from cascading effects or higher-order effects and demonstrate why it is important to analyse interdependencies and cascading effects.

The case studies considering the sector for agriculture and the sector for air transport were scenario-based approaches for risk management. This means that for a set of different risks, one scenario for each risk, is developed and for each scenario the three questions in the risk triplet have to be answered. This means that it is not enough to only answer the question "what are the consequences?"; the question "What is the likelihood?" also needs to be answered to be able to take decisions regarding which are the most cost-effective risk reduction options according to which sectors are vulnerable and which sectors can be considered key sectors. In many of the scenarios that have to be considered when analysing the risk to the whole nation it is hard and sometimes impossible to calculate the likelihood of a harmful event, for example a terrorist attack. Still it is necessary to prioritize between different risk reduction options to be able to allocate resources in an efficient way especially since the recourses to allocate for risk reduction gets smaller as described in Chapter 2.1.4. But this discussion demonstrates that the inoperability I/O model used in a scenario-based way not gives a complete picture of the risk and that these models need to be complemented with at least a likelihood assessment, to get enough material to make a decision about recourse allocation.

5.4 Summary

In this chapter there are several main points made that might be worth to mention once more.

- The results from the agriculture and air transport studies demonstrated how a considerably large part of the total economic loss for a perturbation can come from cascading effects or higher-order effects and shows why it is important to analyse interdependencies and cascading effects.

- Most of the identified key economic sectors have logical connections to almost all other sectors, for example most other sectors need the services from the sector for real estate or construction.

- Some of the identified sectors vulnerable to cascading effects are considered critical for the society by the Swedish Contingency Agency. It is of great importance to strengthen the protection of some of the sectors that are considered to be vulnerable.

- The factor of workforce. Some of the identified resilient sectors might be very dependent on the availability of personnel and this type of dependency is not included in the chosen version of the inoperability I/O model. So the results about resilient sectors should be handled with caution, they might be very vulnerable to events that affect their personnel, e.g. a pandemic flu.

Chapter 6 - Discussion

In this chapter the findings of the work presented in this thesis are discussed in terms of reflections over the research process and source criticism, and reflections over the use of the inoperability I/O model. Finally, areas for future research are suggested.

6.1 Reflections over the research process

In this section every step of the research process is discussed with respect to the scientific standpoints presented in Chapter 1.4.1, alternative methods and source of errors.

6.1.1 Literature review

A literature review is in most scientific work the foundation for the continued work and gives a scientific weight to the empirical studies. All the literature used in this thesis was considered to meet the scientific criteria discussed in Chapter 1.4.1, i.e. correctitude and objectivity. The books, reports and articles referred to in this thesis are all considered to meet the scientific criteria.

When it comes to the literature about the original inoperability I/O model, most literature in the area are written by the original developers. To get a wider scope and higher validity, the later part of the literature search was focused on finding literature written by authors not in cooperation with the original developers to obtain a more balanced picture.

6.1.2 Scenarios

In the process of choosing and designing scenarios the aim was to develop scenarios that would fully accommodate the objectives of the thesis. If other scenarios were chosen the detailed results would probably differ but in the overall main conclusions made in the thesis would probably be the same since the main objective of the thesis was the usefulness and suitability of the inoperability I/O model and not the detailed results. One of the main points made in Chapter 4.1.5 was the relative small importance of the initial perturbation, i.e. if a 10 % initial perturbation were chosen or a 5 % would not affect the overall results for the rankings, trends and the dependency and key sector analyses.

6.1.3 Data collection

In this thesis the main focus was the demand-reduction based inoperability I/O model, i.e. the combination of the physical inoperability I/O model and economic data material, for more information about the demand-reduction based model se Chapter 2.2.4. The use of the demand-reduction based inoperability I/O model by definition meant the use of economic input/output data. This type of data material is only collected and processed by SCB, so if the demand-reduction based inoperability I/O model was to be studied the data material had do come from SCB. The data material from SCB can be considered to be accurate and credible since SCB is a national authority and collects and handles a massive amount of statistical data.

In some versions of the inoperability I/O model other types of data input can be used, i.e. expert input or regional data. As discussed in Chapter 5.2 a contribution to the analyses would have been data over workforce dependencies, e.g. salaries and wages. This type of information is included in the input/output data from SCB but because of time restrictions this had to be disregarded in this thesis.

6.1.4 Computer programming

In the computer programming process R was used for the calculation instead of the more widely spread software Matlab. The reason for this was simply the author's familiarity with R and the many available possibilities to make diagrams. One of the biggest advantages of using R is the fact that it is an open source software, i.e. it is available for anyone to copy, read, modify and redistribute the source code. It was assumed that the choice of calculation software would not affect the results. This assumption was confirmed as an accurate one in the interrater reliability test that is discussed further down in this chapter under reliability. In this test the comparison version were programmed with Matlab.

In the case study process the Demand-reduction based model was used. This means that the chosen focus was demand-reduction induced perturbation. The reason for this was the clear interpretation of the induced perturbation and the results.

6.1.5 Analysis of results

There are several ways to define concepts like key sectors, vulnerability and resilience. The definitions chosen in this thesis were presented in Chapter 3.4.4. The choice of definition has certainly affected both the process (when designing scenarios and during the computer programming) and the results. These definitions were chosen because they were considered to be easy to interpret and practically easy to use in the analyses.

6.2 The inoperability I/O model

The main objective of this thesis was to assess if inoperability I/O modelling is a suitable approach to analyse interdependencies in a Swedish context. Below the model will be discussed in terms of reliability and validity, and finally the model's suitability for a Swedish context.

6.2.1 Reliability

In this specific case study the reliability of the programmed model used for the calculations in R were tested in an interrater reliability test, to see if there were any human errors in the modelling process. This test was conducted by another user that programmed the same model and used the same data material. The same scenario was then calculated for both users and the same results were obtained.

This version of the inoperability I/O model is static and chance do not affect the results, i.e. the results from the inoperability I/O model can be considered to be reliable in the sence that the same results will be obtained with the same input data. In this case the input data is economical transactions between sectors. The data material was considered to be systematically collected and processed, and the process was assumed to lack any personal judgements, and therefore the data material was considered to be reliable, i.e. if the data material was to be collected a second time the same data material would be obtained.

In other versions of the inoperability I/O model the input data consists of expert assessments. In this case the reliability of the model will depend of the reliability of the expert judgements. Setola et al (2009) demonstrates a method to assess the reliability of the expert judgements.

6.2.2 Validity

The question of validity considers if the model measure what it is supposed to measure. In this thesis the inoperability I/O model has been used to model and quantify cascading effects or higher-order effects that are caused by interdependencies. So the model has been used to measure effects arising from interdependencies. So the question of validity deals with the question does the model measure interdependency effects in an adequate way?

When applying the inoperability I/O model the assumption is made that the level of economic dependency between various sectors is the same as the level of physical dependency, i.e. in general, two sectors that have a large amount of economic interaction will have a similarly large amount of physical interdependency. This might be an accurate or at least adequate way of describing interdependencies in some cases but not all. To illustrate this problem let us consider two factories, A and B. Factory A uses 10 % of it's budget to finance electricity and factory B uses 50 % of its budget. With this background the inoperability I/O model would say that factory B is more sensitive to a power outage than factory A. Would this be an accurate conclusion? In most cases the answer would be no, both factories would probably not be able to keep the production going in the case of a power outage. But however crude this assumption may be, the economic transactions are founded on data from SCB that reflect real interactions (physical, logical etc.) between economic sectors. These real physical interactions are translated into SEK units by multiplying interactions of physical quantities by producer's prices, and in turn these prices indicate how a sector values the physical interdependencies. Still the degree of in-accuracy in the results from the inoperability I/O model is a question since there are several other commodities with the same characters as electricity, e.g. water and other basic commodities. Addressing this question would for example require identifying sector pairs where financial couplings are roughly proportional to physical couplings, much greater or much less. The inoperability I/O model would thereafter be adjusted for those cases where the physical couplings are much different from economic couplings. This approach would require a massive amount of data collection considering the lack of corresponding data on physical interdependencies.

As discussed above there are arguments that both increase and decrease the belief for the validity of the inoperability I/O model. But what are the alternatives? Especially when considering the availability of economic data from SCB and the corresponding lack of data on physical interdependencies and the extraordinary cost required to collect such information on the same scale of economic data collections. To collect information about physical interdependencies from for example expert judgements would not only require a large amount of resources but would also bring in the discussion about reliability as discussed in section 6.2.1 above, how reliable are the experts? The inoperability I/O model might be the most suitable way of describing nationwide interdependencies if one considers available resources. There are a few ways that the validity of the model can be at least partly decided and enhanced without extraordinary costs.

One possible way to add confidence to the results from the inoperability I/O model is to carry out a study of the top sectors resulting from an inoperability I/O analysis to

determine how close the physical ties are relative to economic ties. Such a study might be enough limited to carry out at an acceptable cost when compared with costs of poor risk management.
Another way of increasing the validity of the model can be to integrate detailed physical engineering models. For example direct and indirect losses due to significant physical damage are not directly considered without the integration of engineering models. Engineering models can be used to create input to the inoperability I/O model and to describe some of the more complex physical interdependencies e.g. electricity with network models.

6.2.3 Swedish context

The overall objective of the thesis was to decide if the inoperability I/O model can be applied to Swedish conditions and if it is a suitable approach.

The data material from SCB is presented in a suitable way for inoperability I/O modelling, as described in Chapter 3.2 and discussed above. Technically the inoperability I/O model can be applied to the original model without any difficulty. When considering validity and accuracy regarding Swedish conditions there are some questions about the model that have to be discussed.

One of the main points made in this thesis is the importance of foreign trade, i.e. import and export. The results in Chapter 4 illustrates that in several of the dependency and key sector analyses, the sector for import was identified as a top sector, which confirms the assumption that import have to be included in the model to get adequate results. In the original inoperability I/O model it is unclear if and how import and export is included.

So is the inclusion of import enough to get a model suitable for Swedish conditions? There are still the difficulties with the validity and the discussion of it is enough to just model economic interdependencies. Maybe the model should mostly be seen as a complement to other types of analyses. The inoperability I/O model gives one part of the picture not a complete one. There are many examples of the same type of problem in the area of risk management; even the concept of risk itself cannot be explained just by one point of view. The complex nature of risk is for example explained and discussed by Klinke & Renn (2006) and maybe we should look at interdependencies the same way, i.e. there is no "right" way.

There is also the question: do we need a complete interdependency analysis on a national level in Sweden? In most cases, a terrorist attack or other harmful events, e.g. hurricanes, most likely impact a defined region of our country while leaving surrounding regions intact. So is the need only on a regional level? The answer to that question would be no, there is a need at a national level to be able to identify vulnerable sectors and key sectors so that an effective allocation of resources can be made. That might be the most adequate way to use inoperability I/O modelling on a national level. Another way to use the model is for scenario development, by using I/O analyses it is possible to build scenarios, if we get a disturbance in one sector, what will happen next, i.e. which other sectors will be affected?

Another advantage of the inoperability I/O model is that the consequences can be given in monetary values (SEK) which means that the results can be used directly in a cost-benefit analysis and exclude the step of valuation, i.e. translate consequences into monetary values. But again it should still be just one part of the whole picture.

6.3 Future research

Based on the results from the work presented in this thesis, some areas can be identified for further studies.

- There is a need for a validity evaluation of the inoperability I/O model for Swedish conditions. This can be carried out by studying a few sector pairs and identify those pairs where financial couplings are roughly proportional to physical couplings, much greater or much less. The inoperability I/O model could thereafter be adjusted for those cases where the physical couplings are much different from economic couplings. The evaluation can also be based on the results from this thesis, where the identified top sectors can be studied.

- The inoperability I/O model can be applied to a national level as well as a regional level. It could be an interesting approach to apply the model to Swedish data material at a regional level.

- Another interesting approach would be to integrate detailed physical engineering models with inoperability I/O modelling. The next in step in my research would be to integrate detailed physical models of the electric transmission systems with regional inoperability input-output models by performing a case study, using a representative model of the Swedish transmission system and Swedish regional input-output data.

- Finally a physical-based approach is another field of relevant future research. For example Setola (2007) applied the physical-based inoperability I/O model to estimate the consequences of a failure in the IP network of a hospital where the input came from interviews with personnel.

Chapter 7 - Conclusion

In this chapter the main conclusions of the work are summarised. The aim was to answer the research questions in Chapter 1.2.

In order to answer the main research question a literature study was conducted and the result was summarized in Chapter 2. Based on the literature a case study for Swedish conditions was designed in Chapter 3. The results from the case study were summarized in Chapter 4 and analysed in Chapter 5. The main points of the work were:

Is it possible to apply Swedish data material to the inoperability I/O model in a suitable way?
Technically the inoperability I/O model can be applied to the original model without any difficulty since the data material from SCB is presented in a suitable way for inoperability I/O modelling. When considering validity and accuracy regarding Swedish conditions there are some questions about the model that have to be discussed. One of the main points made in this thesis is the importance of foreign trade, i.e. import and export. To get adequate results import has to be included in the model in one way or another.

Which economic sectors in Sweden are most vulnerable and most resilient to ripple effects?
The results in this thesis demonstrated that some of the identified sectors vulnerable to cascading effects are considered critical for the society by the Swedish Contingency Agency, e.g. the sector for collection, purification and distribution of water, the sector for sewage and refuse disposal and sanitation, the sector for electricity, gas, steam and hot water supply as well as the sector for land transportation. It is argued that the protection of these sectors needs to be strengthened and that risk reducing work should be focused to these. The identified resilient sectors included: the sector for public administration, defence and compulsory social security, the sector for tanning and dressing of leather, the sector for health and social work and the sector fore education. It was also found that an important factor when considering resilient (and vulnerability) is the workforce. Some of the identified resilient sectors might be very dependent on the availability of personnel and this type of dependency is not included in the chosen version of the inoperability I/O model.

Which economic sectors can be considered key sectors, i.e. have a considerably large influence on other economic sectors?
The results from the key sector analysis demonstrated that a few sectors can be deemed overall key sectors, these included: the sector for real estate, the sector for manufacture of basic metals, the sector for construction, and the sector for import. Most of the identified key economic sectors have logical connections to almost all other sectors, for example most other sectors need the services from the sector for real estate or construction.

