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Modelling of Critical Infrastructure Interdependencies for Vulnerability Analysis

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Interdisciplinary Graduate School
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A thesis submitted to the Nanyang Technological University

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Abstract

Critical infrastructures are systems required for producing and distributing essential goods and services needed for the proper functioning of a city or state. These infrastructures function in collaboration with one another, forming an interconnected networked structure with resulting interdependencies that make them potentially vulnerable to significant impact and disruption due to physical or other forms of hazards. This thesis describe a critical infrastructure interdependency model that analyses the interdependencies accordingly, based on a Leontief input-output model that is generalizable to almost all forms of critical infrastructure systems. To demonstrate its applications, two case studies (Singapore Pulau Bukom refinery fire in 2011 and Japan Tohoku earthquake in 2011) are presented to demonstrate how the model can be used to compute how the disruption/impact in one infrastructure sector cascades to other sectors. Next, the critical infrastructure interdependency model is extended to accommodate features of a physical critical infrastructure, such as their topological network structure, so as to enhance the model's applicability to real world disruptive scenarios, such as a terrorist attack on one or more entities within the network. Scenarios involving a single physical infrastructure network as well as two physical infrastructure networks have been analysed and implemented in a software environment to simulate various possible scenarios of a disruptive event and provide the overall impact in terms of economic losses. Finally, the model is used for all types of critical infrastructures at a national scale to analyse worst case scenarios possible if an area of a specified size is being disrupted by some hazard (e.g. a dirty bomb). The developed model helps to provide a better understanding of the severity and extent of the disruptive scenarios and serves as a quick and cost effective decision deployment tool for use by relevant stakeholders.

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Nomenclature

Symbol	Definition
n	Number of sectors
x_i	The total output of sector *i*
z_{ij}	The intermediate sales by sector i to all other sectors *j*
f_i	The final external demand for goods and services produced by sector *i*
Z	The input-output table
F	The final demand of all sectors
X	The total output of all sectors
a_{ij}	Leontief's technical coefficient
A	The direct requirement matrix
$(\mathrm{I}-\mathrm{A})^{-1}$	The total requirement matrix or interdependency matrix
ΔX	The change in overall impact for all economic sectors due to the cascading impact from ΔF
ΔF	The change in final external demand due to disruptive event
Δx_i	The change in overall impact for all economic sectors due to the cascading impact from ΔF in sector *i*
Δf_i	The change in final external demand due to disruptive event in sector *i*
η	The efficiency of the network
v	The set of nodes in the network
d_{ij}	The shortest path length between nodes *i* and *j*.
e_{loss}	The resultant percentage change in network performance
w_{loss}	The monetary loss per day for sector *i* due to the e_{loss}
φ_i	The latitude of point *i*
λ_i	The longitude of point *i*
R	the Earth's radius

c	The angular distance in radians of Earth
d	The distance between two points on the Earth’s surface

Chapter 1 Introduction

1.1 Infrastructure systems

In the modern world, infrastructure is a network of independent man-made systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services (The President's Commission on Critical Infrastructure Protection, 1997) essential to the defence, economic security and the smooth functioning of the government and the society as a whole. Critical infrastructure is a term usually used to describe assets that are essential for the functioning of a society and economy. Infrastructure is typically planned, built, and managed in dedicated systems of assets, such as in electricity power grids, water network grids and public transport network systems, and can be publicly or privately owned, as shown in Figure 1. Reliable access to these services enables positive economic development. However, these systems can also negatively impact the nation as a result of resource depletion, pollution or even the inaccessibility to infrastructure due to disruptive events. Therefore, as infrastructure systems impact countries on a national scale, the assessment of negative impacts brought about by the inaccessibility to critical infrastructure is pivotal (Ton & Wang, 2015). Additionally, there is also a need to account for future long-term impacts to the economy, which arise due to the inaccessibility to critical infrastructure. For example, a nation that heavily relies on its telecommunication network will be substantially affected in the event of a disruptive event that causes the failure of a part of the telecommunication network. Similarly, such incidents can also happen to the electricity, water and transportation critical infrastructure, causing a major economical impact and disturbance to the society.

Critical infrastructure, which among others includes electrical, water, transportation and financial critical infrastructure, has been in the spotlight in recent years due to the immense amount of attention drawn to various major events ranging from man-made disasters (e.g. the terrorist attacks on 11 September 2001 in the United States) to natural disasters (e.g. the 2005 Hurricane Katrina and the 2011 Tohoku Earthquake) that caused significant damage to the well-being of the societies. These events usually cause a domino effect that affects other infrastructure.

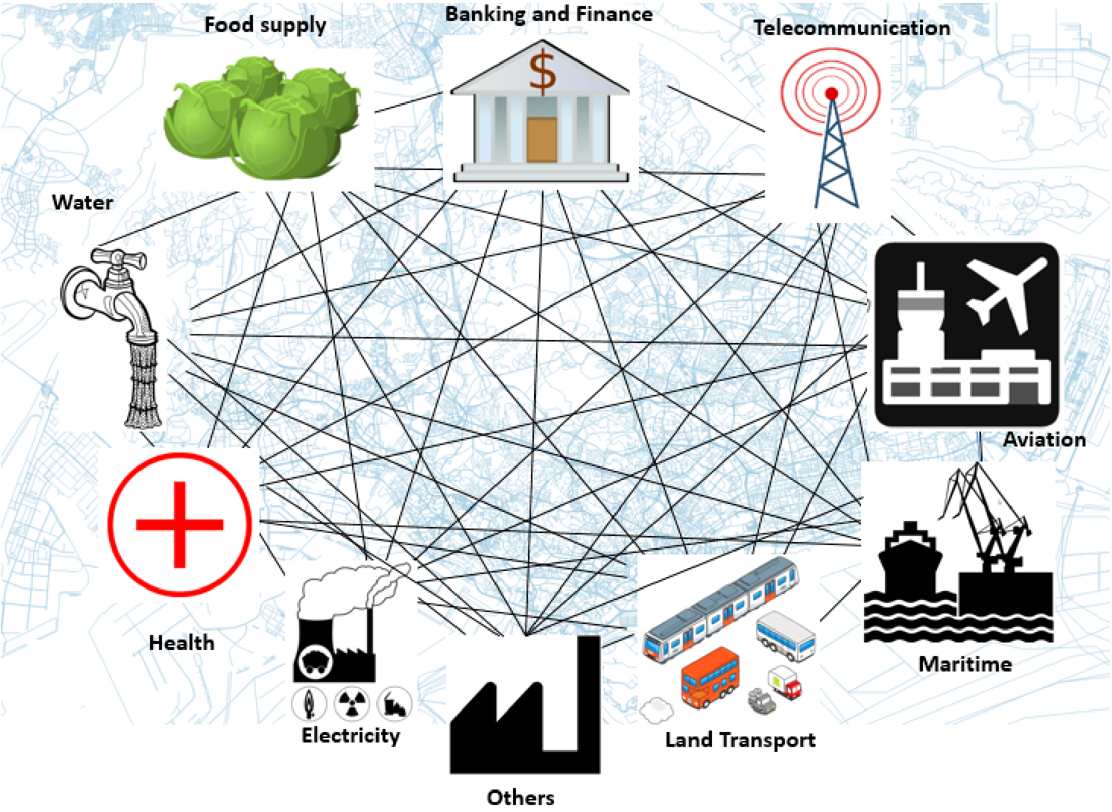


Figure 1-1: Critical infrastructure are interconnected to each other in a nation

However, critical infrastructure is growing in complexity (Sterman, 1994) as new technologies emerge, and the cooperation among such infrastructure is becoming more complex in terms of asset management, national security and infrastructure protection (Bush et al, 2005). These systems come together to create a complex network of interdependent critical infrastructure, which experience cascading (domino) effects in the event of a catastrophic disruption that affects some part of the network. Two infrastructure are termed ‘interdependent’ when one’s successful operation relies on the other. It is necessary to take into account these relationships, or ‘interdependencies’, in any model so that potential weaknesses to a disruptive event in combined sets, or networks, of infrastructures can be identified (Haimes et al., 2008).

A failure in any of the critical infrastructure would likely have an enormous impact on one or all of the following aspects of the society: health, safety, security, economic, social well-being and the functioning of the government. (Conrad et al., 2006) The failure of critical infrastructure is thus undesirable, due to the significant inconveniences and extensive financial losses caused to the society.

Many countries have also turned their attention to the potential aftermath effect from a disaster. The United States was the first country to make a stand to focus on critical infrastructure protection with the publication of “Critical Foundations: Protecting America’s Infrastructure” in 1997 (The President’s Commission on Critical Infrastructure Protection, 1997). The findings of this report placed emphasis on the possibility of devastating effects caused by a lack of knowledge of critical infrastructure. The report recommended different measures to enable a higher level of resilience in the critical infrastructure, which includes industry cooperation – particularly in information sharing (Pant et al., 2014; MacAskill & Guthrie, 2014)). The European Council began a similar focus in 2004, which was published in a report called the “Critical Infrastructure Protection in the fight against terrorism” (European Commission, 2004). It led to a council directive for the identification and designation of European critical infrastructure and the assessment of the need to improve their protection.

1.2 Disruptions that motivate current research

This section provides background on natural disasters and man-made disruptions that cause huge economic impact on a nation. These examples of case studies mentioned below are not exhaustive, and other countries share similar challenges in terms of natural disasters and man-made disruptions.

The Hurricane Katrina is an example of an event that triggers domino effects. Hurricane Katrina struck the states of Louisiana, Mississippi, and Alabama on 29 August 2005. The aftermath of this disaster demonstrated the far-reaching effects of a natural disaster on a community when basic societal needs are not met promptly. The Bush Administration spent US$105 billion on repairs and reconstruction in the region, making Hurricane Katrina the costliest natural disaster in US history at that point in time (St. Onge & Epstein, 2006). Commercial, residential, critical infrastructure building were physically affected. In particular to critical infrastructure, electric utility (broken electricity line), land road transportation (damaged road system), water utility (contaminated water) were reported to have an estimated losses of USD$231 Million, USD$3 Billion and USD$1 billion at that time point respectively (without consideration of any potential cascading impact to other economic sectors). However, one study estimated the total economic loss in Louisiana and Mississippi to exceed approximately US$150 billion (Burton & Hicks 2005). The study showed that in damage loss assessment, both direct and indirect effects of the disaster affected the economy financially, and how a disaster could affect an economic sector, cascading its impact to affect the other economic sectors through the first affected economic sector (although there was no particular mention of the detailed monetary figure on the direct or indirect effects, respectively). The magnification of the disruption as a result of the interconnecting infrastructures caused a large impact on the fuel, agriculture export, gambling and tourism industries. This disaster also exposed the weaknesses in the processes relating to the government’s response to disasters (The Economist, 2005).

Another example is the 9/11 terrorist attacks in the United States. These attacks comprised of a series of four coordinated attacks planned and executed by the Islamic terrorist group Al-Qaeda in New York City and the Washington, D.C. metropolitan area on Tuesday, 11 September 2001. This event had caused great havoc in economic sectors in United States, particularly in the banking and the commercial sector (due to drop in public confidence from the terrorist attack), and direct infrastructure damages to building. This man-made disaster caused an overall drop in passenger enplanement (Federal Aviation Administration, 2003) and a 3.5% reduction in total hotel room demand (Ernst and Young, 2002) relative to the 2000 estimates.