Can we see any increasing/decreasing trend in the extent of interdependencies from the year 2000 to 2008?
The results from the case studies show no overall increasing or decreasing trend in either overall inoperability or weighted overall inoperability. Thus when using calculations from the inoperability I/O model no specific overall trend can be identified. According to the

results the economic interdependencies between sectors have not increased from 2000 to 2008.

In conclusion, to answer the main research question if the inoperability I/O model can be applied to study Swedish critical dependencies and if the model is suitable for a Swedish context, the inoperability I/O model is a cost-effective efficient alternative for comprehensively accounting for physical linkage between national sectors and otherwise a similar or even greater specific data collection effort would be required. To get any adequate result for Swedish conditions the effects of import has to be included in the model in one way or another. There are some suggestions of how to handle import and export in Miller & Blair (1985).

The model is still only an approximation of physical interdependencies with economic dependencies and should be used with caution, and with an overall perspective where the details are not over-emphasised. Further evaluation is needed to be able to add more confidence to the results and the model's suitability for Swedish conditions. The thesis has also demonstrated that a considerably large part of the total economic loss after a disturbance can come from cascading effects or higher-order effects and shows why it is important to analyse interdependencies.

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Appendix A - Sector description

Sector Nr. (i)	Description	x_i, [mSEK]
S1	Agriculture, hunting and related service activities	53199
S2	Forestry, logging and related service activities	38362
S3	Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing	1559
S4	Mining of coal and lignite; extraction of peat	1156
S5	Mining of metal ores, Other mining and quarrying	32984
S6	Manufacture of food products and beverages, Manufacture of tobacco products	146147
S7	Manufacture of textiles	8217
S8	Manufacture of wearing apparel; dressing and dyeing of fur	2713
S9	Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear	1431
S10	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	87060
S11	Manufacture of pulp, paper and paper products	124455
S12	Publishing, printing and reproduction of recorded media	70353
S13	Manufacture of coke, refined petroleum products and nuclear fuels	109711
S14	Manufacture of chemicals and chemical products	145574
S15	Manufacture of rubber and plastic products	41013
S16	Manufacture of other non-metallic mineral products	38345
S17	Manufacture of basic metals	156306
S18	Manufacture of fabricated metal products, except machinery and equipment	132590
S19	Manufacture of machinery and equipment n.e.c.	240357
S20	Manufacture of office machinery and computers	5924
S21	Manufacture of electrical machinery and apparatus n.e.c., Manufacture of radio, television and communication equipment and apparatus	180071
S22	Manufacture of medical, precision and optical instruments, watches and clocks	49828
S23	Manufacture of motor vehicles, trailers and semi-trailers	267272
S24	Manufacture of other transport equipment	39681
S25	Manufacture of furniture; manufacturing n.e.c.	39170
S26	Recycling	7826
S27	Electricity, gas, steam and hot water supply	128812
S28	Collection, purification and distribution of water	13320
S29	Construction	337910
S30	Sale, maintenance and repair of motor vehicles and	539472

	motorcycles; retail sale services of automotive fuel, Wholesale trade and commission trade, except of motor vehicles and motorcycles, Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods	
S31	Hotels and restaurants	101685
S32	Land transport; transport via pipelines	170147
S33	Water transport	43258
S34	Air transport	31217
S35	Supporting and auxiliary transport activities; activities of travel agencies	230002
S36	Post and telecommunications	132518
S37	Financial intermediation, except insurance and pension funding	107069
S38	Insurance and pension funding, except compulsory social security	60565
S39	Activities auxiliary to financial intermediation	12961
S40	Real estate activities	476034
S41	Renting of machinery and equipment without operator and of personal and household goods	32135
S42	Computer and related activities	159265
S43	Research and development, Other business activities	459183
S44	Public administration and defence; compulsory social security	252337
S45	Education	226959
S46	Health and social work	424809
S47	Sewage and refuse disposal, sanitation and similar activities	24209
S48	Activities of membership organisation n.e.c.	67140
S49	Recreational, cultural and sporting activities	108828
S50	Other service activities	26213
S51	Private households with employed persons	1018
S52	Import	1397423
		53199

Appendix B - R Code

B.1 Trends

```
### Read data ###

make=read.delim("/Users/LinnSvegrup/Desktop/Exjobb/Data/R data/00/MAKE00.txt")
use=read.delim("/Users/LinnSvegrup/Desktop/Exjobb/Data/R data/00/USE00.txt")
X=read.delim("/Users/LinnSvegrup/Desktop/Exjobb/Data/R data/00/X00.txt")
Y=read.delim("/Users/LinnSvegrup/Desktop/Exjobb/Data/R data/00/Y00.txt")
P=read.delim("/Users/LinnSvegrup/Desktop/Exjobb/Data/R data/00/PP00.txt")

### Convert to matrices and vectors ###

makematrix=matrix(0,52,52)
usematrix=matrix(0,52,52)
xmat=matrix(0,52,1)
ymat=matrix(0,52,1)
pmat=matrix(0,52,1)

for(e in 1:nrow(make)) {
		xmat[e]=X[e,]
		ymat[e]=Y[e,]
		pmat[e]=P[e,]
		for (s in 1:nrow(make)){
				makematrix[e,s]=make[e,s]
				usematrix[e,s]=use[e,s]
		}
}

Xvec=c(xmat)
Yvec=c(ymat)
Pvec=c(pmat)


### Transform make matrix from basic prices to purchasers prices ###

diff=Pvec-Yvec

for(k in 1:52) {
		for(i in 1:52) {

		makematrix[k,i]=makematrix[k,i]+(makematrix[k,i]/Yvec[i]*diff[i])
		}
}
```

```
### Transform yvec och xvec from basic prices to purchasers prices ###

yvec=rep(0,52)
for(l in 1:52){
		yvec[l]=sum(makematrix[,l])
}

xvec=rep(0,52)
for(a in 1:52){
		xvec[a]=sum(makematrix[a,])
}


### Make transformation matrix ###

diagx=diag(xvec)
diagy=diag(yvec)


### Make normalized matrix U and V ###

U=usematrix%*%solve(diagx)
V=makematrix%*%solve(diagy)

### Make A matrix and A* ###

A=V%*%U
Astjärna=solve(diagx)%*%A%*%diagx

### Make identity matrix ###

enhet=matrix(0,52,52)
for(w in 1:52){
		for(q in 1:52){
				if(w==q){
						enhet[w,q]=1
						}
				}
		}

### Calculate q ###

		ansmat=matrix(0,52,52)
for (k in 1:52){
		c=rep(0,52)
		c[k]=0.10

		q=solve(enhet-Astjärna)%*%c
```

```
        ansmat[,k]=q
}

### Take 10 highest q and put the result in matrix mx and matrix results ###

mx=matrix(0,10,104)
for (i in 1:52){
        d=ansmat[,i]
        for(t in 1:10){
                z=0
                p=0
                for(u in 1:52){
                        if(d[u]>z){
                                z=d[u]
                                p=u
                        }
                }
                d[p]=0
                mx[t,i]=z
                mx[t,i+52]=p
        }
}

results=matrix(0,10,104)
for(r in 1:52){
        results[,r*2-1]=mx[,r+52]
        results[,r*2]=mx[,r]
}


### Sum columns and rows ###


sumcol=rep(0,52)
for(w in 1:52){
        sumcol[w]=sum(ansmat[,w])
}

sumcol

sumrow=rep(0,52)
for(w in 1:52){
        sumrow[w]=sum(ansmat[w,])
}

sumrow
```

```
### Calculate Economic loss E ###

                ansmatE=matrix(0,52,52)
for (k in 1:52){
                c=rep(0,52)
                c[k]=0.10

                q=solve(enhet-Astjärna)%*%c
                ansmatE[,k]=diagx%*%q
}


### Take 10 highest E and put the result in matrix mx ###

mx=matrix(0,10,104)
for (i in 1:52){
                d=ansmatE[,i]
                for(t in 1:10){
                                z=0
                                p=0
                                for(u in 1:52){
                                                if(d[u]>z){
                                                                z=d[u]
                                                                p=u
                                                }
                                }
                                d[p]=0
                                mx[t,i]=z
                                mx[t,i+52]=p
                }
}

results=matrix(0,10,104)
for(r in 1:52){
                results[,r*2-1]=mx[,r+52]
                results[,r*2]=mx[,r]
}


### Summera kolumner och rader ###


sumcol=rep(0,52)
for(w in 1:52){
                sumcol[w]=sum(ansmatE[,w])
}

sumcol
```

```
sumrow=rep(0,52)
for(w in 1:52){
        sumrow[w]=sum(ansmatE[w,])
}

sumrow


### Dependency and influence index ###

Aindex=Astjärna

for(m in 1:52) {
Aindex[m,m]=0
}

iindex=rep(0,52)
for(n in 1:52){
        iindex[n]=sum(Aindex[,n])
}

iindex

dindex=rep(0,52)
for(t in 1:52){
        dindex[t]=sum(Aindex[t,])
}

dindex

### THE END ###
```

B.2 Dependency and key sector analysis

```
### Read data ###

make=read.delim("/Users/LinnSvegrup/Desktop/Exjobb/Data/R data/08/MAKE08.txt")
use=read.delim("/Users/LinnSvegrup/Desktop/Exjobb/Data/R data/08/USE08.txt")
X=read.delim("/Users/LinnSvegrup/Desktop/Exjobb/Data/R data/08/X08.txt")
Y=read.delim("/Users/LinnSvegrup/Desktop/Exjobb/Data/R data/08/Y08.txt")
P=read.delim("/Users/LinnSvegrup/Desktop/Exjobb/Data/R data/08/PP08.txt")

### Convert to matrices and vectors ###

makematrix=matrix(0,52,52)
```

```
usematrix=matrix(0,52,52)
xmat=matrix(0,52,1)
ymat=matrix(0,52,1)
pmat=matrix(0,52,1)

for(e in 1:nrow(make)) {
        xmat[e]=X[e,]
        ymat[e]=Y[e,]
        pmat[e]=P[e,]
        for (s in 1:nrow(make)){
                makematrix[e,s]=make[e,s]
                usematrix[e,s]=use[e,s]
        }
}

Xvec=c(xmat)
Yvec=c(ymat)
Pvec=c(pmat)


### Transform make matrix from basic prices to purchasers prices ###

diff=Pvec-Yvec

for(k in 1:52) {
        for(i in 1:52) {

        makematrix[k,i]=makematrix[k,i]+(makematrix[k,i]/Yvec[i]*diff[i])
        }
}

### Transform yvec och xvec from basic prices to purchasers prices ###

yvec=rep(0,52)
for(l in 1:52){
        yvec[l]=sum(makematrix[,l])
}

xvec=rep(0,52)
for(a in 1:52){
        xvec[a]=sum(makematrix[a,])
}


### Make transformation matrix  ###

diagx=diag(xvec)
diagy=diag(yvec)
```

```
### Make normalized matrix U and V ###

U=usematrix%*%solve(diagx)
V=makematrix%*%solve(diagy)

### Make A matrix and A* ###

A=V%*%U
Astjärna=solve(diagx)%*%A%*%diagx

### Make identity matrix ###

enhet=matrix(0,52,52)
for(w in 1:52){
        for(q in 1:52){
                if(w==q){
                        enhet[w,q]=1
                        }
                }
        }

### Calculate q ###

        ansmat=matrix(0,52,52)
for (k in 1:52){
        c=rep(0,52)
        c[k]=0.10

        q=solve(enhet-Astjärna)%*%c
        ansmat[,k]=q
}

### Take 10 highest q and put the result in matrix mx and matrix results ###

mx=matrix(0,10,104)
for (i in 1:52){
        d=ansmat[,i]
        for(t in 1:10){
                z=0
                p=0
                for(u in 1:52){
                        if(d[u]>z){
                                z=d[u]
                                p=u
                        }
                }
```

```
                        d[p]=0
                        mx[t,i]=z
                        mx[t,i+52]=p
        }
}

results=matrix(0,10,104)
for(r in 1:52){
        results[,r*2-1]=mx[,r+52]
        results[,r*2]=mx[,r]
}
results

### Sum columns and rows ###


sumcol=rep(0,52)
for(w in 1:52){
        sumcol[w]=sum(ansmat[,w])
}

sumcol

sumrow=rep(0,52)
for(w in 1:52){
        sumrow[w]=sum(ansmat[w,])
}

sumrow


### Calculate Economic loss E ###

        ansmatE=matrix(0,52,52)
for (k in 1:52){
        c=rep(0,52)
        c[k]=0.10

        q=solve(enhet-Astjärna)%*%c
        ansmatE[,k]=diagx%*%q
}


### Take 10 highest E and put the result in matrix mx ###

mx=matrix(0,10,104)
for (i in 1:52){
        d=ansmatE[,i]
```

```
		for(t in 1:10){
			z=0
			p=0
			for(u in 1:52){
				if(d[u]>z){
					z=d[u]
					p=u
				}
			}
			d[p]=0
			mx[t,i]=z
			mx[t,i+52]=p
		}
}

results=matrix(0,10,104)
for(r in 1:52){
		results[,r*2-1]=mx[,r+52]
		results[,r*2]=mx[,r]
}
results

### Summera kolumner och rader ###


sumcol=rep(0,52)
for(w in 1:52){
		sumcol[w]=sum(ansmatE[,w])
}

sumcol

sumrow=rep(0,52)
for(w in 1:52){
		sumrow[w]=sum(ansmatE[w,])
}

sumrow


### Dependency and influence index ###

Aindex=Astjärna

for(m in 1:52) {
Aindex[m,m]=0
}
```

```
aiindex=rep(0,52)
for(n in 1:52){
        aiindex[n]=sum(Aindex[,n])
}

aiindex

adindex=rep(0,52)
for(t in 1:52){
        adindex[t]=sum(Aindex[t,])
}

adindex


Sindex=solve(enhet-Astjärna)

for(å in 1:52) {
Sindex[å,å]=0
}

siindex=rep(0,52)
for(ä in 1:52){
        siindex[ä]=sum(Sindex[,ä])
}

siindex

sdindex=rep(0,52)
for(ö in 1:52){
        sdindex[ö]=sum(Sindex[ö,])
}

sdindex

### THE END ###
```