Singapore has also suffered from certain forms of disruption. Singapore’s mass rapid transit system had recently seen an increase in the frequency of breakdowns, causing huge inconveniences for commuters. As a result of breakdowns, affected passengers seek other forms of transportation, leading to an increased demand for other modes of road transportation, and thus greater congestion. Investigations into the breakdowns had been conducted by the authorities which took approximately three months for the identification of the problem. A single fault point, which was a “rogue” train in the train system (LTA, 2016), caused other trains within its proximity to lose their communication signals and triggered a safety feature in the transportation system, thus causing the train to halt and resulting in the breakdown.

A common observation from the examples discussed was that they showcased how disruptions (or disasters) were able to affect different infrastructures. In fact, the amplification of the after-effects is the consequence of the interconnection among the different infrastructures (Min et al, 2007). In this sense, it is logical to think that real networks do not work independently, and require interaction with some other infrastructure network to be operational.

The growing trend of public-private partnership (Tiong & Anderson 2003) for the management of infrastructure projects and information technology has increased interconnectedness and interdependencies between critical infrastructures. Therefore, two problems arise (Zimmerman, 2001). The scale of the network of infrastructure becomes too huge and interconnected, making analysis of the infrastructure difficult. Additionally, as the scale of the network of infrastructure increase, there will be more interconnected infrastructures from other critical infrastructure systems, thus increasing the potential of a cascading impact to other infrastructure systems and the overall complexity in the management of the risk analysis (Marti, 2014; Kaplan & Garrick, 1981). The lack of visibility of the interdependent critical infrastructure motivate us to seek to understand large-scale critical infrastructure and their complexity.

1.3 Research issues

As illustrated in the above real world examples of disruptive events, interdependency is a major concern in critical infrastructure. Interdependency refers to the links between critical infrastructures and their associated strength of dependency on one another. In consideration of the disruptions mentioned previously, this research seeks to answer the following research questions:

1) What is the network relationship (interdependence) between critical infrastructures?
2) How do we simulate the impact of a hazard within a critical infrastructure network system, and how will this impact propagate to other critical infrastructure?

3) How do we analyse two or more critical infrastructures that happen to fail simultaneously?
4) How do we analyse and simulate the worst case scenario, and thereby identify the most critical parts of a critical infrastructure network?

1.4 Research approach and methodology to counter the problems

In this thesis, the objective is to develop a quick and inexpensive critical infrastructure interdependency model that can be useful for the provision of good estimates of the impact on the whole critical infrastructures of a city or state due to disruptions in any part of the critical infrastructure system. The methods that will be taken to achieve this objective are:

1) An investigation of the possible data required in modelling the critical infrastructure model
2) A comparison and analysis of the results evaluated from the critical infrastructure model based on case studies, so as to demonstrate the feasibility of the critical infrastructure model
3) An embedment of the physical infrastructure network with the critical infrastructure model to analyse the impact of a hazard and its propagation
4) An analysis of a geographically-based hazard and its area of impact on all critical infrastructures

1.5 Outline of thesis

This thesis is structured into eight chapters including this introductory chapter on critical infrastructure. Chapter 2 reviews the literature on the topics of critical infrastructure interdependency, reviews the methods used and compares the techniques adopted by other researchers. Chapter 3 explains the Leontief’s input-output model as a base for the critical infrastructure interdependency model. It formulates an input-output model and describes how critical infrastructure can be modelled by an input-output model. Chapter 4 uses the critical infrastructure interdependency model and simulates cases studies like the Singapore Pulau Bukom island fire and the effects of the Tohoku Earthquake on the electricity sector in Japan. The work done in Chapter 4 aims to prove and validate the critical infrastructure interdependency model for use in the later chapters. Chapter 5 describes research work that incorporates a physical infrastructure network into the critical infrastructure interdependency model. Through this type of modelling, a physical infrastructure failure can be modelled into the critical infrastructure interdependency model, making the analysis more relevant to the real world. Chapter 6 expands on this work by modelling two physical infrastructure systems into the critical infrastructure interdependency model and analysing the simultaneous physical infrastructure failures, which proves to be useful towards analysing worst case scenarios. Chapter 7 attempts to model all critical infrastructures in a nation and simulates geographically-based hazards to evaluate the worst case scenario in the occurrence of a hazard in a nation. Lastly, Chapter 8 concludes this thesis and summarises the work done and the original contributions of this paper.

Chapter 2 Literature Review

There are diverse literatures in this area of research, highlighting the interdisciplinary nature of this work. The purpose of this chapter is to review the existing research work from these literatures and indicate some of the gaps that this research attempt to fill. The chapter begins with a description and definition of critical infrastructure and the existence of interdependencies. Next, the chapter describes the literature in modelling infrastructure interdependencies and argues that these metrics and techniques alone are insufficient to provide a good representation of the economic impact on a nation due to research gaps. Finally, a potential research method will be proposed to deal with the gaps.

2.1 Critical infrastructure and its interdependencies

Society relies on the continuous supply of goods, such as energy, and services like banking and the Internet. Infrastructures are more than just a handful of companies engaged in such related activities. They are a network of interdependent, man-made systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services (The President's Commission on Critical Infrastructure Protection, 1997). Infrastructures are critical because their failures would result in debilitating impacts on the health, safety, security, economies and social well-being of the societies and the effective functioning of governments (Alcaraz & Zeadally, 2015).

When examining multiple infrastructures that are connected to each other, we must consider their interdependencies. Interdependency is a bidirectional relationship between two infrastructures, through which the state of each infrastructure influences the state of the other infrastructure through connections. These complex relationships create multiple connections (as a form of physical/non-physical linkages) among infrastructures (National Research Council, 2009). Depending on the characteristics of this linkage, it can transmit impacts through the linkage to other infrastructure. In order to understand and analyse the behaviour of a given infrastructure, the knowledge of the surrounding infrastructure that are connected to the given infrastructure is required (Laugé et al., 2015). In essence, through the interconnections between the infrastructures, any problems that arise in one infrastructure affect many other infrastructures within the same network. Hence, it is essential to understand the behaviour of the entire network of infrastructures, instead of just any single part of it. The need for comprehensive information on the entire infrastructure concerned thus becomes one of the hurdles of critical infrastructure network analysis.

As mentioned by Guckenheimer (2008), infrastructure systems must be analysed as a whole, and the decomposition and analysis of single subsystems do not necessarily provide clues to the behaviour of the whole. Zimmerman (2001) mentioned that “technological changes have improved the provision of services of transport, water, electricity, and communications, often transforming the way we live, while, at the same time substantially increasing the fragility and vulnerability of these systems and the services they provide by making them more complex and interdependent”. This statement further acknowledges that critical infrastructure nowadays are relatively more interconnected, which in turn increases the vulnerability of infrastructure due to its interconnected nature (Johansson & Hassel, 2010).

2.2 Definition of interdependencies

As discussed in the examples of disruptive events in the previous chapter, interdependency is a major concern in critical infrastructure. Interdependency refers to the links between critical infrastructures and their associated strength of dependency on one another. The linkage between components of infrastructure in different sectors is highly critical for the optimal and economic operation of various infrastructures and can improve the operation and performance of these infrastructures in many ways. However, the interconnectedness or interdependency can also introduce more weaknesses into the interdependent networks. Therefore, apart from understanding the performance of a single sector of the infrastructure network, there is a need to understand the functioning and behaviour of its interdependent/interconnected infrastructures (Vespignani, 2010).

There are several ways of describing infrastructure interdependencies. One of the most widely used methodologies was created by Rinaldi et al. (2001), which defined six main dimensions of interdependencies between critical infrastructures. They are listed below:

1) Type of interdependencies (Physical, Cyber, Geographic, Logical)
2) Environment (Business, Public Policy, Security, Health/Safety, Economic, Legal/Regulatory, Technical, Social/Political)
3) Coupling and Response Behaviour (Linear/Complex, Loose/Tight, Adaptive, Inflexible)
4) Type of failure (Common Cause, Cascading, Escalating)
5) Infrastructure characteristics (Organizational, Operational, Temporal, Spatial)
6) State of operation (Repair/Restoration, Stressed/Disrupted)

A closer examination of the four types of the interdependencies identified by Rinaldi et al. (2001) is provided below.

1) Physical interdependencies are related to the production of materials or services used by others. The risk of failure in the normal operating conditions of one infrastructure is a function of the risk in another infrastructure.
2) Cyber interdependencies occur when the state of an infrastructure depends on the information transmitted through the information infrastructure. In this complex system, control of a networked system is dependent on the transmission of information.
3) Geospatial interdependencies involve the physical proximity of one infrastructure to another. An event such as a catastrophic event in an urban area can create simultaneous disruptions in other infrastructures, such as the communication and electrical services to a city.
4) Logical interdependencies contain all other kinds of interdependencies. For example, they can be economic or political, and are basically interdependencies that are not covered under the umbrellas of the physical, cyber and geospatial interdependencies.

Other than Rinaldi et al., other researchers have tried to define their own interdependency types as well. For example, Zimmerman (2001) defined functional interconnectedness and spatial interconnectedness as interdependency types. Taking functional interconnectedness as an example, a failure in the telecommunication sector can extend beyond disrupting the telephone service, to disable air traffic control or mass land transportation control (Omer et al., 2009). In Zimmerman (2001), an example of spatial interconnectedness can mean that, by design, the distribution lines from different utility systems in a country are in close proximity to one another, therefore creating an interconnection between different utility systems. Although they may not be physically connected, they share the same distribution pathway (for example, an underground utility distribution network). According to Wallace et al. (2003), interdependencies are associated with one or more of the following:

1) Input requirements: When one infrastructure depends on input, generally services, from another in order to function, e.g. many parts of transportation infrastructure require an electricity supply to operate.
2) Shared resources: When more than one infrastructure rely on the same physical components or activities, e.g. roads are not only used for transportation but are also used by the emergency services and electricity companies.
3) Exclusive operation: When only one infrastructure can use a particular service at any given time, e.g. a portable generator may only be allowed to be used for emergency services or telecommunications at any one time.
4) Geographical location: When the physical components or activities of more than one infrastructure are located at the same place, e.g. ICT and financial operations are carried out within the same building. The defined location can vary in size from the same room or floor to a city block or larger.

Infrastructures are considered independent if none of the four criteria defined above apply. Otherwise, the infrastructure is considered to be interdependent to some degree with at least one other infrastructure and if a disruption occurs it will affect more than one infrastructure.

There are also other definitions of interdependency given by Dudenhoeffer et al. (2006) and Zhang & Peeta (2011). However, all types of interdependency are just mere descriptions of how one infrastructure is interconnected to another infrastructure.

Moreover, the vast number of definitions actually diversifies the research focus, as different definitions of interdependency will lead to different approaches and requirements to tackle and investigate the notion of interdependency. On the other hand, Mussington (2002) states that one of the shortfalls in the knowledge of critical infrastructure protection is the incomplete understanding of interdependencies among infrastructure systems, which makes the direct implementation of any interdependency defined by researchers like Rinaldi et al. (2001) or Wallace et al. (2003) difficult.

Critical infrastructures are also categorized differently accordingly to the context and level of criticality of different countries. In this thesis, Singapore is used as an example to demonstrate the critical infrastructures categorization in Singapore. In general, Singapore has categorized critical infrastructures (National Security Coordination Centre, 2004; Ho, 2005) as shown in Table 2-1.