B.3 Air transport

```
### Read data ###

make=read.delim("/Users/LinnSvegrup/Desktop/Exjobb/Scenarios/Airtraffic/08/MAKE08.
txt")
use=read.delim("/Users/LinnSvegrup/Desktop/Exjobb/Scenarios/Airtraffic/08/USE08.txt")
X=read.delim("/Users/LinnSvegrup/Desktop/Exjobb/Scenarios/Airtraffic/08/X08.txt")
Y=read.delim("/Users/LinnSvegrup/Desktop/Exjobb/Scenarios/Airtraffic/08/Y08.txt")
P=read.delim("/Users/LinnSvegrup/Desktop/Exjobb/Scenarios/Airtraffic/08/PP08.txt")
```

```
### Convert to matrices and vectors ###

makematrix=matrix(0,52,52)
usematrix=matrix(0,52,52)
xmat=matrix(0,52,1)
ymat=matrix(0,52,1)
pmat=matrix(0,52,1)

for(e in 1:nrow(make)) {
		xmat[e]=X[e,]
		ymat[e]=Y[e,]
		pmat[e]=P[e,]
		for (s in 1:nrow(make)){
				makematrix[e,s]=make[e,s]
				usematrix[e,s]=use[e,s]
		}
}

Xvec=c(xmat)
Yvec=c(ymat)
Pvec=c(pmat)


### Transform make matrix from basic prices to purchasers prices ###

diff=Pvec-Yvec

for(k in 1:52) {
		for(i in 1:52) {

		makematrix[k,i]=makematrix[k,i]+(makematrix[k,i]/Yvec[i]*diff[i])
		}
}

### Transform yvec och xvec from basic prices to purchasers prices ###

yvec=rep(0,52)
for(l in 1:52){
		yvec[l]=sum(makematrix[,l])
}

xvec=rep(0,52)
for(a in 1:52){
		xvec[a]=sum(makematrix[a,])
}


### Make transformation matrix  ###
```

```
diagx=diag(xvec)
diagy=diag(yvec)


### Make normalized matrix U and V ###

U=usematrix%*%solve(diagx)
V=makematrix%*%solve(diagy)

### Make A matrix and A* ###

A=V%*%U
Astjärna=solve(diagx)%*%A%*%diagx

Asstjärna=t(A)

### Make identity matrix ###

enhet=matrix(0,52,52)
for(w in 1:52){
		for(q in 1:52){
				if(w==q){
						enhet[w,q]=1
						}
				}
		}

### Calculate inoperability q ###

c=rep(0,52)
c[34]=0.10
c[31]=0.10


q=solve(enhet-Astjärna)%*%c

qs=solve(enhet-Asstjärna)%*%c


### Sum inoperability ###

sumq=sum(q)

sumqs=sum(qs)

### Calculate Economic loss E ###
```

```
E=diagx%*%q

Es=diagx%*%qs
### Sum Economic loss ###

sumE=sum(E)

sumEs=sum(Es)

### THE END ###
```

B.4 Agriculture

```
### Read data ###

make=read.delim("/Users/LinnSvegrup/Desktop/Exjobb/Scenarios/Airtraffic/08/MAKE08.
txt")
use=read.delim("/Users/LinnSvegrup/Desktop/Exjobb/Scenarios/Airtraffic/08/USE08.txt")
X=read.delim("/Users/LinnSvegrup/Desktop/Exjobb/Scenarios/Airtraffic/08/X08.txt")
Y=read.delim("/Users/LinnSvegrup/Desktop/Exjobb/Scenarios/Airtraffic/08/Y08.txt")
P=read.delim("/Users/LinnSvegrup/Desktop/Exjobb/Scenarios/Airtraffic/08/PP08.txt")

### Convert to matrices and vectors ###

makematrix=matrix(0,52,52)
usematrix=matrix(0,52,52)
xmat=matrix(0,52,1)
ymat=matrix(0,52,1)
pmat=matrix(0,52,1)

for(e in 1:nrow(make)) {
		xmat[e]=X[e,]
		ymat[e]=Y[e,]
		pmat[e]=P[e,]
		for (s in 1:nrow(make)){
				makematrix[e,s]=make[e,s]
				usematrix[e,s]=use[e,s]
		}
}

Xvec=c(xmat)
Yvec=c(ymat)
Pvec=c(pmat)


### Transform make matrix from basic prices to purchasers prices ###
```

```
diff=Pvec-Yvec

for(k in 1:52) {
        for(i in 1:52) {

        makematrix[k,i]=makematrix[k,i]+(makematrix[k,i]/Yvec[i]*diff[i])
        }
}

### Transform yvec och xvec from basic prices to purchasers prices ###

yvec=rep(0,52)
for(l in 1:52){
        yvec[l]=sum(makematrix[,l])
}

xvec=rep(0,52)
for(a in 1:52){
        xvec[a]=sum(makematrix[a,])
}


### Make transformation matrix  ###

diagx=diag(xvec)
diagy=diag(yvec)


### Make normalized matrix U and V ###

U=usematrix%*%solve(diagx)
V=makematrix%*%solve(diagy)

### Make A matrix and A* ###

A=V%*%U
Astjärna=solve(diagx)%*%A%*%diagx

Asstjärna=t(A)

### Make identity matrix ###

enhet=matrix(0,52,52)
for(w in 1:52){
        for(q in 1:52){
                if(w==q){
                        enhet[w,q]=1
                        }
```

```
                }
        }

### Calculate inoperability q ###

c=rep(0,52)
c[1]=0.10


q=solve(enhet-Astjärna)%*%c

qs=solve(enhet-Asstjärna)%*%c


### Sum inoperability ###

sumq=sum(q)

sumqs=sum(qs)

### Calculate Economic loss E ###

E=diagx%*%q

Es=diagx%*%qs

### Sum Economic loss ###

sumE=sum(E)

sumEs=sum(Es)

### THE END ###
```