Table 2-1: Different categories of critical infrastructure in Singapore

No	Name of critical infrastructure	Description
1	Banking and Finance	All banking and finance products and service
2	Telecommunication	Telecommunications products and services
3	Electricity	Electricity
4	Water	Water & Sewerage
5	Land Transport	Land transport & supporting services
6	Healthcare	Medical and health services
7	Food supply	All food products
8	Air transport	Air transport & supporting services
9	Sea transport	Water transport & supporting services
10	Petrochemical	Petrochemicals & its products

2.3 Evidence of interdependencies

In normal operations, some interdependencies are not apparent at all. However, under some disruptive scenarios, they emerge and become obvious. In order to reveal such interdependencies, researchers have conducted studies showing such interdependencies that emerge due to extreme events.

2.3.1 9/11 terrorist attacks

Mendonca & Wallace (2006) investigated the impact of the 2001 World Trade Centre attack on critical infrastructure systems in the New York City metropolitan area. The results illustrated the effect of an attack on all of the infrastructure systems considered. The infrastructure systems considered are emergency services, transportations, information & communications, electric power, banking & finance, gas & oil related services, water supply systems and government services. Approximately 20% of these reported disruptions to the infrastructures involved interdependencies. These disruptions were caused by an indirect impact from the initial terrorist attack (the direct impact). The authors also highlighted that for the infrastructure systems considered, indirect impacts arose as a result of interdependencies among infrastructures. The study aimed to identify incidents which resulted in the disruption of critical infrastructures and the corresponding services and interdependencies between critical infrastructures which were affected.

The study generally found that the number of reported service disruptions from the eight critical infrastructures were relatively high compared to the subsequent weeks. The reported disruptions persisted throughout the 13 weeks of the period of study but showed a general diminishing trend. During the first few days, transportation, government services and banking experienced the most disruption whereas oil, gas and water supplies were little affected. In fact, reported disruptions to banking far outnumbered those related to emergency and other services including water, power, oil and gas. It can thus be argued that infrastructures were affected in different ways and on different timescales. The majority of all possible pairwise interdependencies observed were significant. There was no correlation between infrastructure types and their interdependency types in the study. This statement actually hints that the interdependencies between infrastructures may have been hidden from the researchers, amounting to an amount of 20% economic impact to the interdependency of the critical infrastructures. Although 20% seems to be a small percentage, the study also mentioned the possibility of the understatement of disruptions and cover-up issues, which may further add to the amount of possible disruptions concerning interdependency.

2.3.2 2003 North American Blackout

On 14 August 2003, large areas in the midwest and northeast parts of the United States and Ontario, Canada, experienced an electric power blackout. The outage affected areas with an estimated population of 50 million people and 61,800 megawatts (MW) of electric load in the states of Ohio, Michigan, Pennsylvania, New York, Vermont, Massachusetts, Connecticut, New Jersey and neighbouring Canadian province, Ontario. The power was not restored for as long as four days in some parts of the United States. Certain areas of Ontario also suffered rolling blackouts for more than a week before full power was restored. The total costs incurred as a result of power outage in the United States were estimated to be between US$4 billion and US$10 billion (Electricity Consumers Resource Council (ELCON), 2004). In Canada, the gross domestic product dropped by 0.7% in August and manufacturing shipments in Ontario decreased by CA$2.3 billion (U.S.-Canada Power System Outage Task Force, 2004).

In a report by the US-Canada Power System Outage Task Force (2004), the outcomes of an investigation conducted on the outage to determine its causes and the reasons why it was not contained was documented. Apart from some violations of standards that triggered the blackout, the report listed the phasing in which the cascading failure occurred. The origin of the blackout was the shutdown of two power production anchors from FirstEnergy (the power station of concern) on a normal afternoon when electricity requirement was moderately high. There was also a loss of one other power production anchor (Eastlake 5) unit, which played a significant factor in the outage. FirstEnergy’s control computer started to fail thereafter, leading to the failure of three 345-kV transmission lines. Thereafter, the collapse of a 138-kV system and further cascading failures of transmission systems led to the North American Blackout.

Evident in the above example, the simple failure of a single electric production unit could lead to a collapse of a large network of electrical transmission systems. The hidden dependency caused large economic losses to the North American economy due to the failure in the electric production unit. Judging from the above event, it can be noted that disruptions are usually accompanied by a high price tag in terms of economic losses brought about by the hidden interconnection effect of critical infrastructures. This interconnection effect is what researchers’ term “interdependencies”.

2.4 Existing conceptual and qualitative studies

Before reviewing the modelling and simulation approaches of critical infrastructure interdependencies, their conceptual and qualitative studies should first be looked into. These studies often provide the definitions of critical infrastructure systems, their interdependencies and offer organisational and administrative strategies to better protect these critical infrastructures and illustrate their modelling complexity. These studies are also usually accompanied with some examples used by different institutions around the world. Most of the time, they do not provide any details on the modelling and simulation approaches used to analyse the critical infrastructures, but rather point out what can be done using their software or approaches.

Government reports usually belong to this type of conceptual studies. For example, a report by the United States under The President's Commission on Critical Infrastructure Protection (1997) documented a review on critical infrastructure protection. It recommended a series of strategies and policies for critical infrastructure protection, such as the establishment of cooperation and information sharing among infrastructure stakeholders. Furthermore, it recommended the instilment of the idea of infrastructure protection for the relevant stakeholders, reforming laws to enhance infrastructure protection and initiating programmes for research and development into the technology and tools needed for infrastructure protection. The European Programme for Critical Infrastructure Protection (European Commission, 2004) also started similar conceptual studies, provided protection measures like the establishment of a critical infrastructure warning information network. Based on critical infrastructure system expert groups at the European Union level, the European Commission encouraged critical infrastructure information sharing, identification and analysis of critical infrastructure interdependencies. Japan set up the Japanese National Information Security Centre (NISC) in April 2005. One of Japan's main aims was to enforce critical information infrastructure protection. Australia conducted similar studies on critical infrastructure resilience strategies and recognised that the best way to enhance critical infrastructure resilience was through the partnership with critical infrastructure stakeholders (Biringer et al., 2013; Reed Kapur & Christie, 2009; Panteli & Mancarella, 2015). This would raise awareness of infrastructure interdependencies and their vulnerabilities (Haimes, 2006), thus facilitating collaboration and information sharing, so that a better understanding and analysis of interdependencies could produce effective critical infrastructure protection.

Government reports generally provide detailed organisation and administrative protection strategies. However, they do not study the specific techniques needed to realise the modelling and simulation of critical infrastructure interdependencies for the assessment of strategy effectiveness and create decision support uses (Hansman et al, 2006). Researchers from universities and institutions have tried to come up with methods to realise infrastructure protection strategies. Bologna & Setola (2005) proposed many recommendations to increase situational awareness, such as preparation for the worst and the identification of common mode failure events. Biriere (2011) recommended the establishment of a “fusion centre” that would facilitate cooperation and coordination among different critical infrastructure systems. With the fusion centre as a centralised information sharing medium, a unified preparation and mitigation effort can be created. The fusion centre will enables rapid restoration of critical infrastructure in the event of any emergency event. Apart from that, other researchers (Zimmerman 2001; Rinaldi 2001; Wallace et al 2003; Dudenhoeffer et al 2006; Zhang & Peeta 2011) have also proposed ways to describe interdependencies, which is detailed in Section 2.2.

On the whole, conceptual and qualitative studies have motivated research on critical infrastructure interdependencies. It has paved the way towards a better understanding of critical infrastructure interdependencies and its analysis and modelling to devise protection strategies for critical infrastructure. These efforts have motivated the research community to delve deeper into the development of a model that would effectively capture critical infrastructure information and establish the relevant interdependencies. With the establishment of interdependencies, the behaviour of the critical infrastructure and their interdependencies can be simulated and analysed.

2.5 Literature review of the modelling approaches in infrastructure interdependencies

The modelling of multiple infrastructure systems is difficult because a single infrastructure system is already very complex and difficult to understand. The attempt to combine various infrastructures adds an extra dimension of complexity to the problem, and is not trivial (Satumtira & Dunas-Osorio 2010). The interdependency studies of multiple critical infrastructures are usually carried out using predictive methods or empirical approaches. Predictive methods include agent-based simulation approaches, input-output approaches and network approaches and other approaches. Empirical methods aim to study past disruptive events in order to predict the underlying infrastructure interdependencies based on the disruption.

2.5.1 Empirical approaches

Critical infrastructure network analysis is usually done by analysing interdependencies in the network according to historical accidents, disaster data and expert experience on the critical infrastructure. It can identify significant failure patterns and quantify interdependency strengths in the network. This will enable a more informed decision making process for infrastructure owners and allow the provision of a risk analysis (Kröger, 2008) on the infrastructures that might be affected by possible disasters. Pederson et al. (2006) provided an examination of this class of approaches up to the year 2006. The survey identifies approximately thirty models created for use in this area and reviews their characteristics and capabilities.

It is usually highly difficult to identify all interdependencies among critical infrastructures under normal operations, because some interdependent relationships are undetectable through standard data collection (Laefer, 2006) or emerge only after the occurrence of a disruptive event (Krimgold, 2006). Therefore, historical events like natural disasters are usually used to identify all the interdependency relationships between critical infrastructures. The understanding of the aftermath of these events is usually achieved through interviews or assessment reports from infrastructure owners and experts, or via incident records collected from different media like newspapers, media reports, and Internet news outlets (Vugrin et al., 2011). Different types of information from the incident reports are all collected and analysed in order to identify the frequency and level of significance of a single disruptive event.

Chang et al. (2009) proposed the creation of a database that was capable of quantifying the consequences and impacts of an interdependency failure in the occurrence of extreme events from a societal point of view. It is characterised by an impact index and an extent index. Based on these two indices, a ratio of impact to extent is calculated to enable the identification of whether the infrastructure failure interdependencies are intensive (causing serious localised damage) or extensive (widespread, but does not cause serious damage). Wallace et al. (2003) also created a database that included three months of incident reports relating to the 9/11 terrorist attacks, in order to analyse the interdependency relationships during the restoration process (Cavdaroglu et al., 2013). The results demonstrated that banking and finance services, along with government and emergency services, were increasingly impacted both directly and interdependently during the restoration process. However, critical infrastructure with physical linkages, such as transportation and power, endured many interdependency-related incidents only during the first week of the restoration (Leu et al., 2010).

Empirical approaches can be used to identify the potentially important interdependencies between critical infrastructures and increase the crisis management capability for infrastructure stakeholders and enhance their ability to respond to future disruptive events (Araneda et al., 2010). However, due to reporting bias, cases of underreporting of interdependency failures may occur, which may have significant effects on the critical infrastructure. Additionally, due to the different types of data collection methodologies employed by different researchers, there is no uniform and standardised way for the collection of information on critical infrastructure interdependencies. This leads to additional work and time needed to analyse the data according to the respective researcher methodologies, as information has to be sorted out from the beginning again. On this note, although the reliance of the empirical approaches on historical events may provide good and accurate predictions of future similar events based on the data gathered, there will still be problems if a completely new disruption occurs as the historical data collected does not have information on the interdependency patterns for the new disruption.