Appendix C - Complete results

C.1 Overall inoperability

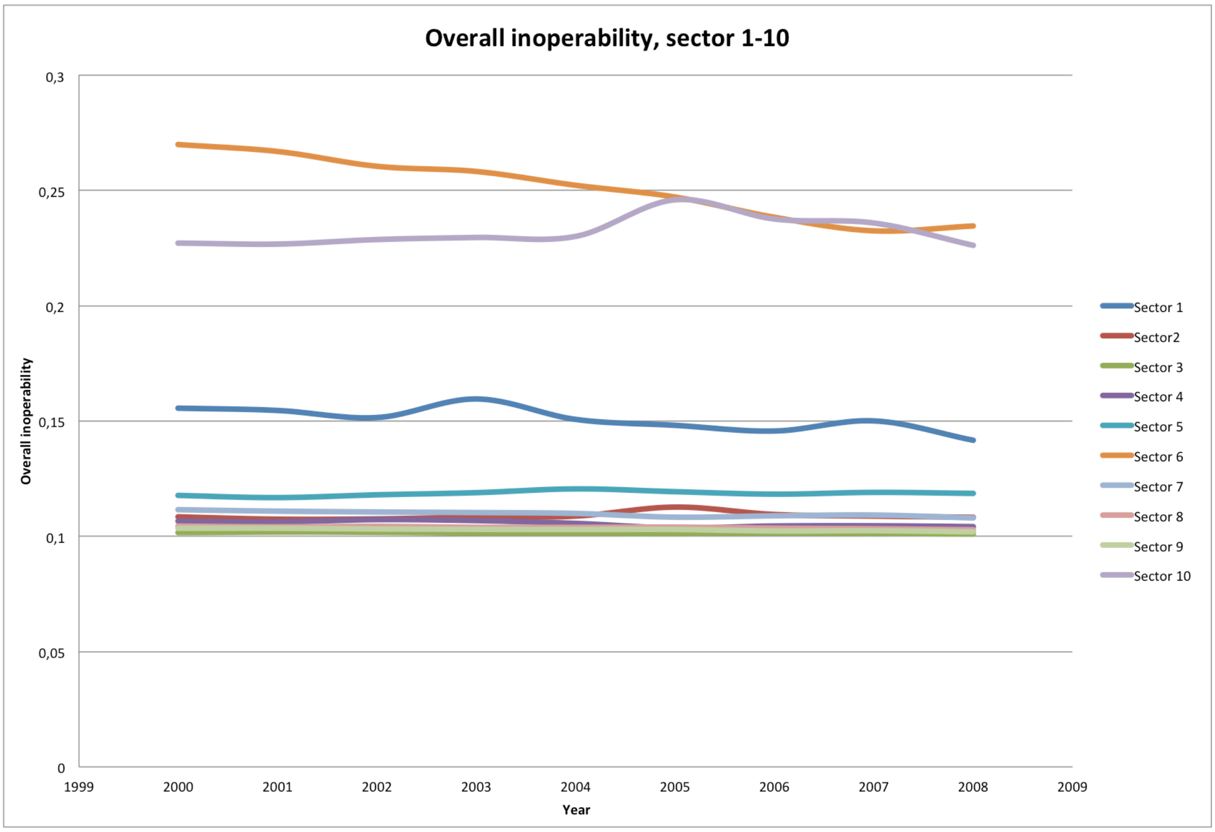

Figure 39: Overall inoperability, Sector 1-10

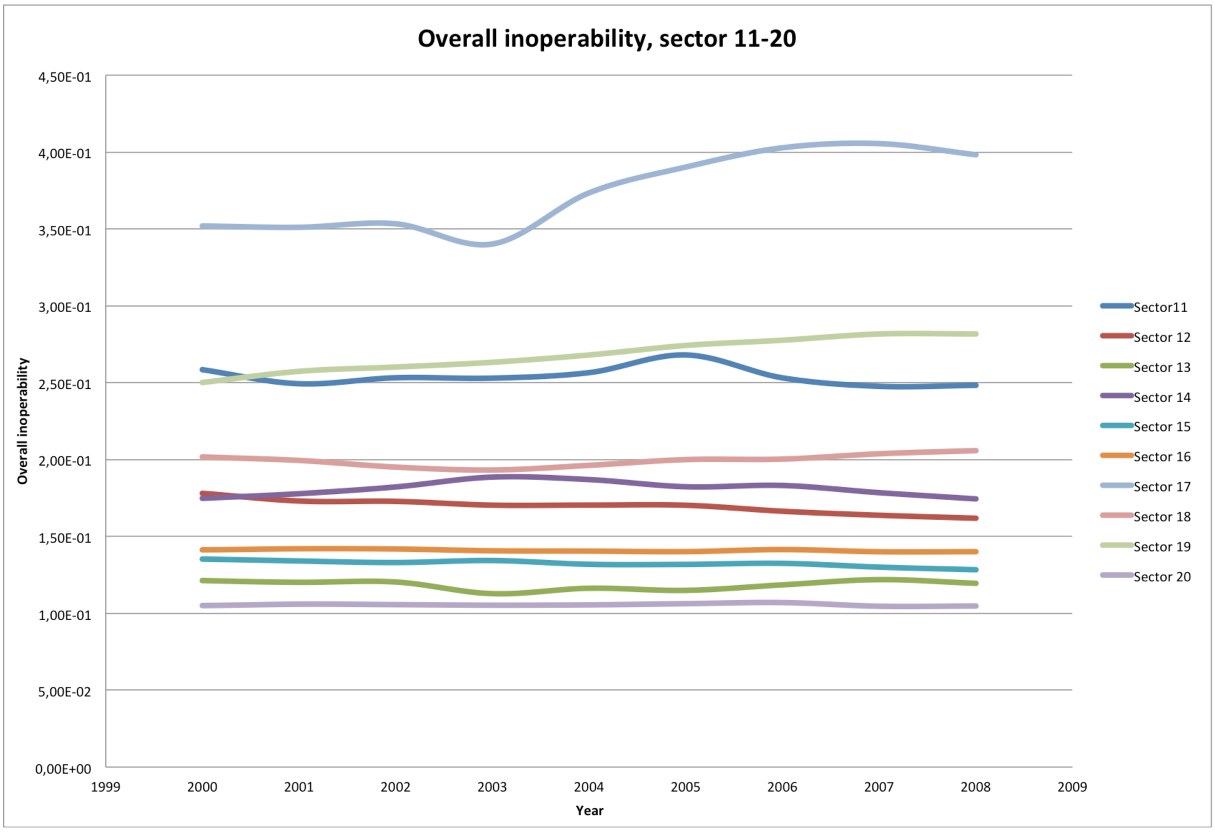

Figure C-2: Overall inoperability, Sector 10-21

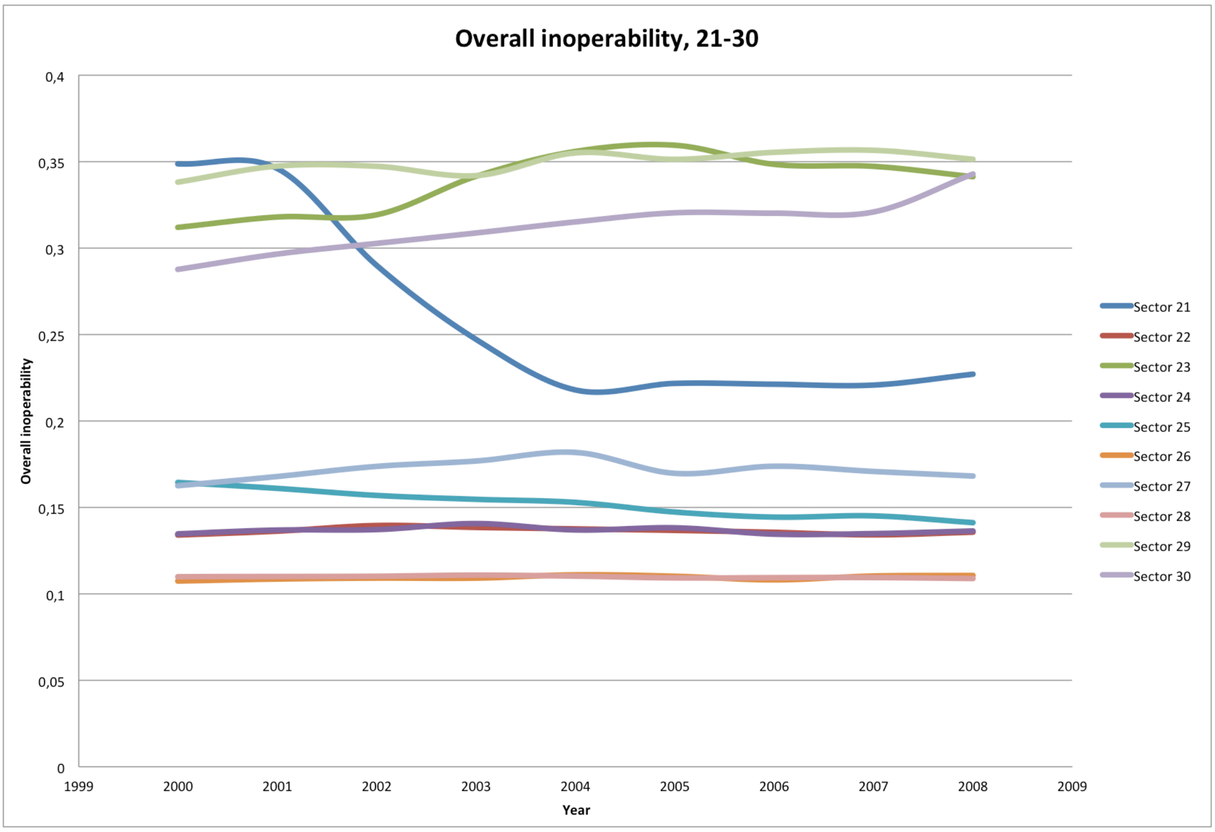

Figure C-3: Overall inoperability, Sector 21-30

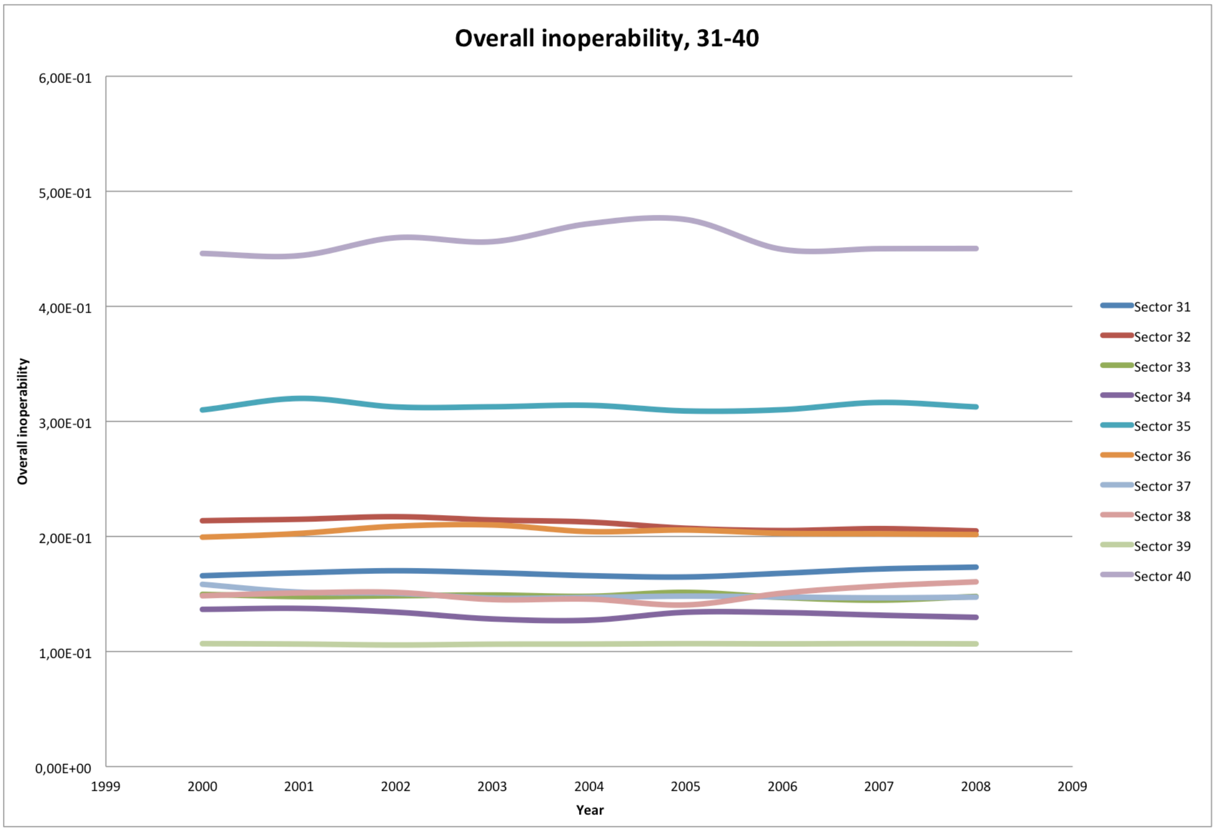

Figure C-4: Overall inoperability, Sector 31-40

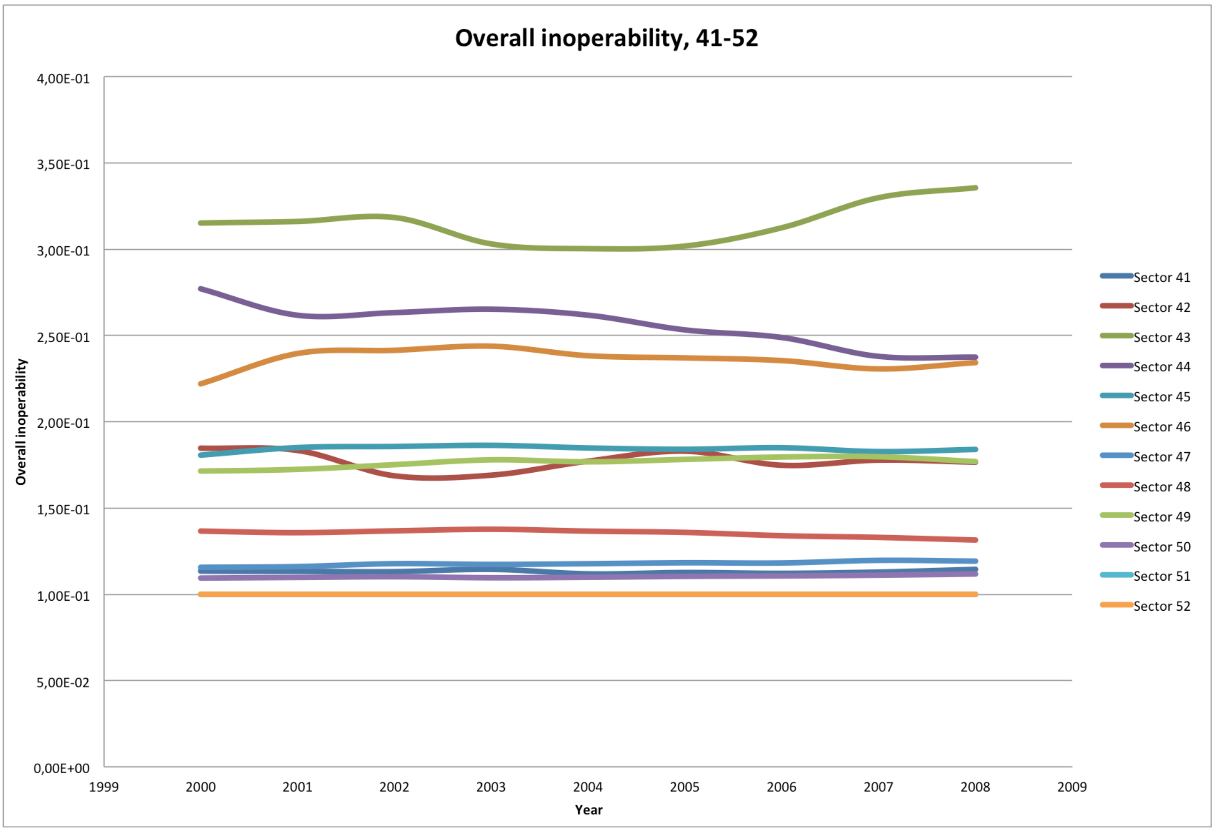

Figure C-5: Overall inoperability, Sector 41-52

C.2 Economic loss

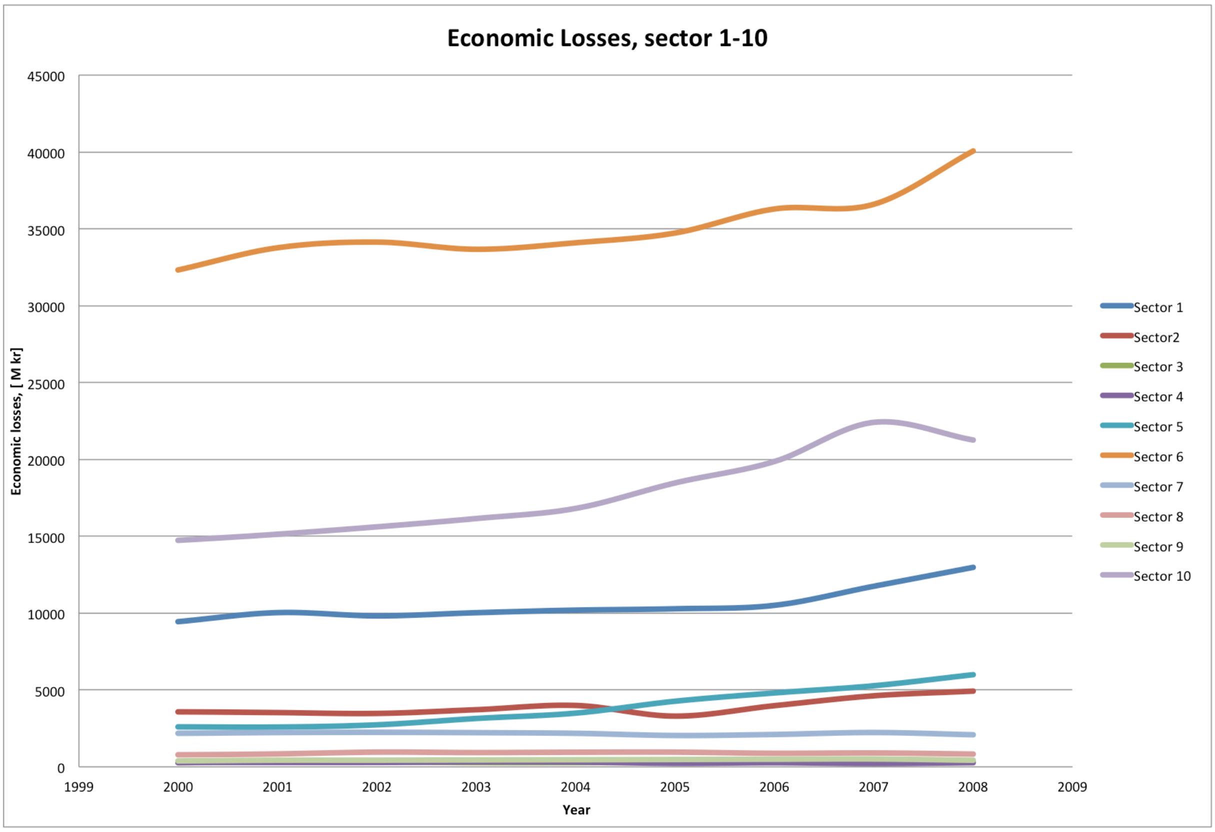

Figure C-6: Economic loss, Sector 1-10

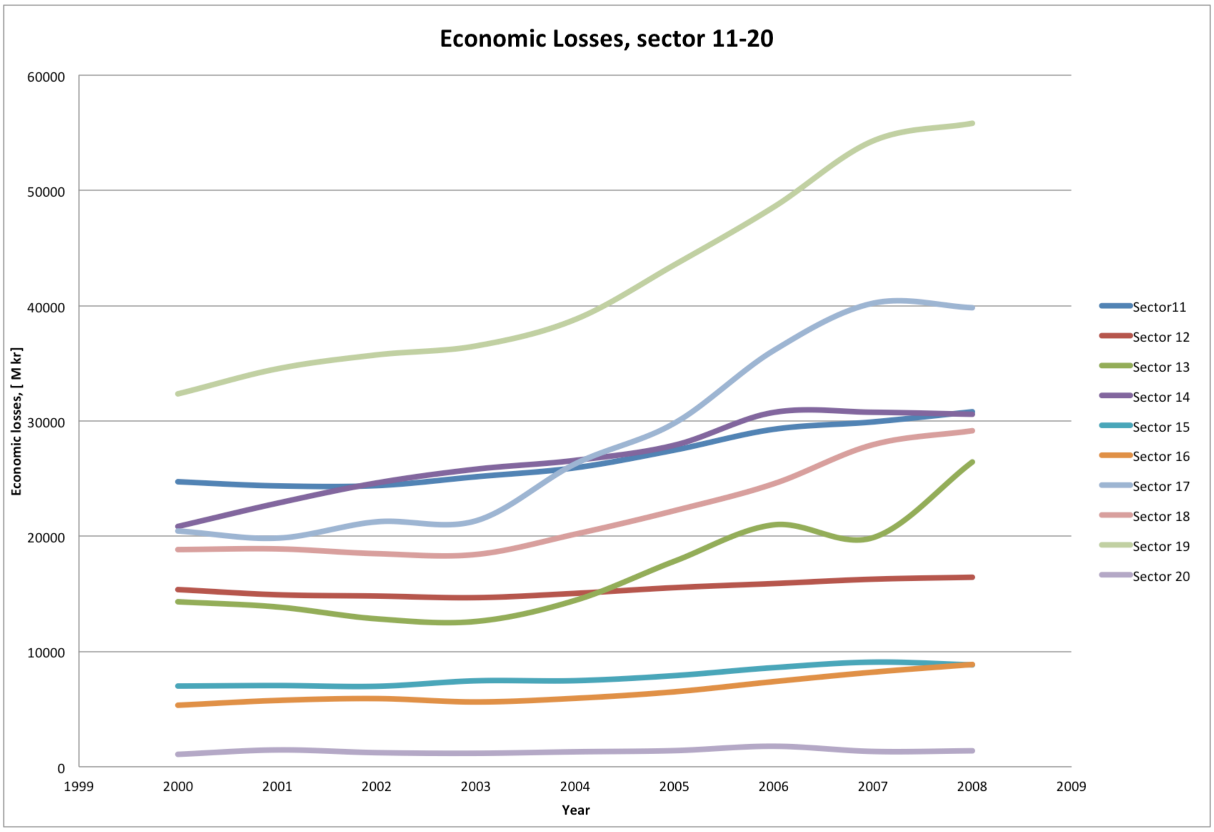

Figure C-7: Economic loss, Sector 11-20

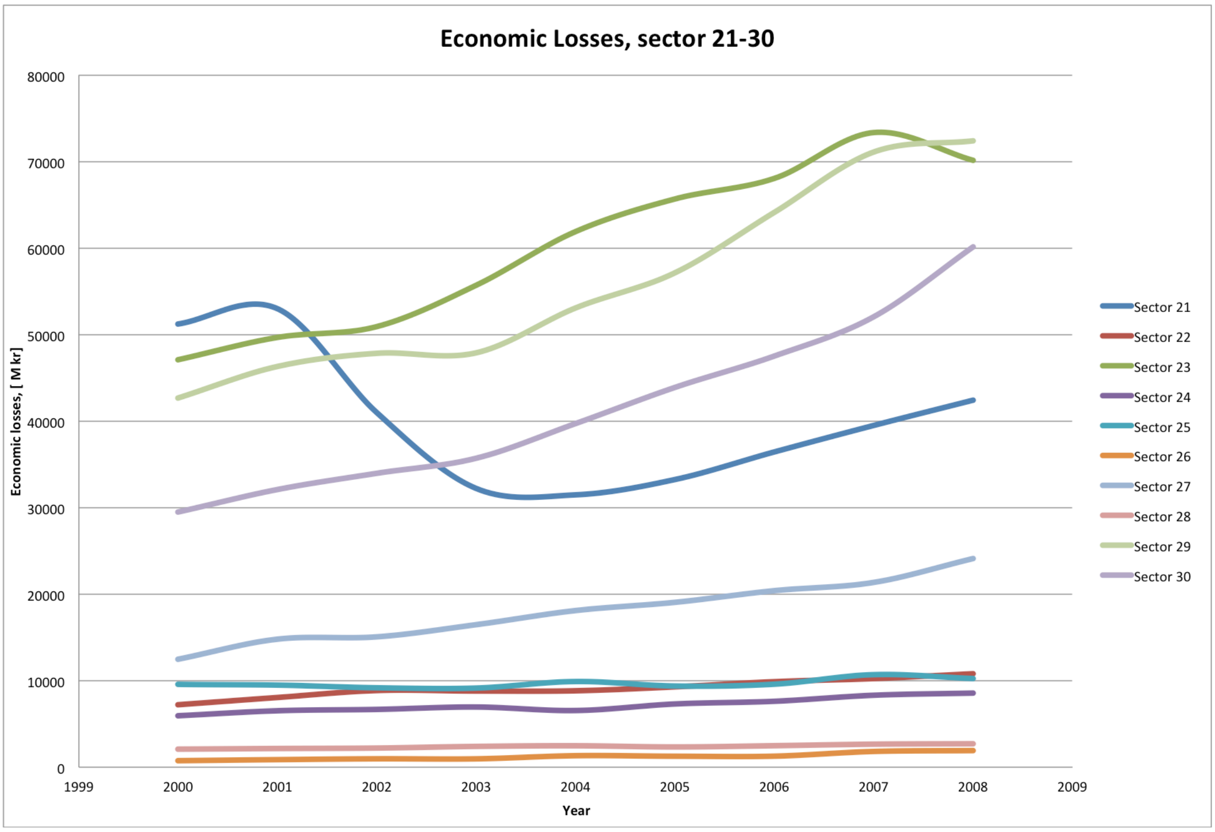

Figure C-8: Economic loss, Sector 21-30

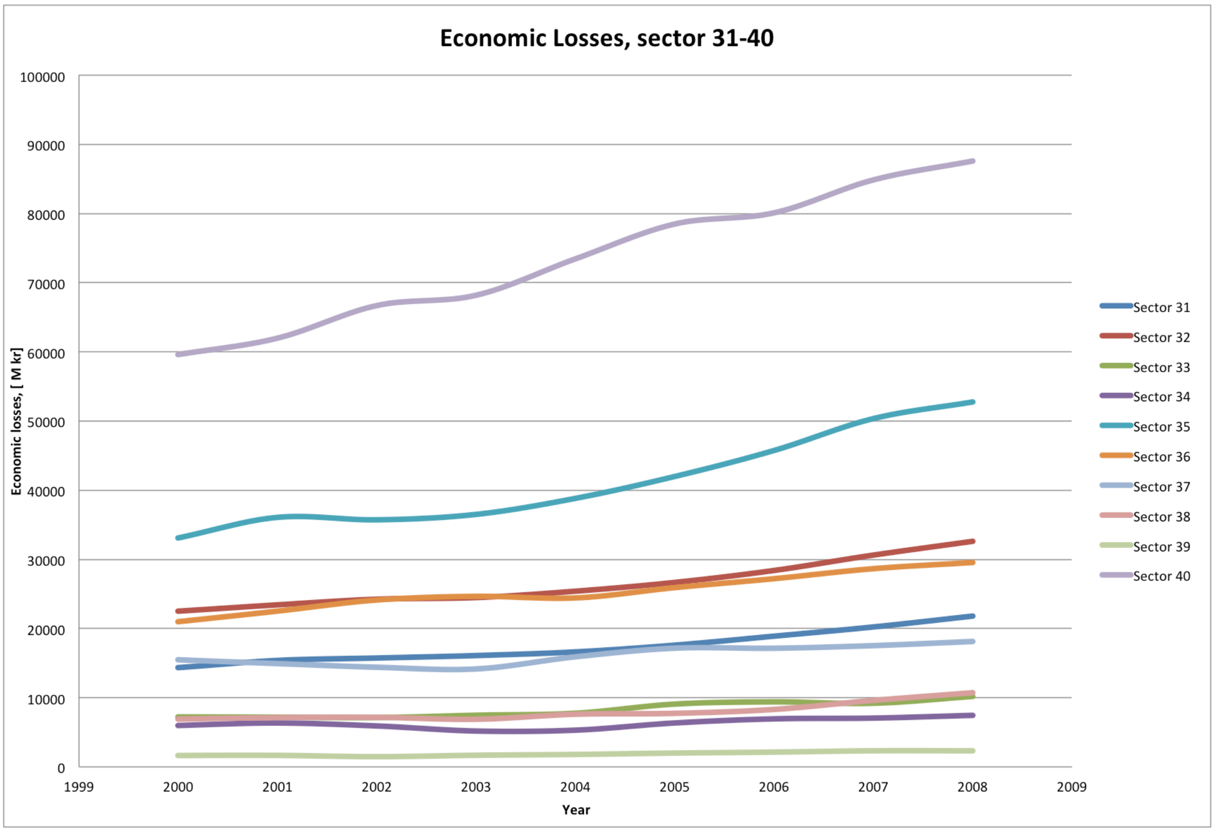

Figure C-9: Economic loss, Sector 31-40

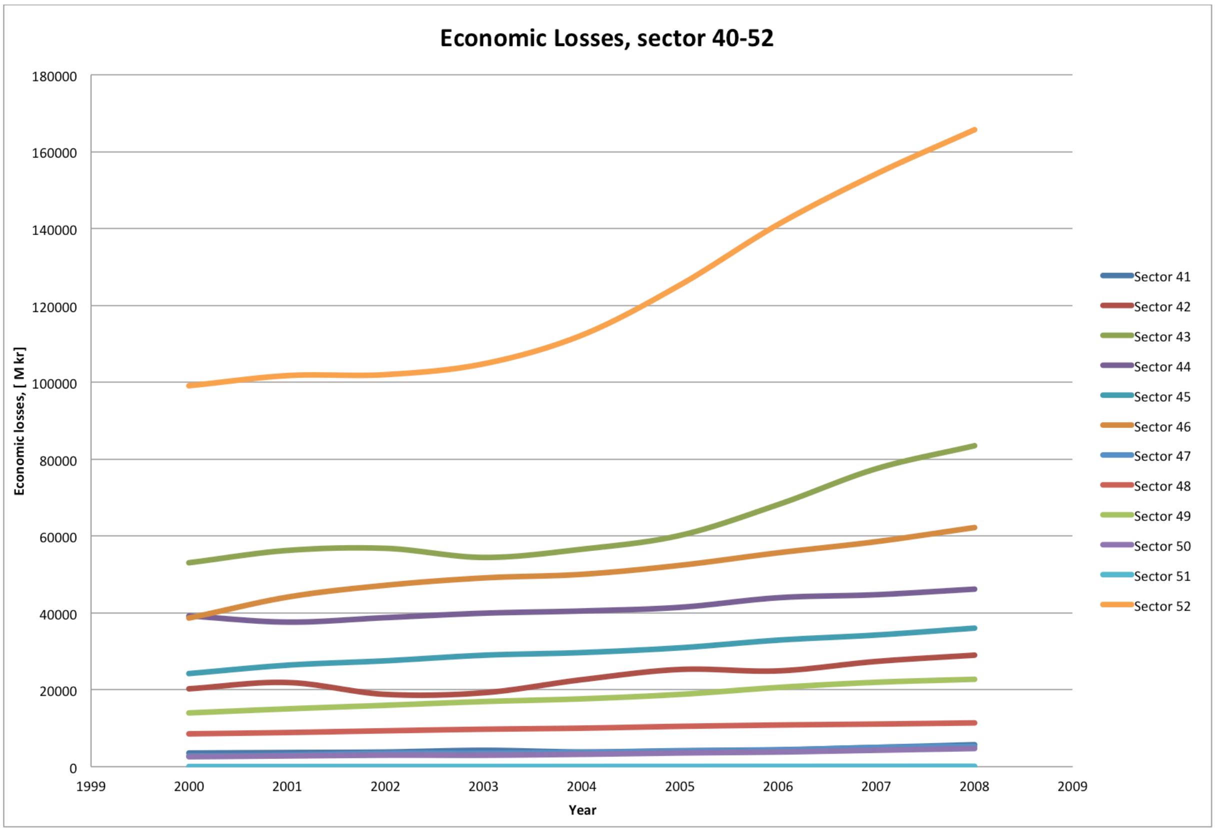

Figure C-10: Economic loss, Sector 41-52

C.3 Weighted overall inoperability

Figure C-11: Weighted Overall inoperability, Sector 1-10

Figure C-12: Weighted Overall inoperability, Sector 11-20

Figure C-13: Weighted Overall inoperability, Sector 21-30

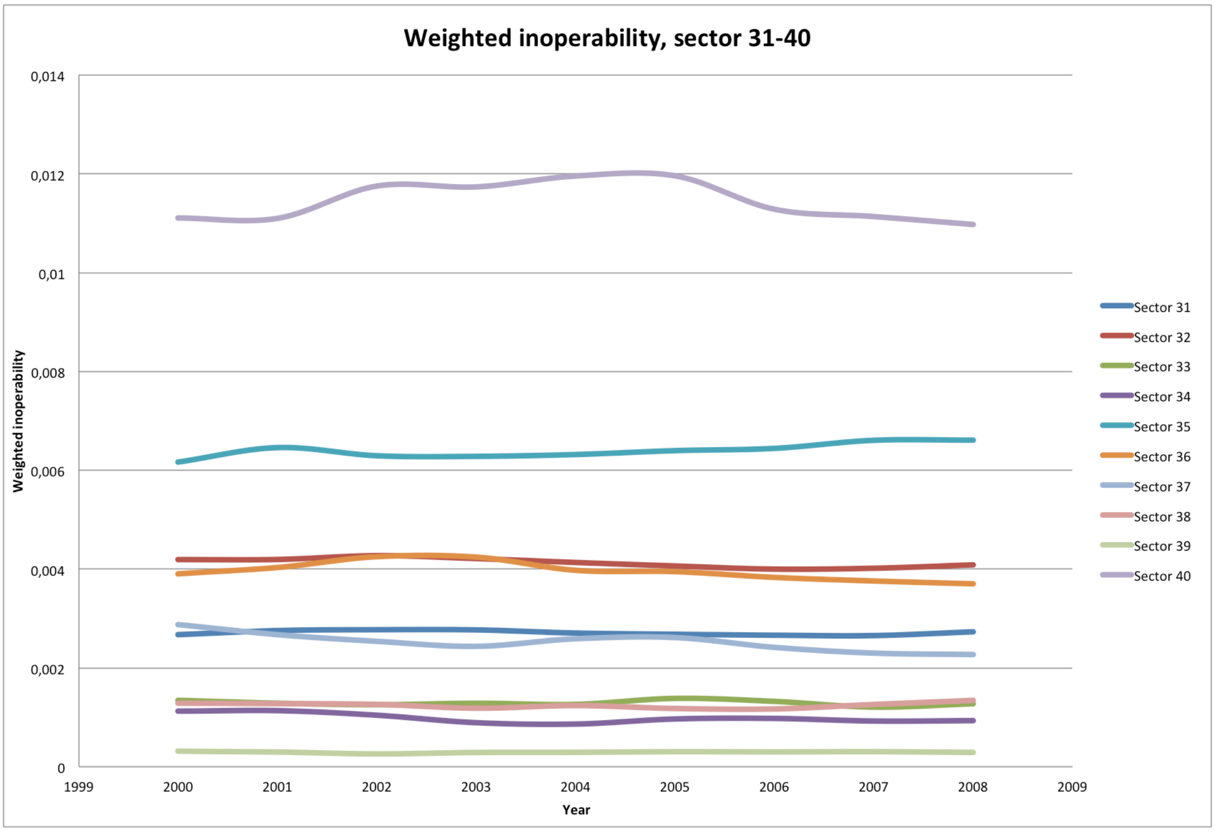

Figure C-14: Weighted Overall inoperability, Sector 31-40

Figure C-15: Weighted Overall inoperability, Sector 41-52

C.4 Initial perturbation