2.5.2 Agent based simulation approach

Due to the level of complexity involved in modelling large-scale infrastructure systems, simulation becomes a natural choice to address the modelling of infrastructure interdependencies.

Critical infrastructures are usually regarded as complex adaptive systems (CASs) (North, 2001a; North, 2001b; Amin, 2002; Rinaldi, 2004; Little, 2002). In order to model CASs, one way is to use agent-based approaches, which adopt a bottom-up approach and assume that a complex behaviour or phenomenon emerges from many individual and simple interactions of autonomous agents (Kaegi et al., 2009). Each agent interacts with one another and the environment based on a set of rules, which mimic how a real world scenario may happen. Most critical infrastructure components can be viewed as agents, hence the reason why agent-based modelling is widely used to model critical infrastructure interdependencies. The objectives, behaviour and constraints of agents are modelled in the form of rules (Macal & North, 2010; Zhang et al., 2005)

Most agent-based models compose of:

1) Agents at different scales
2) Decision-making heuristics models
3) Learning and adaptive rules
4) Interaction topology
5) Environment parameters

The simulation system creates a real world like environment, allowing each agent to interact with both the environment and other agents, simulating what would happen if there were other events that were introduced into the environment or agent. Casalicchio et al. (2009) and Kaegi et al. (2009) have attempted to use the agent-based modelling approach to model interdependent infrastructures. One of the advantages of agent-based modelling (Zeigler et al., 2000) is that it supports both discrete as well as continuous modelling (e.g. modelling a disruption as a discrete event in an agent-based simulation within a specific time frame).

Agent-based approaches model the behaviours of decision-makers and other system participants in critical infrastructures. They allow the assessment of the effects of various types of interdependencies during defined discrete events (Detty & Yingling, 2000; Legato & Mazza, 2001; Chtioui et al., 2016). A range of scenarios and mitigating actions can be considered. It is also possible to integrate other modelling techniques, so as to conduct a more comprehensive analysis.

However, there is also a downside to this type of approach. Firstly, careful definition of agent behaviours is required as this can significantly affect the quality of the results and such assumptions are usually based on modeller experience and cannot be verified theoretically. The calibration of simulation parameters is also still a challenge in the research world, due to the lack of relevant data and the difficulty in modelling participant behaviour. In most cases, simulations focus on only one type of interdependency, e.g. logical (economic) or physical. Finally, most modelling methods end up as a ‘black box’, and users are thus unable to develop an understanding of the fundamental mathematical nature of the model.

2.5.3 Input-output approaches

Due to the lack of theoretical capabilities of simulation approaches, economic theory has been used to develop mathematical formulation and models. Input-output modelling is one of the main approaches used to conduct this type of interdependency modelling due to its ability to capture interaction among multiple systems.

In 1951, Wassily Leontief proposed the input-output economic model (Leontief, 1951). It was a static and linear model of all purchases and sales between sectors of an economy based on the relationships of production. Based on this input-output model, Haimes and Jiang (2001) proposed a Leontief-based input-output model to formulate the interdependencies among critical infrastructure systems in terms of failure risk. The Leontief input-output inoperability model (IIM) goes by this basic formula (Crowther & Haimes, 2005) $\mathrm{X} = \mathrm{AX} + \mathrm{C}$. In this model, the output x_i represents the risk of inoperability, which is defined as the inability of a critical infrastructure to perform its intended functions. a_{ij} denotes the probability of inoperability such that the jth infrastructure contributed to the ith infrastructure due to their interconnectedness. c_i refers to the additional risk of inoperability that is inherent in the complexity of the ith infrastructure. Hence, given a perturbation from one or multiple infrastructures or industries of the economy, the IIM can estimate the ripple effects measured by infrastructure inoperability.

The IIM offers a good interpretation of interdependencies and can be used to analyse the inoperability of critical infrastructure due to different types of perturbation. It has been successfully applied to various situations, such as the reduction in demand for air transportation following the terrorist attack on 9/11 (Santos, 2006), the financial and inoperability effects of the US northeast blackout in 2003 (Anderson et al., 2007) and the economic impact of cyber-attacks on the oil and gas sector (Santos et a., 2007; Formicola et al., 2014).

This method allows the user to understand the fundamental mathematical nature of the model, the probabilities associated with disruption and transmission of risk, and any linked impacts. IIM-based models are useful for macroeconomic level or industry sector level interdependency analysis in the aftermath of disruptive events. This model can provide analytical solutions that are useful for parameter sensitivity analysis in future work. However, due to the early stages of its development, this model has several limitations. The first limitation is that each infrastructure system is modelled as a single node in the input-output model, which may not reveal details of the risk transmission at component level. The second limitation is the assumption of a linear risk transmission in the input-output model, which may not be realistic in real world scenarios. When applying the IIM, the assumption made in the Leontief input-output model still applies. Based on the assumption of a constant technology and overall economic structure, when a perturbation occurs, the perturbation is assumed to be not too drastic (perturbation that caused changes to the nation economic structure) to the operations of the infrastructure. Therefore, based on this assumption, the input-output model is good for approximating impact of small perturbations to the infrastructure, but not larger perturbations, which causes the input-output model to fail with large errors, due to the assumption of a constant economic structure.

2.5.4 Network approach

Infrastructure systems are often linked through a network-type structure and many modelling approaches do not reflect this aspect. Network structures can provide a valuable way of assessing physical interdependencies and is suitable for analysing cascading disruption. Since critical infrastructure can be described through its network and the linkage between infrastructures can be used to describe the inter-relations among them, the network approach becomes a natural candidate for interdependency studies. The performance of an infrastructure can be analysed by modelling the component failure from the hazard at a component level, and then simulating the cascading failure within the modelled network at a system level (Tai et al., 2013).

Lam et al. (2013) demonstrated that by modelling the relationships and observing how disruption cascades within a complex infrastructure system, vulnerabilities can be identified, enabling planning for recovery and response. Jeong et al. (2006) and Qiao et al. (2007) developed network-based models to address security issues in water systems. These models treat water systems as networks of plants, storage tanks and transmission links. The graph theory methodology can be adopted to aid in the network analysis, such as the use of connectivity, vertex degree, path length, clustering coefficient and redundancy ratio.

With network approaches, the spatial impacts of potential disruptive events can be examined. They depend on either the probabilities of disruption or the linkages to other network components in the network. As such, it is difficult to determine these linkages using empirical data. Some linkages may be significant and easy to model, but some linkages may be insignificant (in term of their linkage strength) and omitted in the end, causing inaccurate modelling. These network models are also usually static, and the economic perspective of the infrastructure is not taken into account. Therefore, the types of interdependencies that can be modelled are usually limited. One of the main challenges with this type of approach is the variety of infrastructures in each network which need to be considered. Each type of infrastructure within a network has its own flow dynamics which is necessary to capture for simulating the relevant linkages (Lee et al., 2007). For example, a power plant generates and supplies electricity as a flow to other infrastructures, while a waterworks plant generates and supplies water as a flow to other infrastructures. It is difficult to model the two types of flows in a single model.

2.5.5 Other approaches

Besides the above approaches, there are other approaches that model and analyse critical infrastructure interdependencies.

Hierarchical holographic modelling (HHM) is a methodology that helps to identify possible risk scenarios (Haimes, 1981). It can provide an understanding of risk at different levels and a multidimensional view of critical infrastructures with particular regard to the identification of vulnerabilities. Thus, the HMM can be seen as a method within the Theory of Scenario Structuring (Kaplan et al., 2001), as it has a similar function to the failure mode and effect analysis (FEMA) (Kmenta & Ishii, 2005) and the scenario tree (Gülpınar et al, 2004). Through the HMM, multiple mathematical models can be developed and coordinated to create and capture the different perspectives of interdependent critical infrastructures. However, the difficulty in its application to critical infrastructure frameworks has deterred the further development of this technique.

Dong (2002) developed the idea of a 'supernetwork' which combines the transportation, telecommunication, energy and finance networks. This approach is grounded in generalised network theory and employs the inequality technique. However, its calibration and use is still a major hindrance to this approach.

In contrast to other approaches, the HHM and supernetwork approaches have established only the conceptual construction of their own methodology, instead of procedures for real application. Therefore, additional study will be required to enable real-world implementation of these two approaches.

2.6 Limitations of existing model/Potential research gaps

As discussed in Section 2.5, existing approaches lack one or more key features. Firstly, most of the approaches require system calibration, which is difficult because of the difficulty in obtaining confidential data from various infrastructure stakeholders. In order to solve this problem, most researchers source for data through interviews of infrastructure experts and from media records. However, these approaches may not enable the collection of complete data and thus affect the calibration result, which will be an issue. Even if there was expert knowledge involved, there may still be some unforeseen interdependencies between the critical infrastructures that are hard to identify. Secondly, there is no standardised way of data collection, as different methodologies from researchers have different definitions on critical infrastructures and their interdependencies. Thirdly, most approaches focus on a risk modelling perspective and fail to appreciate "business as usual" and "what-if" scenarios. It is very important to look into these two types of scenarios as rapid urbanisation in current times is driving the need for infrastructure owners to look into capacity requirement and to revamp the aging infrastructures in developed countries (Urban Land Institute and Ernst & Young, 2013). With due consideration for infrastructure interdependencies, the two types of scenarios would be able to address the level of resiliency and redundancy required. Therefore, it is crucial to find a modelling framework that can cater to both disruptive and normal equilibrium scenarios (Cimellaro et al., 2010). Fourthly, since the operational, economic and physical characteristics of different infrastructures are totally different, a unified method that encompasses these characteristics is required. Therefore, in order to link all of the critical infrastructures together, a common metric or denomination may be required. In our case, a monetary value is being used. Fifthly, most of the methods are able to cater only to one type of interdependency. A generalised method should be created so that all types of interdependencies can be incorporated. Sixthly, network approaches contain some unique feature, like the network and spatial characteristics of the infrastructure systems, which is not found in other approaches. However, the network approaches that are used in most literature lack the properties to capture the economic perspective of the network of infrastructures of concern.

As discussed, the current research aims to develop a model that provides solutions to the above discussed issues, and most importantly, to form a simple and convenient solution that is more applicable by the real world. To summarize this section, the six research gaps are:

1) Difficulty in model calibration due to difficulty in obtaining confidential data that are proprietary.
2) No standardised way of data collection which makes data usage difficult.
3) Most model focus on a risk modelling perspective and fail to appreciate “business as usual” and “what-if” scenarios.
4) Lack of unified method (or metric) to categorize different properties of infrastructures together.
5) Lack of model to cater the interdependencies of different critical infrastructures together.
6) Pure usage of network approach to tackle critical infrastructure interdependencies lack the economical aspect of different critical infrastructures.

The research objective is to develop a quick and inexpensive critical infrastructure interdependency model that can be useful for the provision of good estimates of the impact on the whole critical infrastructures of a city or state due to disruptions in any part of the critical infrastructure system.

2.7 Comparison of the approaches

In the literature, there are several criteria for the comparison of different approaches. Yusta et al. (2011) studied what the current researchers were focused on. The paper reviewed 55 journal articles, reports, and standards between years 1999 to 2010, based on features like the type of critical infrastructures, modelling technique, maturity and availability of the technique and risk management stages (methods are classified based on their functionality in each stage of risk management programmes). Ouyang (2014) reviewed the more recent approaches based on the quantity of input data required, accessibility of input data, types of interdependencies, computation complexity and maturity.

From the two review papers, some general criteria have been used for the review in this report.

1) Quantity of input data: This criterion refers to the amount of input data required for the application of the methods reviewed in Section 2.5.
2) Accessibility of input data: This criterion refers to the availability of required input data, as relevant data may face issues of data confidentiality and limited access (Rinaldi, 2004).
3) Number of types of interdependencies possible in model: This criterion refers to the number of different types of interdependencies that can be modelled in the approach reviewed.
4) Maturity of approaches: This criterion refers to the level of development of each approach, and is purely based on the amount of relevant publications and applications that have been published.

Based on the results of these review papers (Ouyang 2014; Yusta et al 2011; Georgios et al 2012; Pederson et al, 2006), each of the four criteria for every reviewed approach in Section 2.5 is ranked as “Low”, “Medium” and “High”. An example of how the table can be read is: “Empirical based approach requires Medium amount of input data, a Medium level of accessibility to input data, has a Low number of interdependencies possible in modelling and is considered to be in a Medium level of maturity". The rankings by the four review papers are combined and summarised in Table 2-2.

From Table 2-2, almost all the approaches required at least a medium to large amount of data in order to model the approaches. Both input-output based and network based approaches were generally considered to have a low to medium level of difficulty in terms of the accessibility of data. Empirical, simulation and other approaches were generally considered to rank high in terms of difficulty in the accessibility of data, due to the need to obtain policy decision and human behaviour variables. Data is most of the time difficult to obtain from the infrastructure experts, thus adding to the difficulty in obtaining the required input data.

Table 2-2: Comparison of the approaches with the criteria

Type of approaches	Quantity of input data	Accessibility of input data	Types of interdependencies possible	Maturity of approaches
Empirical based	Medium to High	Medium to High	Low	Medium
Simulation based	High	High	High	High
Input-output based	Medium	Low to Medium	Low	Medium to High
Network based	Low to Medium	Low to Medium	Low	High
Others (includes HHM and "supernetwork")	High	Medium to High	Medium	Low

Network based approaches sometimes require detailed information about component characteristics, which might relate to privacy and security issues and thus difficult to obtain, leading to its medium ranking. For the criterion on the number of types of interdependencies possible in the model, empirical, input-output and network based approaches were generally considered to be able to model only one type of interdependency, and therefore ranked as low. Simulation based approaches like agent-based modelling and other approaches enable the possibility of the inclusion of multiple types of interdependencies in the model, and are therefore ranked as medium to high in terms of the number of types of interdependencies that could be possibly included in the model. For the maturity of each approach, simulation, input-output and network based approaches generally have a high number of publications and are sometimes applied to real-world scenarios, and therefore ranked high in its level of maturity. The current state for empirical studies mostly lies in the prototyping application stage, and is therefore ranked as a medium level of maturity, and as the other approaches are usually unique with a very few number of related publications and applications, they are ranked as low in their level of maturity.

Based on the results from Table 2-2, input-output and network based approaches have been selected for use in the proposed modelling framework of this report. The accessibility of data for these two approaches was a great advantage and motivating factor towards the decision for their adoption in this work of modelling infrastructure interdependencies. The following chapter provides a theoretical and modelling framework for conducting critical infrastructure interdependencies modelling, and describes how such methods offers a unique perspective to interdependencies modelling.

Chapter 3 Critical infrastructure interdependency model

The purpose of this chapter is to provide a theoretical and modelling framework for conducting critical infrastructure interdependency modelling using an input-output (I/O) model. The chapter describes how I/O model can be used as a critical infrastructure interdependency model and its suitability as a critical infrastructure model.

3.1 Proposed method based on Leontief's Input-Output model

This chapter describes Leontief's version of the original Input-Output (I/O) model (Leontief, 1951), which involves a modelling method that is similar to what was described in Section 2.5.3 by Haimes and Jiang (2001), but is different in terms of the use of the data.

Leontief's input-output model is constructed from an observed set of data for one economic area, such as a country's economy. Economic activities in the country can be categorised into a number of sectors (e.g. manufacturing, utilities, transportation, etc.). The necessary data is collected based on the flows of products from each of the sectors (as sellers) to each of the other sectors (as buyers). These types of inter-industry (or inter-sectoral) transactions are measured for a period of time (usually one year) (Henry & Ramirez-Marquez, 2012) and in monetary terms.

The inter-industry transactions ultimately encompass the sales and purchases of physical goods and services across industry sectors. In the accounting of an economic sector, it is possible to capture transactions between and among all sectors in monetary terms. They are represented as the transactions between sectors (from sector *i* to sector

j) in terms of monetary values, denoted by z_{ij}. Sector j's demand for products from other sectors during the year will be relevant to the amount of goods produced by sector j over the same period of time. For example, the demand for fuel from the electricity sector depends on the amount of electricity that is produced for use in the economy.

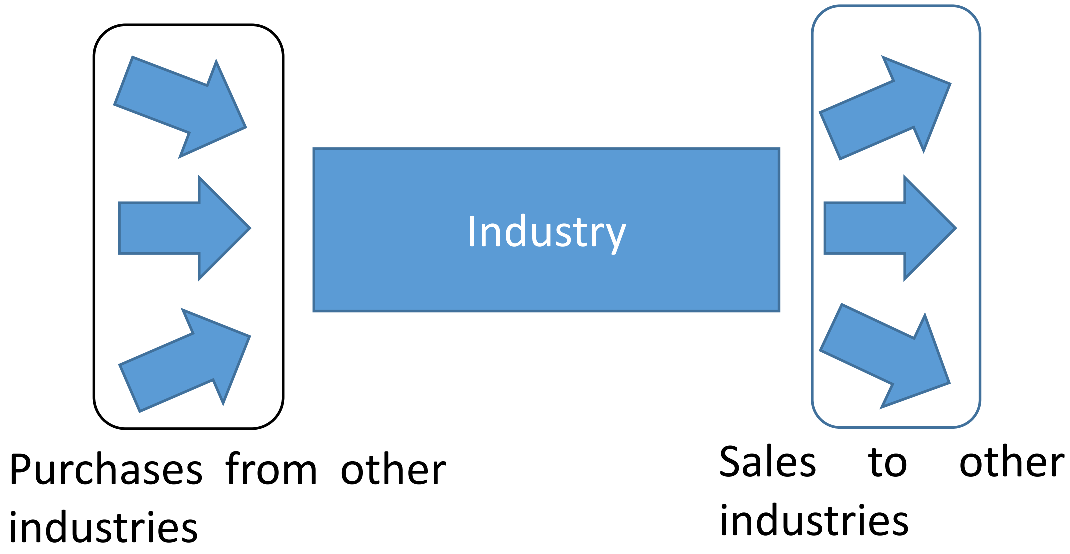


Figure 3-1: Description of purchases (buying products from other industry sectors) and sales (selling products to other industry sectors) in an industry sector

In addition to inter-industry transactions, there are also sales made to other categories of purchasers (households, government, foreign trade) in each sector. The demand arising from these purchasers are generally determined to be relatively unrelated to the amount being produced. For example, the consumer demand for electricity is related to the standard of living of the citizens. Such demands, which are not used as input to an industrial production process, are generally denoted by f_i, the final demand.

The set of data required for an input-output model essentially includes monetary values of the transactions between every pair of sectors (from sector *i* to sector *j*). Major organisations and research agencies have noticed the importance of input-output models and have been encouraging the compilation and further use of these tables for analysis. Under the System of National Accounts 2008 (United Nations; European Commission; Organisation for Economic Co-operation and Development; International Monetary Fund; World Bank Group, 2009) that was produced and released under the auspices of the United Nations (UN), the European Commission (EC), the Organisation for Economic Co-operation and Development (OECD), the International Monetary Fund (IMF) and the World Bank (WB) Group. The UN Statistical Commission encouraged countries to compile and report their national accounts for the purpose of the publication, which included the compilation of input-output tables.

The World Input-Output Database (WIOD) (Timmer, 2012) was funded by the EC, Research Directorate General, and International Input-Output Association (IIOA) and was established based on an informal world-wide network of economists and other interest groups in input-output analysis, such as the OECD. The UN Statistics Division and most countries' statistic division departments maintain the database of the national input-output table for each country in their own organisation. From the point of view of a nation's economy, input-output tables are freely available and accessible by every individual, which is advantageous for the research of infrastructure interdependency modelling.

3.2 Definition of I/O model and the mathematical model concept

The core of the I/O interdependency model formulated in Lin et al.’s work (2016a; 2016b) is Leontief’s (I/O) model (Leontief, 1986). Leontief’s I/O model structured all economic sectors of a country as an interconnected network. Each economic sector produces and receives goods and services in the process of production. The intermediate sales of goods and services for a sector to produce its respective goods and services and the final external demand for goods and services produced by that sector is captured in Leontief's I/O model, which is useful in understanding the interdependence of all economic sectors in a country. The I/O model brings about the possibility of inducing "perturbation" to an economic sector (Haimes & Jiang, 2001; Santos 2006; Santos et al. 2007), as a result of an event (e.g. a natural disaster) that causes the final external demand f of the economic sector to change. This “perturbation” will in turn cause a cascading effect on all linked economic sectors and the overall impact of the perturbation can be evaluated. Different researchers have proven that there will be a potential supply chain impact when disruption happens due to the cascading impact on other sectors (Kajitani et al., 2013). Understanding the interdependencies and the cascading effect on other economic sectors as a result of a catastrophic event is highly critical in the development of an effective security plan (The Infrastructure Security Partnership, 2006).

The I/O model is formulated based on the demand-pull I/O quantity model (Miller & Blair, 2009). Assuming that the economy is categorised into n sectors, with x_i representing the total output of sector i, z_{ij} representing intermediate sales by sector i to all other sectors j and f_i representing the final external demand for goods and services produced by sector i, the Leontief I/O model is formulated as follows:

$$x_i = z_{i1} + z_{i2} + z_{i3} + \cdots + z_{in} + f_i = \sum_{j=1}^{n} z_{ij} + f_i \qquad \text{or} \qquad \mathrm{X} = \mathrm{Z} + \mathrm{F} \tag{3.1}$$

Equation (3.1) describes how sector *i* supplies goods and services to sector *j* and satisfies the final external demand f_i for sector *i*. Z represent the input-output table which consist of the flow of goods and services between each economic sectors. Leontief's technical coefficient a_{ij}, which is defined as the amount of goods and services from sector *i* used to produce a unit value of goods and services in sector *j*, can be represented as:

$$a_{ij} = \frac{z_{ij}}{x_j} \tag{3.2}$$

Substituting equation (3.2) into equation (3.1) leads to:

$$x_i = a_{i1}x_1 + a_{i2}x_2 + a_{i3}x_3 + \cdots + a_{in}x_n + f_i = \sum_{j=1}^{n} a_{ij}x_j + f_i \tag{3.3}$$

Applying equation (3.3) to all the *n* sectors in the economy gives rise to:

$$\begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} + \begin{pmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{pmatrix} \tag{3.4}$$

or simply:

$$\mathrm{X} = \mathrm{AX} + \mathrm{F} \tag{3.5}$$

where $$\mathrm{X} = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix},\ \mathrm{A} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix},\ \mathrm{F} = \begin{pmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{pmatrix} \tag{3.6}$$