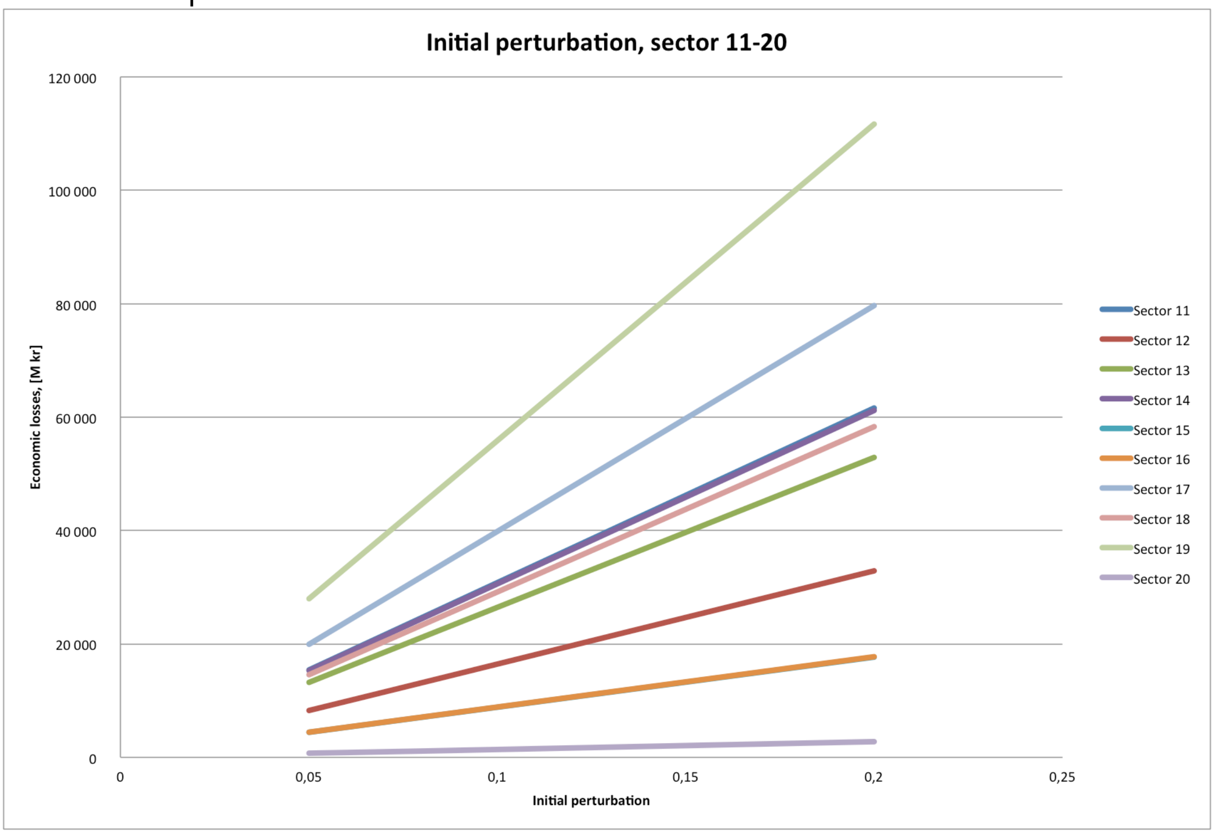

Figure C-16: Overall inoperability, Sector 11-20

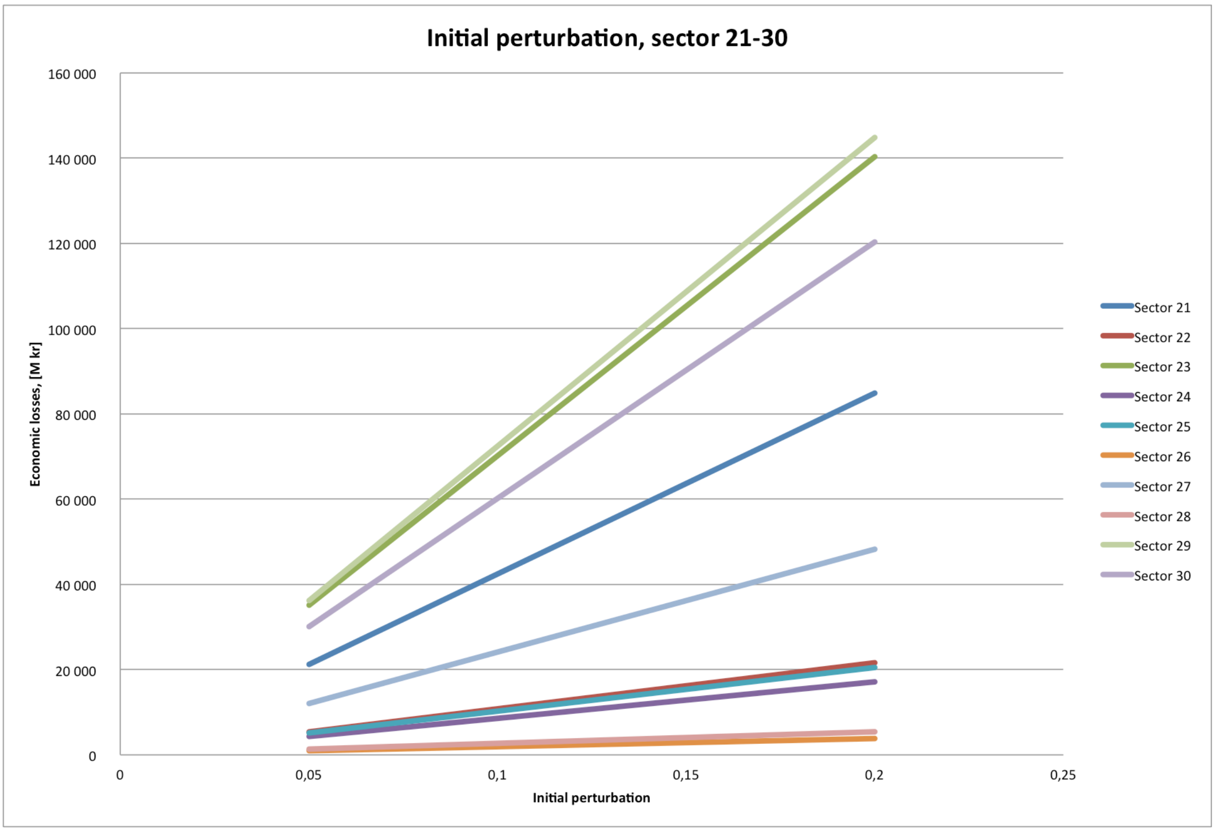

Figure C-18: Overall inoperability, Sector 21-30

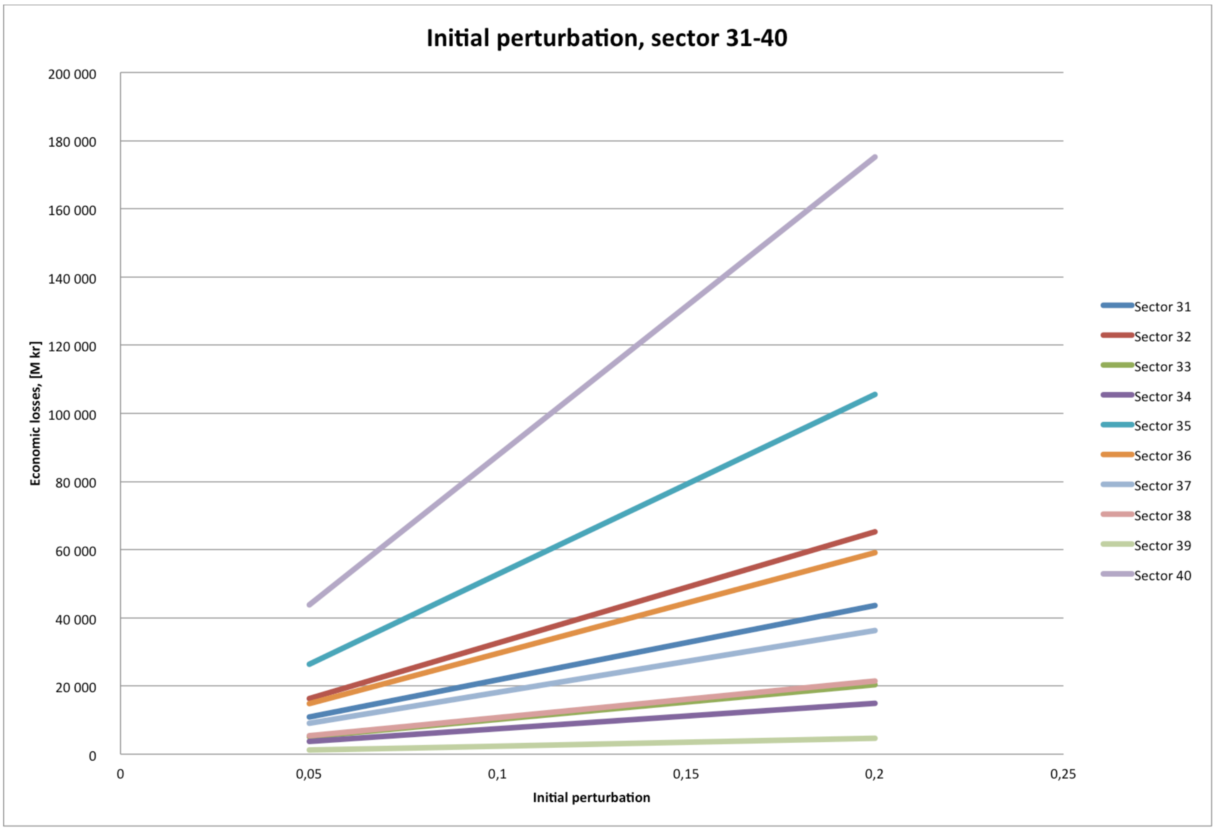

Figure C-19: Overall inoperability, Sector 31-40

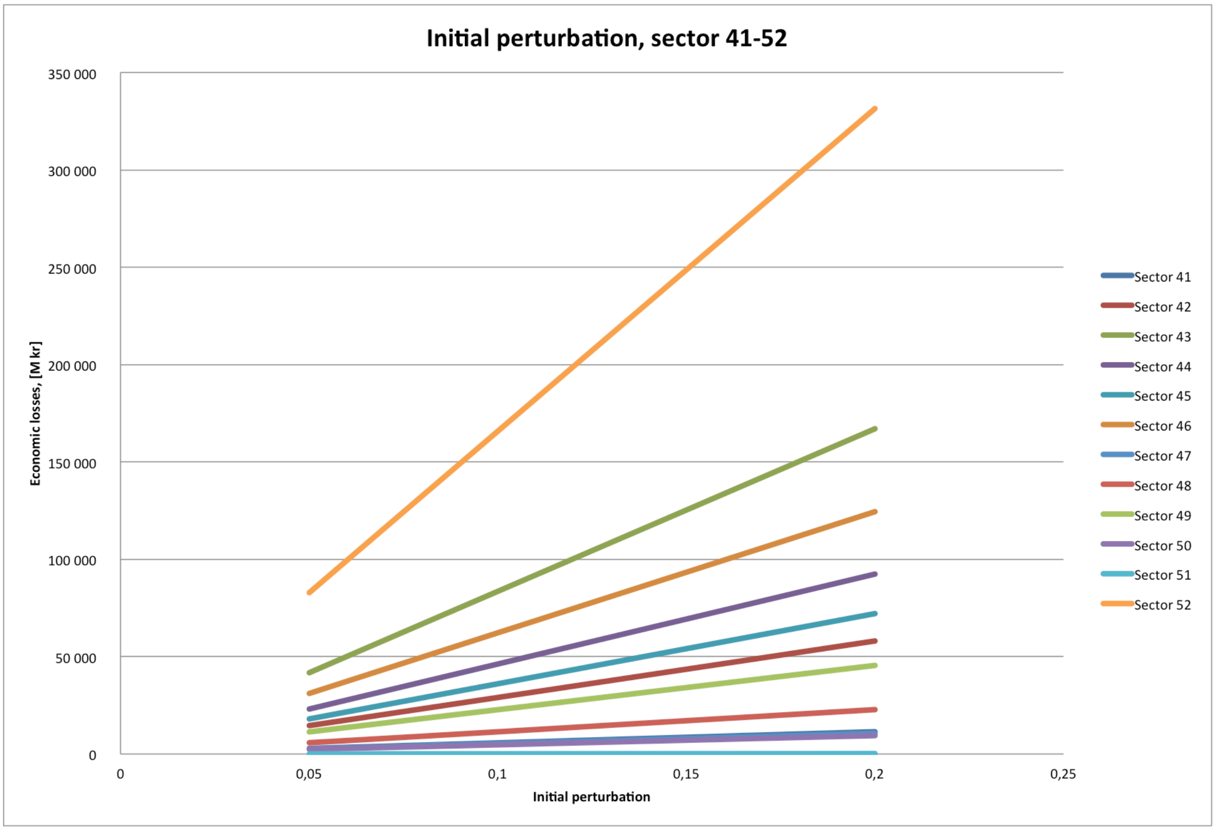

Figure C-20: Overall inoperability, Sector 41-52

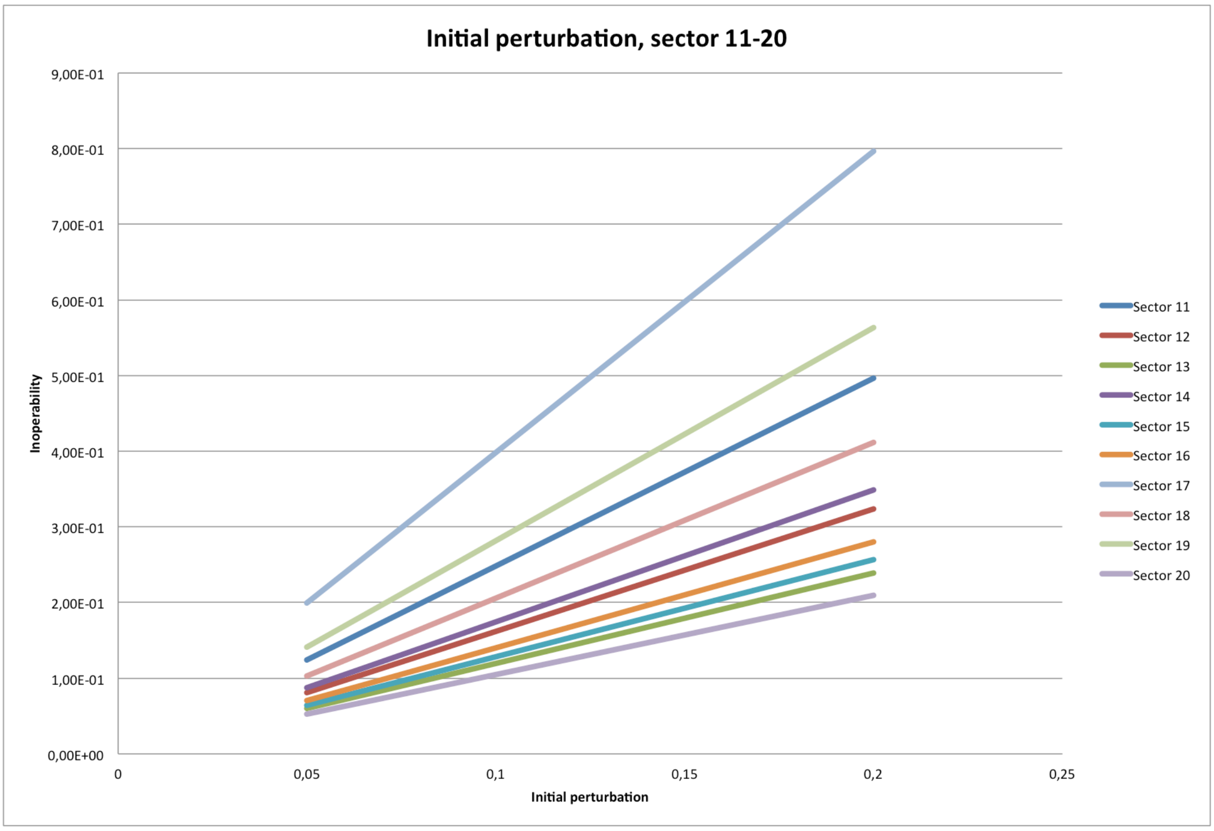

Figure C-22: Overall inoperability, Sector 31-40

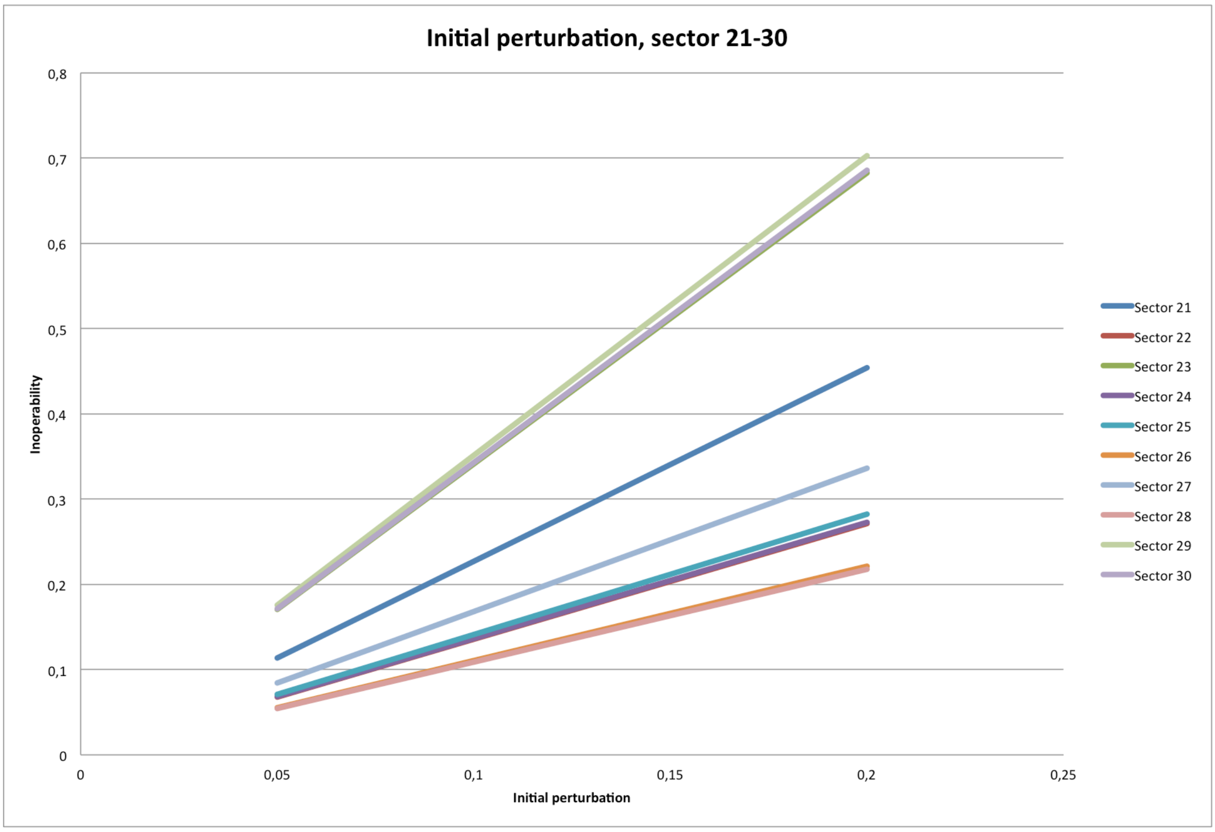

Figure C-23: Overall inoperability, Sector 31-40

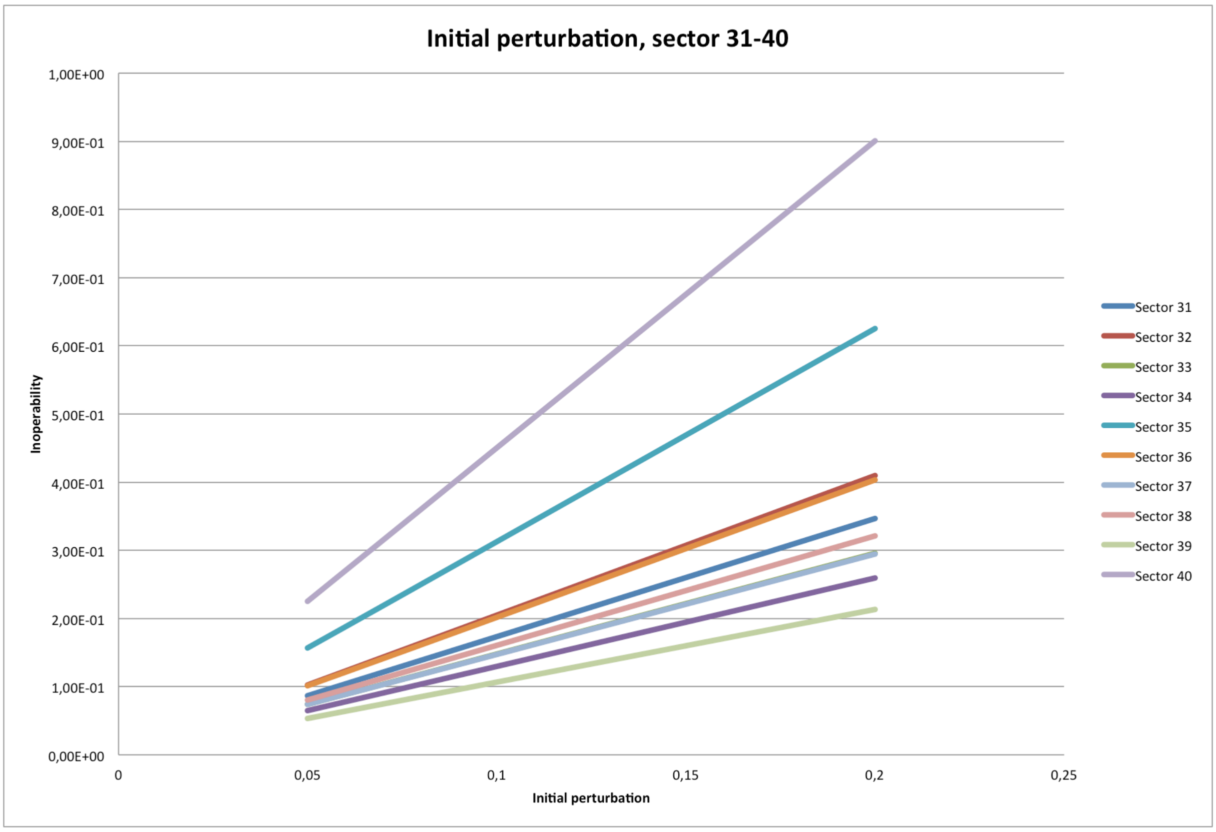

Figure C-24: Sector 31-40

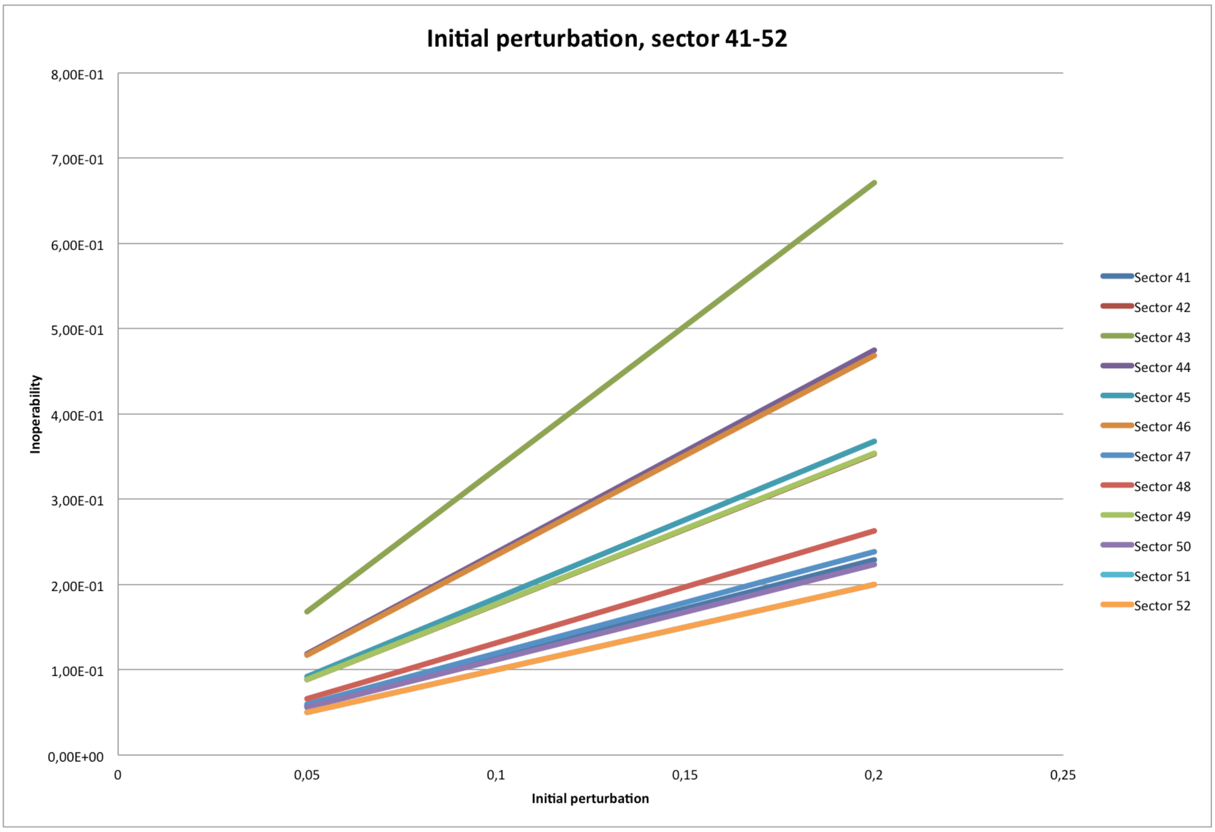

Figure C-25: Sector 31-40

C.5 Influence index

Table C-1: Influence index and overall influence index

Sector	i-index, first order effects	Average	Sector	i-index, higher order effects	Average
40	2,149	0,042	40	3,434	0,066
17	1,701	0,033	17	2,665	0,051
29	1,392	0,027	29	2,498	0,048
35	1,125	0,022	30	2,353	0,045
30	1,081	0,021	43	2,189	0,042
43	1,078	0,021	23	2,102	0,040
23	0,852	0,017	35	2,010	0,039
11	0,807	0,016	19	1,705	0,033
19	0,769	0,015	44	1,355	0,026
46	0,743	0,015	11	1,347	0,026
6	0,718	0,014	46	1,322	0,025
44	0,706	0,014	6	1,227	0,024
10	0,688	0,014	21	1,110	0,021
21	0,474	0,009	10	1,084	0,021
32	0,471	0,009	18	0,920	0,018
31	0,416	0,008	32	0,901	0,017
27	0,410	0,008	36	0,835	0,016