Equation (3.5) can be rearranged to obtain:

$$(\mathrm{I} - \mathrm{A})\mathrm{X} = \mathrm{F} \tag{3.7}$$

The matrix A, which is the direct requirement matrix, represents the technological state of the country for all economic sectors in the production of its goods and services. Equation (3.7) is used to solve for the total output X by matrix inversion as shown in equation (3.8). Due to the linearity of equation (3.8), equation (3.9) can be formulated, with equation (3.10) showing the expanded form of equation (3.9).

$$\mathrm{X} = (\mathrm{I} - \mathrm{A})^{-1}\mathrm{F} \tag{3.8}$$

$$\Delta\mathrm{X} = (\mathrm{I} - \mathrm{A})^{-1}\Delta\mathrm{F} \tag{3.9}$$

$$\begin{pmatrix} \Delta x_1 \\ \Delta x_2 \\ \vdots \\ \Delta x_n \end{pmatrix} = \begin{pmatrix} 1 - a_{11} & -a_{12} & \cdots & -a_{1n} \\ -a_{21} & 1 - a_{22} & \cdots & -a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ -a_{n1} & -a_{n2} & \cdots & 1 - a_{nn} \end{pmatrix}^{-1} \begin{pmatrix} \Delta f_1 \\ \Delta f_2 \\ \vdots \\ \Delta f_n \end{pmatrix} \tag{3.10}$$

$(\mathrm{I} - \mathrm{A})^{-1}$ is commonly known as the total requirement matrix of the I/O model and is also referred to as the interdependency matrix that determines the strength of dependency between critical infrastructure sectors (Miller & Blair, 2009) in this study. The greater the monetary transactions between two industry sectors in an economy, the more interconnected they are. ΔX is referred to as the change in overall impact for all economic sectors due to the cascading impact from ΔF. ΔF is the change in final external demand and is used to estimate the initial impact due to a disruptive event (e.g. a disruptive event causing a power plant to be shutdown, resulting in the inability to satisfy external demand (ΔF) for electricity). As critical infrastructure sectors are also industry sectors in any nation's economy, this work will treat critical infrastructure sectors similarly to industry sectors in the input-output model.

3.3 The nature of the I/O model and its suitability for critical infrastructure interdependency modelling

One of the main reasons for the use of input-output model is the concreteness of empirical data and the compactness that the model can provide. The data of the input-output tables provided by the national statistics departments is usually very comprehensive and consistent with the standards recommended by the United Nations Statistics. By its nature, the input-output tables encompass all formal economic activities that occur in an economy. The input-output tables play a fundamental role in the construction of national accounts, which thus provides greater confidence in the data.

The nature of the input-output model also provides a possible way to analyse the economy as an interconnected system of industries that can be directly and indirectly affected by one industry sector or another. This is a central advantage of input-output models. Input-output models trace the linkages established from the raw material stage to the sale of the product in the form of goods. This advantage enables the estimation of economic impacts from any changes to the economy based on these inter-industry transactions. This allows for decomposition analysis that can account for a decline in production, which not only leads to a decline in other raw material industries, but also affects, for example, power producing industries. The ability to analyse and capture the economy's direct and indirect reaction to a change in the economic environment (any perturbation) makes input-output models unique. Understanding the large-scale critical infrastructure network and its interdependencies can help us identify the interdependent links and their corresponding strengths (Santos et al., 2007; Wang et al., 2013; Tai et al., 2013; Kizhakkedath et al., 2013), and enables the development of a model to evaluate and predict the impact of a disruption, including the cascading and overall impact to economic sectors that are linked by these interdependencies. This can aid stakeholders in analysing worst case scenarios (Lam et al., 2013; Lin et al., 2016a; Lin et al., 2016b) using the interdependency model, and in establishing resource allocation (Murray & Gurubesic 2012) strategies for the protection of critical infrastructure.

The design of the input-output tables also allows for decomposition, enabling the easy identification of the sources of change, the direction of change and the magnitude of the change. It provides insight into how a macroeconomic phenomenon, such as a change in final demand, corresponds to microeconomic change as industries respond to change in economic conditions.

These advantages may be helpful in the current research as critical infrastructure network analysis requires a model that is able to link infrastructure together, according to physical and logical interdependencies (Rinaldi et al., 2001). The assumption made in the proposed method in this chapter is that monetary transactions from the input-output tables are similar to physical (in term of economic) interdependencies. The greater the monetary transactions between two industry sectors in an economy, the more interconnected they are. For example, electricity sector requires water cooling while water sector will require electricity to run water refining works. The water supplied to electricity sector (and vice versa) cost a fixed amount of monetary value and depends on the supply and demand of the water/electricity. If the water sector is being disrupted, the electricity sector will have difficulty in maintaining the usual electricity supply to the nation, and thus, a drop in electricity output. Indirectly, the initial disruption reduces water supply due disruption in electricity sector (as an indirect impact). This example shows that physical goods and services (in term of monetary values) plays a big part in the critical infrastructure systems and they are interdependent to each other.

3.4 Direct effect, indirect effect, and total impact of a hazard under the critical infrastructure interdependency model

In order to prevent confusion, the definition of direct and indirect effects are being provided here. Natural disasters can cause physical destruction to infrastructure, such as power plants, electricity transmission lines and transportation. From an economic standpoint, this damage is considered as damage to stock, and is related to both physical and human capital. The ensuing disturbance of economic activities is referred to as the loss arising from the disaster. In literature (Okuyama, 2009; Rose & Guha, 2004), this type of initial losses is called the direct effect of a disaster. In addition, there are ‘indirect effects’ which are losses which arise due to the relationships between industries. An example of a direct effect would be damage to an electricity generating plant preventing its operation. On the other hand, other industry sectors that are not damaged by the disaster but require the use of electricity cannot operate and resume production until power is restored. This type of disruption to these industry sectors is an indirect effect of a disaster. Total impact is the sum of direct and indirect effects of the disaster. The direct effect, indirect effect and total impact are described in Figure 3-2.

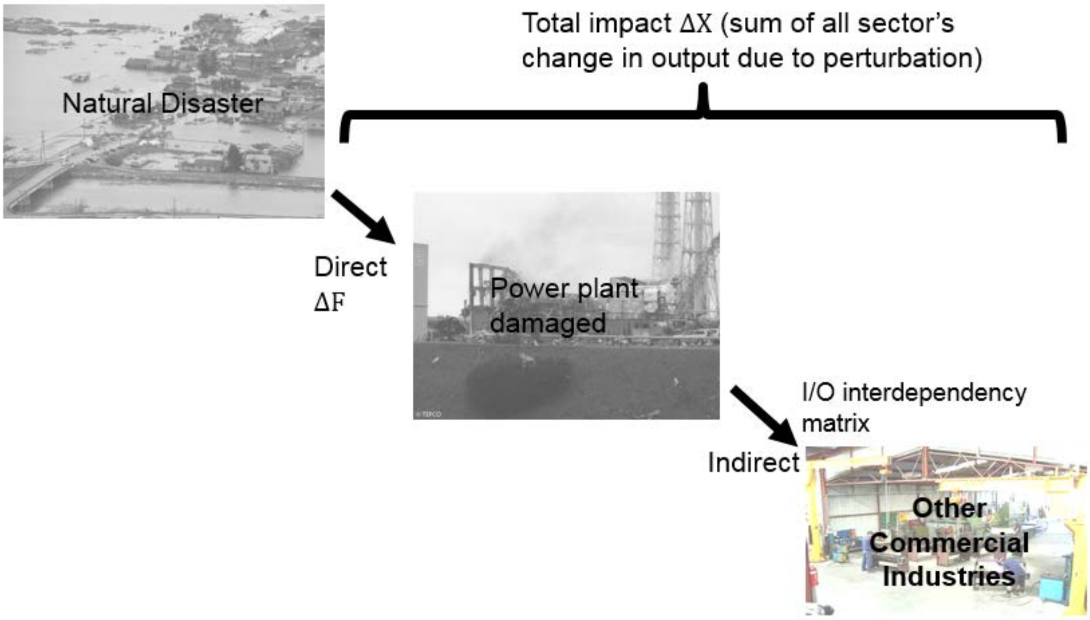


Figure 3-2: The direct, indirect and overall impact of a disaster

The direct effect can be interpreted as change in final demand ΔF (Okuyama, 2009; Rose & Guha, 2004), as damages to the *i* th sector affect the demand in different sectors. This change in demand, ΔF, can be seen from two main areas, one of which is due to the damage to the i^{th} sector, where the demand from external sources f_i (consumer from outside the industry sector) will change as they seek other sources of supply. The other demand change is caused by the disaster, as the i^{th} sector does not have the capability to supply goods and services due to the damages incurred on the i^{th} sector (Okuyama, 2009). The infrastructure interdependency model reflects the absolute economic impact to the economy, but however will not be able to reflect the criticality of the situation as some critical infrastructure are more critical than other critical infrastructure in the context of the specified nation (Genge et al., 2015; Setola et al., 2009; Oliva et al, 2010). Criticality is defined as the degree of importance and is used to illustrate some critical infrastructure (e.g. electricity sector) that are more important to the others (e.g banking and finance), as electricity sector is the fundamental fuel to power up a modern society.

3.5 Example scenario

As an illustrative sample calculation to better illustrate I/O modelling for infrastructure interdependency modelling, consider the following scenario. Assume that there was a targeted terrorist attack on electric power plant, A. Based on the power failure, estimate the direct effect of the damage dealt by the terrorist attack imposing a change in external demand (ΔF) due to the power plant being unable to operate. It is important to note that in almost all economic infrastructures, the attack would have most probably induced collateral damages to other sectors as well. However, to simplify the problem, it is assumed that only sector A suffered \$1000 (Δf_1) in losses due to the change in final demand from consumers external to the industry sectors. This initial estimated effect will then be used as input vector (ΔF) for the I/O model. The output vector (ΔX) will be the consequence of the change in demand in all sectors, due to the combined impact of the direct and indirect effect. This scenario illustrates a situation where an electric power plant was unable to produce electric power for a period of time due to a terrorist attack, and all industry sectors suffered an economic loss of ΔX (inclusive of direct and indirect effect) amount as compared to its potential profits when operating in a normal condition. Let us use an example of an input output table (Table 3-1) to better illustrate input-output modelling. The shaded 3x3 region in the table represents the inter-industry transaction (or inter-industry demand matrix) among 3 sample sectors A, B and C. Row A (solid line) represents the sale of product A to other sectors, while column A (dashed line) represents the purchases required from other sectors to produce A. They are denoted as:

$$x_1 = z_{11} + z_{12} + z_{13} + f_1 \tag{3.11}$$

or $1450 = 150 + 500 + 500 + 300$

Using equation (3.1) to (3.6) and data from Table 3.1, due to $\Delta f_1 = 1000$, we are able to evaluate the following:

$$\mathrm{Z} = \begin{pmatrix} 150 & 500 & 500 \\ 200 & 100 & 1000 \\ 650 & 800 & 400 \end{pmatrix}, \ \Delta \mathrm{F} = \begin{pmatrix} 1000 \\ 0 \\ 0 \end{pmatrix} \tag{3.12}$$

$$\mathrm{A} = \begin{pmatrix} 0.10345 & 0.31250 & 0.16949 \\ 0.13793 & 0.062500 & 0.33898 \\ 0.44828 & 0.50000 & 0.13559 \end{pmatrix} \tag{3.13}$$

$$(\mathrm{I} - \mathrm{A})^{-1} = \begin{pmatrix} 1.5750 & 0.87208 & 0.65081 \\ 0.66643 & 1.7178 & 0.80431 \\ 1.2022 & 1.4459 & 1.9596 \end{pmatrix} \tag{3.14}$$

In the above equations, Z is the inter-industry matrix, A is the direct requirement matrix and $(\mathrm{I} - \mathrm{A})^{-1}$ is the total requirement matrix.

Using equation (3.8), the $(\mathrm{I} - \mathrm{A})^{-1}$ matrix above, the assumed \$1000 change in final demand (ΔF) dealt to sector A, and the direct and indirect effect of the perturbation can be calculated as follows:

Table 3-1: Example of input-output table

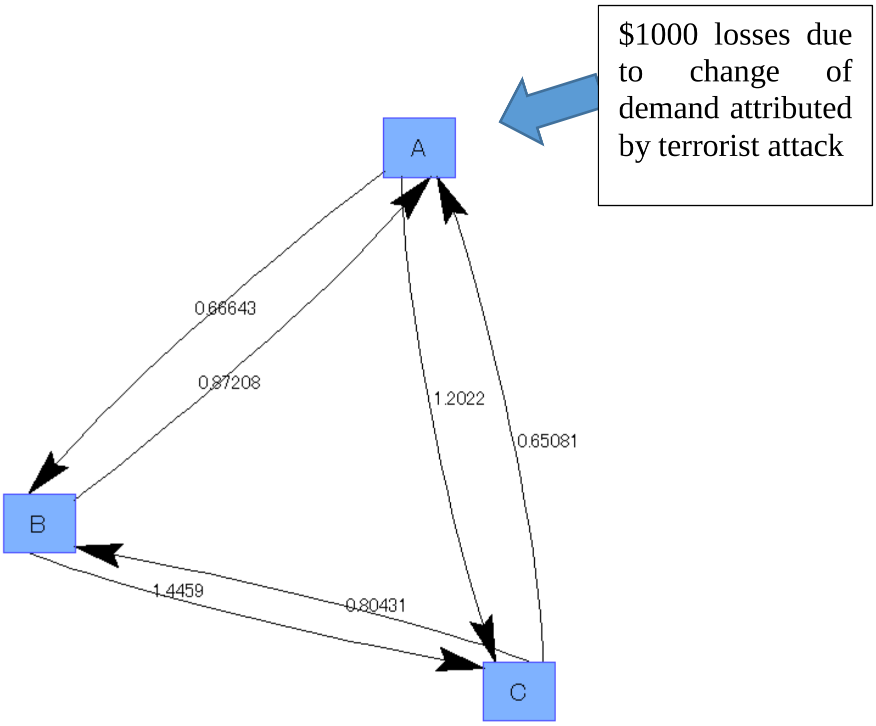
		To (buying) *j*			**Final demand (f_i)**	**Total Output (x_i)**
		A	B	C		
From (selling), *i*	A	150	500	500	300	1450
	B	200	100	1000	300	1600
	C	650	800	400	1100	2950
Value added		450	200	1050		
Total Outlays (x_j)		1450	1600	2950		

$$\Delta X = (I - A)^{-1}\Delta F$$

$$= \begin{pmatrix} 1.5750 & 0.87208 & 0.65081 \\ 0.66643 & 1.7178 & 0.80431 \\ 1.2022 & 1.4459 & 1.9596 \end{pmatrix} \begin{pmatrix} 1000 \\ 0 \\ 0 \end{pmatrix}$$
$$= \begin{pmatrix} 1575.0 \\ 666.43 \\ 1202.2 \end{pmatrix} \tag{3.15}$$

Equation (3.15) shows that for the \$1000 loss in sector A due to the change in final demand as a result of the perturbation, through the use of the I/O model, it can be seen that the direct and indirect effect of the perturbation will cause a \$1575.00 output reduction for sector A, \$666.43 output reduction for sector B and \$1202.20 output reduction for sector C. In network form, this can be illustrated as shown in Figure 3-3.

From Figure 3-3, we can clearly see the effect of the $1000 change in final demand on sector A propagating through the total requirement matrix $(\mathrm{I}-\mathrm{A})^{-1}$ across the network. The $(\mathrm{I}-\mathrm{A})^{-1}$ matrix assigns a weight to the linkages between each pair of nodes (sectors), which represent interdependency strength between the nodes. The interdependency strength between the nodes is the key attribute of the proposed model, as it contains information about how much a node can affect another node in the infrastructure network. In the proposed method, the economic relationships among different infrastructures are assumed to be the same in accordance with their physical interdependencies (based on the methodologies by Rinaldi et al. (2001) described in Section 2.2).



$1000 losses due to change of demand attributed by terrorist attack

Figure 3-3: Network form of the three sectors based on their interdependency weightage. 0.66643 is calculated through I/O model from equation (3.14) based on I/O table from Table 3-1. If Sector A suffered a $1000, Δf_A, initial disruption, a $666.43 of Δx_B will be impacted to sector B through "0.66643" linkages above.

3.6 Assumptions

Since the proposed I/O model follows the original Leontief input-output model, the assumptions made are also similar. It is assumed that the technology and overall economic structure do not change in the short period of time as described in Section 2.5.3. As the economy will find a stable equilibrium eventually, the proposed model will be useful in the analysis of a steady-state condition of the infrastructure sometime after the perturbation, but will not be useful for an immediate impact analysis where non-equilibrium states can occur (Miller & Blair, 2009). Static models only address production or the ‘current account side’ of an economy and omit investment. Instead of being incorporated within the input-output matrix of inter-industry flows, investment is taken into account within final demand. As technological changes affect the structure of capital stock and the sourcing of capital equipment which in turn may directly affect growth, this is considered to be one of the main limitations of this type of model. Therefore, the direct-requirement matrix (A) is fixed unless technology changes. A dynamic model that is able to incorporate this type of activities may be needed (Rosato et al., 2008). Computable general equilibrium (CGE), which is considered as an extension of the input-output model, may be an answer to this issue (Zhang & Peeta, 2011). However due to the current data constraints and the need to assume a few important parameters in CGE, the practicality of the CGE model is still currently being researched. It is also assumed that there are no influences from external forces, such as help from neighbouring countries. There is also a significant time lapse between the collection of data and the availability of the input-output tables. It will usually take two to three years for an input-output table to be tabulated and released publicly. It is therefore not realistically possible to get the most up-to-date information on the status of current economic structures. The use of the latest input-output table closest to the disruption event date is thus recommended to increase the accuracy of the snapshot of the economy and the identification of the industrial interconnections at that period of time.

Chapter 4 Analysing impact on critical infrastructure: Benchmarking via two case studies

The purpose of this chapter is to describe the development and testing of the critical infrastructure I/O interdependency model used to answer the research questions in Section 1.3. The input-output interdependency model is a quick decision tool for stakeholders of critical infrastructure to understand the economic impacts of a disruptive event. To demonstrate its applications, two case studies (Singapore Pulau Bukom refinery fire in 2011 and Japan Tohoku earthquake in 2011) are being presented in this chapter. The chapter describes how the model in Section 3.2 is used to compute the effects on other economic sectors. It also seeks to compare and analyse the computed cascading effects. Understanding the severity and extent of the disruptive event is very important and the input-output interdependency model serves as a quick and cost effective decision deployment tool for use by the relevant stakeholders.

Through the use of the I/O model for interdependency analysis, it is possible to model different complex critical infrastructures together and perform risk analyses on specific infrastructure that are of interest (Burmester et al., 2012). As the I/O table involves all economic sectors in a country, this interdependency analysis includes some non-critical infrastructure. Researchers can either focus solely on the critical infrastructure of interest in the I/O table or aggregate the relevant economic sectors into their appropriate aggregated critical infrastructure sectors to perform the analysis (Lin et al., 2016a; 2016b). The potential results are the identification of interdependencies between specific critical infrastructure and other interconnected critical infrastructure, the evaluation of the impact on other sectors and overall impact when a disruption happens, and consequently simulating the effects of the worst possible case scenario based on the critical infrastructure model developed. With these results, a stakeholder can then develop strategies to mitigate their losses in the event of a disruption. The results in this chapter is published in Lin et al. (2017).

4.1 Singapore Pulau Bukom island fire case study

In this chapter, the case involving the Singapore Pulau Bukom island fire that happened in 2011 is studied through the application of the I/O interdependency model, presenting results that aid in the understanding of how a disruptive event can impact other critical infrastructures (Jaradat & Keating, 2014).

4.1.1 Critical infrastructure disruption during the Pulau Bukom island fire

Singapore is one of the top oil refining centres of the world, with its oil and gas industry making up 5% of its GDP. The chemicals production industry, which is usually associated with petroleum products, also enjoys a large presence in Singapore. Singapore’s Pulau Bukom Island houses one of the biggest oil and gas manufacturing sites of the Royal Dutch Shell. The Pulau Bukom manufacturing site can process up to 500,000 barrels of crude oil per day, accounting for 36% of Singapore’s total refining capacity (Chua, 2012). A fire that broke out on 28 September 2011 progressively led to a complete manufacturing site shutdown on 29 September 2011. This caused the Royal Dutch Shell to quote force majeure contractual clause in order to be released from contractual obligations and liabilities due to the catastrophic event that happened at its plant. The Pulau Bukom manufacturing site began to resume operations at a reduced capacity in mid October 2011 after obtaining clearance from the Singapore Ministry of

Manpower and Singapore Civil Defence Force, and progressively resumed operations at full capacity at the end of December 2011 (Yaw, 2011).

Using this case study, we conducted a detailed investigation of this disruption using the I/O interdependency model to evaluate the cascading impact to other critical infrastructures as a result of their links to the oil and gas industry. This enables stakeholders to recognise and learn about such important interconnections, so that any potential future crisis can be foreseen and possibly prevented/controlled.

4.1.2 Analysing oil and gas industry using Singapore input-output table

Using the 136-sector 2007 Singapore I/O table (Appendix A) compiled by the Singapore Department of Statistics (Singapore Department of Statistics, 2010), the I/O interdependency model is formed to obtain the interdependencies of all the sectors in Singapore. All of the economic sectors in Singapore are classified and organised in the I/O table based on the 2005 Singapore Standard Industrial Classification (SSIC, 2005), which aggregates smaller sectors into corresponding larger aggregated sectors. All analyses of the Singapore Pulau Bukom fire case study are based on Singapore Dollars.