36	0,408	0,008	45	0,832	0,016
45	0,387	0,008	31	0,724	0,014
18	0,356	0,007	42	0,695	0,013
42	0,333	0,007	49	0,669	0,013
49	0,326	0,006	27	0,626	0,012
14	0,313	0,006	14	0,623	0,012
38	0,299	0,006	12	0,471	0,009
37	0,218	0,004	38	0,441	0,009
33	0,208	0,004	37	0,422	0,008
12	0,205	0,004	33	0,376	0,007
25	0,201	0,004	25	0,374	0,007
1	0,190	0,004	16	0,311	0,006
16	0,179	0,004	48	0,311	0,006
34	0,176	0,004	1	0,306	0,006
48	0,170	0,003	22	0,287	0,006
22	0,146	0,003	34	0,281	0,005
15	0,138	0,003	15	0,246	0,005
13	0,136	0,003	24	0,239	0,005
24	0,114	0,002	13	0,180	0,004
5	0,087	0,002	47	0,154	0,003
47	0,083	0,002	5	0,146	0,003
41	0,064	0,001	41	0,139	0,003
50	0,059	0,001	50	0,116	0,002
28	0,052	0,001	28	0,088	0,002
26	0,032	0,001	26	0,072	0,001
2	0,030	0,001	39	0,057	0,001
7	0,028	0,001	2	0,051	0,001
39	0,026	0,001	7	0,048	0,001
20	0,022	0,000	20	0,041	0,001
8	0,019	0,000	8	0,025	0,001
3	0,007	0,000	4	0,011	0,000
4	0,006	0,000	3	0,011	0,000
9	0,005	0,000	9	0,008	0,000
51	0,000	0,000	51	0,000	0,000
52	0,000	0,000	52	0,000	0,000

C.6 Dependency index

Table C-2: Dependency index and overall dependency index

Sector	d-index, first order effects		Sector	d-index, higher order effects	
28	0,9835	0,0189	26	1,9286	0,0371
26	0,9621	0,0185	4	1,7081	0,0328
47	0,9085	0,0175	28	1,6285	0,0313
4	0,8410	0,0162	47	1,6247	0,0312

39	0,8377	0,0161	39	1,4600	0,0281
2	0,7171	0,0138	32	1,4217	0,0273
32	0,6936	0,0133	2	1,3643	0,0262
43	0,6362	0,0122	12	1,2626	0,0243
5	0,6103	0,0117	5	1,2036	0,0231
12	0,6049	0,0116	43	1,1819	0,0227
16	0,6027	0,0116	34	1,1253	0,0216
34	0,5948	0,0114	41	1,1188	0,0215
41	0,5777	0,0111	16	1,0719	0,0206
15	0,5298	0,0102	35	0,9439	0,0182
35	0,5044	0,0097	36	0,9061	0,0174
18	0,4956	0,0095	10	0,9006	0,0173
37	0,4798	0,0092	18	0,9003	0,0173
10	0,4760	0,0092	15	0,8985	0,0173
1	0,4719	0,0091	37	0,8685	0,0167
27	0,4586	0,0088	24	0,8291	0,0159
36	0,4442	0,0085	27	0,8196	0,0158
52	0,4377	0,0084	13	0,7708	0,0148
24	0,4231	0,0081	52	0,7646	0,0147
13	0,3862	0,0074	17	0,7589	0,0146
42	0,3834	0,0074	1	0,7479	0,0144
40	0,3759	0,0072	42	0,7456	0,0143
30	0,3644	0,0070	30	0,6890	0,0132
31	0,3490	0,0067	33	0,6808	0,0131
17	0,3486	0,0067	31	0,6503	0,0125
33	0,3272	0,0063	40	0,6301	0,0121
29	0,3076	0,0059	14	0,5866	0,0113
14	0,3053	0,0059	49	0,5653	0,0109
49	0,2587	0,0050	29	0,5233	0,0101
22	0,2567	0,0049	38	0,4930	0,0095
21	0,2504	0,0048	21	0,4891	0,0094
38	0,2325	0,0045	11	0,4117	0,0079
7	0,2279	0,0044	22	0,4079	0,0078
3	0,2125	0,0041	7	0,3505	0,0067
50	0,1995	0,0038	50	0,3418	0,0066
11	0,1952	0,0038	3	0,3381	0,0065
25	0,1822	0,0035	19	0,3274	0,0063
44	0,1813	0,0035	25	0,2999	0,0058
19	0,1732	0,0033	48	0,2992	0,0058
6	0,1595	0,0031	44	0,2898	0,0056
48	0,1587	0,0031	6	0,2742	0,0053
20	0,1308	0,0025	20	0,2267	0,0044
9	0,1257	0,0024	23	0,1868	0,0036
23	0,0837	0,0016	9	0,1831	0,0035
45	0,0691	0,0013	45	0,1194	0,0023
8	0,0433	0,0008	8	0,0743	0,0014

46	0,0250	0,0005	46	0,0451	0,0009
51	0,0000	0,0000	51	0,0000	0,0000

C.7 Key sector analysis

Table C-3: Key Sector analysis

Sector	Total economic loss for all perturbations/ m SEK
1,00	12979,22
2,00	4927,78
3,00	327,39
4,00	270,51
5,00	5995,75
6,00	40069,46
7,00	2088,10
8,00	831,32
9,00	430,55
10,00	21264,27
11,00	30803,40
12,00	16444,46
13,00	26447,28
14,00	30585,95
15,00	8838,01
16,00	8872,47
17,00	39834,02
18,00	29157,78
19,00	55836,81
20,00	1382,59
21,00	42441,41
22,00	10806,38
23,00	70173,34
24,00	8569,85
25,00	10252,44
26,00	1919,57
27,00	24126,28
28,00	2709,92
29,00	72427,75
30,00	60168,15
31,00	21804,65
32,00	32617,34
33,00	10184,77
34,00	7455,11
35,00	52767,61
36,00	29554,01
37,00	18134,21

38,00	10726,33
39,00	2328,41
40,00	87600,99
41,00	5716,82
42,00	29021,12
43,00	83514,45
44,00	46195,64
45,00	36047,22
46,00	62221,38
47,00	5290,32
48,00	11392,93
49,00	22740,11
50,00	4724,21
51,00	101,80
52,00	165735,33

Table C-4: Key Sector analysis

Sector	Total inoperability for all perturbations
1,00	0,1417
2,00	0,1083
3,00	0,1011
4,00	0,1042
5,00	0,1186
6,00	0,2346
7,00	0,1080
8,00	0,1029
9,00	0,1020
10,00	0,2262
11,00	0,2483
12,00	0,1619
13,00	0,1195
14,00	0,1744
15,00	0,1284
16,00	0,1401
17,00	0,3983
18,00	0,2058
19,00	0,2817
20,00	0,1048
21,00	0,2271
22,00	0,1357
23,00	0,3414
24,00	0,1364
25,00	0,1412
26,00	0,1107
27,00	0,1682
28,00	0,1089

29,00	0,3515
30,00	0,3429
31,00	0,1733
32,00	0,2048
33,00	0,1479
34,00	0,1297
35,00	0,3126
36,00	0,2017
37,00	0,1473
38,00	0,1606
39,00	0,1066
40,00	0,4503
41,00	0,1145
42,00	0,1766
43,00	0,3356
44,00	0,2375
45,00	0,1840
46,00	0,2343
47,00	0,1192
48,00	0,1315
49,00	0,1769
50,00	0,1118
51,00	0,1000
52,00	0,1000

C.8 Dependency analysis

Table C-5: Dependency analysis

Sector	Total economic loss for all perturbations/ m SEK
S52	292455,66
S43	106587,46
S40	84164,17
S29	59622,89
S35	47546,57
S46	45432,44
S32	41070,60
S23	40859,09
S19	38194,64
S17	36167,08
S30	35294,98
S44	33275,90
S21	31950,69
S27	31133,60
S36	30265,85

S6	30228,66
S42	30116,06
S18	29384,07
S14	28288,48
S13	27892,60
S45	25738,74
S11	21741,24
S37	21386,48
S10	19622,89
S49	19314,40
S31	19305,01
S12	19282,00
S1	13722,18
S38	10624,54
S16	9653,17
S2	9282,12
S15	8860,67
S48	8780,58
S5	8662,32
S24	8312,29
S22	8267,69
S33	7646,63
S25	7609,34
S47	7394,99
S41	6915,52
S34	6729,05
S50	4130,96
S28	4049,54
S39	3205,46
S26	2325,22
S7	1808,74
S20	896,46
S8	619,15
S9	342,03
S4	341,55
S3	252,71
S51	101,80

Table C-6: Dependency analysis

Sector	Total inoperability for all perturbations
26	0,2963
4	0,2740
47	0,2663
28	0,2629
32	0,2569
39	0,2469

12	0,2410
2	0,2396
43	0,2349
5	0,2244
16	0,2161
34	0,2141
41	0,2125
36	0,2088
10	0,2079
17	0,2077
35	0,2060
18	0,2038
24	0,1954
15	0,1936
37	0,1919
27	0,1875
1	0,1859
42	0,1816
13	0,1786
33	0,1784
30	0,1765
52	0,1765
14	0,1708
40	0,1700
49	0,1666
31	0,1660
38	0,1658
21	0,1650
11	0,1547
29	0,1539
23	0,1498
22	0,1478
19	0,1439
6	0,1393
7	0,1383
50	0,1344
25	0,1338
3	0,1338
44	0,1309
48	0,1303
20	0,1233
9	0,1195
45	0,1127
8	0,1077
46	0,1066
51	0,1000

C.10 Air transport disturbance

Table C-7: Economic loss

Sector		Economic loss / m SEK
S1	7,58	0,02
S2	4,41	0,01
S3	0,11	0,00
S4	0,20	0,00
S5	6,51	0,02
S6	12,52	0,03
S7	1,09	0,00
S8	0,24	0,00
S9	0,10	0,00
S10	15,40	0,04
S11	12,80	0,04
S12	26,52	0,07
S13	547,87	1,50
S14	25,55	0,07
S15	8,47	0,02
S16	8,99	0,02
S17	22,27	0,06
S18	28,92	0,08
S19	37,43	0,10
S20	2,01	0,01
S21	30,66	0,08
S22	4,77	0,01
S23	28,90	0,08
S24	153,54	0,42
S25	4,92	0,01
S26	2,29	0,01
S27	39,87	0,11
S28	3,31	0,01
S29	47,95	0,13
S30	110,83	0,30
S31	32,40	0,09
S32	293,44	0,80
S33	31,94	0,09
S34	3193,18	8,75
S35	806,11	2,21
S36	42,85	0,12
S37	32,75	0,09
S38	10,62	0,03
S39	5,13	0,01

S40	83,51	0,23
S41	204,63	0,56
S42	63,43	0,17
S43	215,73	0,59
S44	24,09	0,07
S45	9,16	0,03
S46	10,40	0,03
S47	8,45	0,02
S48	6,57	0,02
S49	22,32	0,06
S50	4,49	0,01
S51	0,00	0,00
S52	1157,88	3,17

Table C-8: Inoperability

Sector	Inoperability
S34	0,1016
S41	0,0063
S24	0,0036
S13	0,0035
S35	0,0035
S32	0,0018
S33	0,0007
S52	0,0007
S30	0,0006
S43	0,0005
S39	0,0004
S42	0,0004
S12	0,0003
S47	0,0003
S36	0,0003
S37	0,0003
S26	0,0003
S31	0,0003
S20	0,0003
S27	0,0002
S28	0,0002
S16	0,0002
S18	0,0002
S49	0,0002
S15	0,0002
S40	0,0002
S5	0,0002
S38	0,0002
S10	0,0002
S21	0,0002

S4	0,0002
S14	0,0002
S50	0,0001
S19	0,0001
S17	0,0001
S29	0,0001
S2	0,0001
S23	0,0001
S1	0,0001
S48	0,0001
S44	0,0001
S11	0,0001
S25	0,0001
S22	0,0001
S7	0,0001
S3	0,0001
S6	0,0001
S8	0,0000
S45	0,0000
S9	0,0000
S46	0,0000
S51	0,0000

C.9 Agriculture disturbance

Table C-9: Economic loss

Sector		Economic loss / m SEK
S1	8201,77	22,47
S2	11,18	0,03
S3	0,50	0,00
S4	10,25	0,03
S5	16,29	0,04
S6	611,68	1,68
S7	1,94	0,01
S8	0,31	0,00
S9	0,11	0,00
S10	39,81	0,11
S11	27,12	0,07
S12	23,02	0,06
S13	373,17	1,02
S14	383,38	1,05
S15	14,56	0,04
S16	41,38	0,11
S17	38,83	0,11

S18	44,35	0,12
S19	126,45	0,35
S20	0,50	0,00
S21	24,80	0,07
S22	6,22	0,02
S23	23,05	0,06
S24	6,78	0,02
S25	3,59	0,01
S26	3,35	0,01
S27	148,35	0,41
S28	3,38	0,01
S29	152,48	0,42
S30	78,64	0,22
S31	19,02	0,05
S32	74,83	0,21
S33	8,03	0,02
S34	10,62	0,03
S35	83,04	0,23
S36	55,33	0,15
S37	84,20	0,23
S38	46,70	0,13
S39	10,92	0,03
S40	57,12	0,16
S41	12,87	0,04
S42	28,49	0,08
S43	200,84	0,55
S44	30,69	0,08
S45	6,48	0,02
S46	51,09	0,14
S47	14,43	0,04
S48	9,70	0,03
S49	12,70	0,03
S50	2,36	0,01
S51	0,00	0,00
S52	1742,50	4,77

Table C-10: Inoperability

Sector	Inoperability
S1	0,1111
S4	0,0082
S6	0,0028
S13	0,0024
S14	0,0023
S52	0,0011
S16	0,0009
S27	0,0009

S39	0,0008
S37	0,0008
S38	0,0007
S47	0,0005
S19	0,0005
S32	0,0005
S43	0,0004
S26	0,0004
S5	0,0004
S10	0,0004
S41	0,0004
S29	0,0004
S30	0,0004
S36	0,0004
S35	0,0004
S34	0,0003
S15	0,0003
S18	0,0003
S2	0,0003
S12	0,0003
S3	0,0003
S17	0,0002
S28	0,0002
S11	0,0002
S33	0,0002
S42	0,0002
S31	0,0002
S24	0,0002
S7	0,0001
S48	0,0001
S21	0,0001
S44	0,0001
S46	0,0001
S40	0,0001
S22	0,0001
S49	0,0001
S23	0,0001
S50	0,0001
S20	0,0001
S25	0,0001
S8	0,0001
S9	0,0000
S45	0,0000
S51	0,0000