4.1.3 Estimation of initial losses for the oil and gas industry

Firstly, based on the I/O table of Singapore, refining and production work make up 66% of the oil and gas industry. Secondly, the Pulau Bukom site accounts for 36% of the total refining capacity (Chua, 2012) and its shutdown was for an estimated total period of one month (Chua, 2012). Thirdly, the oil and gas industry constitutes 5% of Singapore’s GDP (Contact Singapore, 2011) and this GDP stood at $212074 million for 2005 (Singapore Department of Statistic, 2016). With all these information, the initial monthly loss/impact Δf_i in the oil and gas sector due to the Pulau Bukom fire can thus be estimated as illustrated in equation (4.1), where Δf_i is just one component of the ΔF from equation (3.10).

$$\Delta f_i = \frac{1}{12} \times 36\% \times 66\% \times 5\% \times \$212074\,\text{million} = \$210\text{million} \tag{4.1}$$

Equation (4.1) provides the Δf_i of the oil and gas sector only. This Δf_i will be used in equation (3.9) to compute ΔX, which is the overall impact of all sectors. There were several assumptions made in this estimate. The first was that there was no redundancy or storage of extra petrochemicals. The second was that there were no extra imports of petrochemicals from other countries to satisfy the required demand in Singapore, and the third assumption was that the percentage of refining work within the oil and gas industry was not further differentiated according to specific categories (i.e. crude oil, LNG, chemical) as there was no further data to determine the respective categories. The estimate of $210 million loss in equation (4.1) was close to the estimated $187 million in losses that was published by the Royal Dutch Shell (Chua, 2012). Given the above information, a partial calculation based on equation (3.1) – (3.10) is shown in equation (4.2) to showcase how the values in Section 4.1.4 is computed.

$$\begin{pmatrix} \Delta x_1 \\ \vdots \\ \Delta x_{22} \\ \vdots \\ \Delta x_{136} \end{pmatrix} = \begin{pmatrix} 1-a_{(1,1)} & \cdots & -a_{(1,22)} & \cdots & -a_{(1,136)} \\ \vdots & \ddots & \vdots & \vdots & \vdots \\ -a_{(22,1)} & \cdots & -a_{(22,22)} & \cdots & -a_{(22,136)} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -a_{(136,1)} & \cdots & -a_{(136,22)} & \cdots & 1-a_{(136,136)} \end{pmatrix}^{-1} \begin{pmatrix} \Delta f_1 \\ \vdots \\ \Delta f_{22} \\ \vdots \\ \Delta f_{136} \end{pmatrix}$$

$$= \begin{pmatrix} 1.031546 & \cdots & 0.000001 & \cdots & 0.000001 \\ \vdots & \ddots & \vdots & \vdots & \vdots \\ 0.001042 & \cdots & 1.079 & \cdots & 0.001042 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & 1 \end{pmatrix} \begin{pmatrix} 0 \\ \vdots \\ \$210 million \\ \vdots \\ 0 \end{pmatrix}$$

$$= \begin{pmatrix} \$0.0003 million \\ \vdots \\ \$226 million \\ \vdots \\ 0 \end{pmatrix} \tag{4.2}$$

4.1.4 Results of Pulau Bukom fire case study

With the initial loss/impact (Δf_i) of \$210 million due to the Pulau Bukom fire on the oil and gas industry, the overall impact ΔX is calculated to be at \$245 million in total losses, of which \$35 million ($\Delta X - \Delta F$) was contributed by the cascading and higher order impacts resulting from the initial impact. As mentioned in a newspaper article (Ng, 2011), although the Pulau Bukom fire led to a short-term loss of petroleum output, the impact on downstream chemical plants was small as there were alternative sources of feedstock. Therefore, the \$35 million amount accumulating from cascading and higher order impacts might be a good illustration of the overall impact downstream. The cascading impact for each sector is ranked in descending order of magnitude in Figure 4-1. As the input-output model is fundamentally linear, the initial loss/impact ΔF will have a linear relationship with the overall impact ΔX and its corresponding cascading impact. The results in terms of economic losses per day (a computed monthly losses divided by 30 days) for the top ten significant sectors are summarised in Table 4-1. The results in Table 4-1 are useful in illustrating the reduction in economic loss that can be achieved per day of recovery time reduced. The option to reduce economic losses by reducing the number of recovery days is obvious (Ouyang & Duenas-Osorio, 2012). However, the cost of risk mitigation needs to be further evaluated before the execution of the mitigation process. Further sensitivity analysis on $(\mathrm{I}-\mathrm{A})^{-1}$, which provides the interdependency linkages, can be analysed in greater depth (particularly in the tweaking of the sectoral interdependency strength). However, effecting any changes to the content of the input-output table is not within the scope of this analysis, and may thus be a potential research topic for the future.

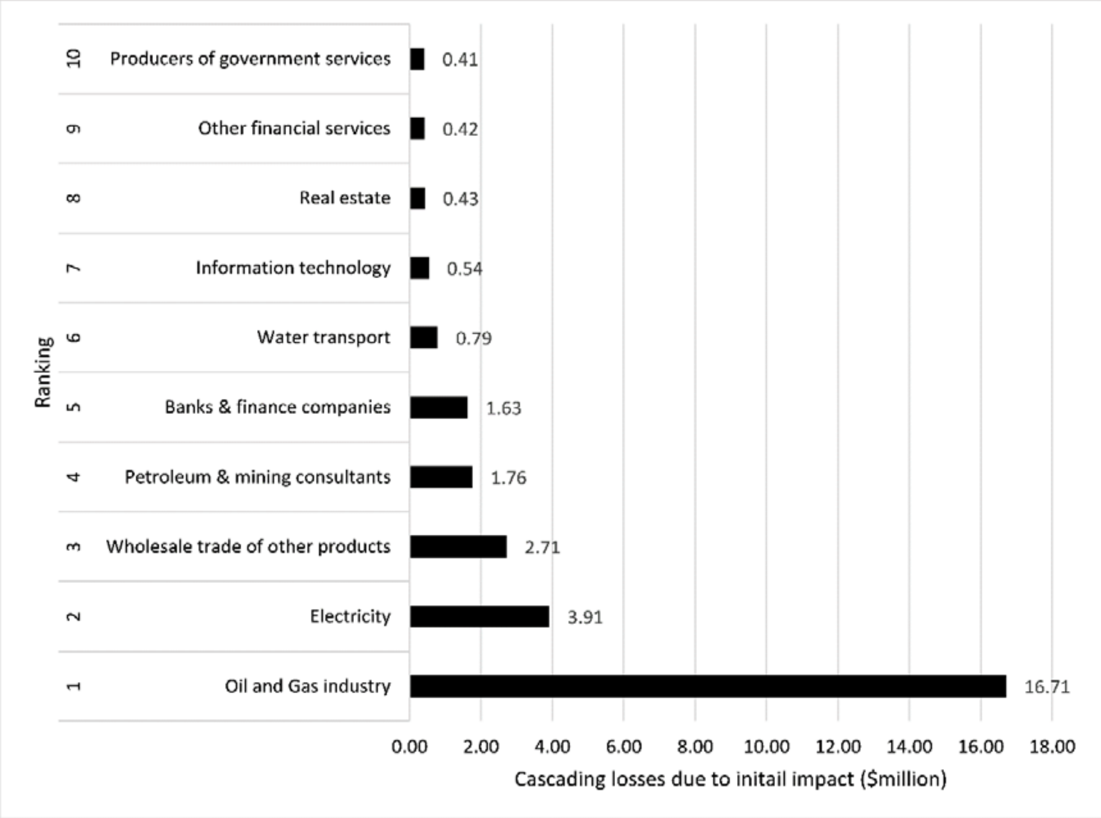


Figure 4-1: Top ten sectors with the highest cascading impacts per month due to the initial estimated loss on oil and gas sector from the Pulau Bukom fire

Table 4-1: Cascading economic losses per day for the top ten most significant sectors based on estimation of ΔF for the Pulau Bukom fire

Rank	Sectors	Loss estimate per day in thousand dollars
1	Oil and Gas industry	557
2	Electricity	130
3	Wholesale trade of other products	90
4	Petroleum & mining consultants	59
5	Banks & finance companies	54
6	Water transport	26
7	Information technology	18
8	Real estate	14
9	Other financial services	14
10	Producers of government services	14

Figure 4-1 presents the top ten resultant cascading impacts due to the initial impact, which is calculated as ($\Delta X - \Delta F$). As shown in Figure 4-1, the oil and gas industry is ranked first with the highest cascading impact. This is due to the fact that after the initial impact, other sectors that are indirectly affected by the initial impact will in turn have further impact on the oil and gas industry itself. Electricity is the second most impacted industry, as intuitively the electricity industry is heavily dependent on oil and gas for the production of their goods and services. The wholesale trade of other products is the third most affected industry, as they may either be highly dependent on oil and gas industry, or the relevant industry that they conduct business with has been indirectly hit by the disruption. The results in Figure 4-1 also showcase the interdependency between the oil and gas industry and the downstream users that utilise products from the oil and gas industry. Stakeholders may want to consider risk mitigation for the respective sectors that are highly ranked in Figure 4-1. The results have been compared with the research findings of the relevant authorities and were validated to be a close estimation. However, it is important to note the relevant assumptions made in the estimate of the initial loss/impact, and that more detailed data is required to refine the analysis.

4.2 Japan Tohoku earthquake case study

On 11 March 2011, an earthquake with a moment magnitude M_w 9.1 occurred off the Pacific coast of Tohoku. The earthquake was not the deadly part of the disaster. It was instead the ensuing tsunami that caused many deaths and widespread damage to coastal prefectures in the Tohoku area. The tsunami also caused a nuclear accident at the Fukushima Daiichi Nuclear Power Plant, which suffered various meltdowns due to the damage of key infrastructure by the tsunami and earthquake and the corresponding failure of main and backup cooling water systems which are rendered inoperable due to flooding. This electrical critical infrastructure crisis highlighted several problems inherent in the electricity grid, which was historically divided into 60 Hz and 50 Hz of electrical power and made the sharing of electricity between regions very difficult. The meltdowns also triggered a full-scale shutdown of all existing nuclear power plants, which further worsened the situation of electricity shortage, and Japan resorted to rolling blackouts to reduce electricity usage. A total of 16.9 trillion yen in losses (equivalent to US$211.3 billion) was estimated to have been incurred due to the catastrophe by the Cabinet Office of Japan (Cabinet Office of Japan, 2011). Various estimates of socio-economic loss have also been made by different groups of researchers using their own specific calculation methodologies (Daniell et al., 2011).

In this case study, the sole focus is on the impact of the electricity critical infrastructure in Japan due to the Tohoku earthquake. The same strategy towards estimating the initial losses as a result of the Fukushima nuclear power plant shutdown has been adopted and verified by Daniell et al. (2011). The initial impact, Δf_i, on the electricity sector alone due to both the earthquake and tsunami was estimated to be within the range of US$58 billion (optimistic) to US$71 billion (pessimistic). Based on this initial estimate, the Japan I/O table (METI, 2005) is being used for our I/O interdependency model analysis on the critical infrastructures.

4.2.1 Analysing electricity industry using Japan input-output table

Using the 53-sector 2011 Japan I/O table (Appendix B) compiled by the Ministry of Economy, Trade and Industry (METI) of Japan (METI, 2014), the I/O interdependency model is formed to obtain the interdependencies of all sectors in Japan. All economic sectors in Japan are classified and organised in the I/O table based on the classification of the 2005 Updated Input-Output Table (METI, 2005), which aggregates smaller sectors into corresponding larger aggregated sectors. All analyses of the Tohoku earthquake case study are based on United States Dollars.

4.2.2 Results of Tohoku earthquake case study

With the optimistic $58 billion loss estimate, Δf_i, from the Tohoku earthquake, the overall loss ΔX is calculated to be $130.8 billion, of which $72.8 billion (ΔX – ΔF) is contributed by the cascading and higher order of impacts due to the initial impact. Similarly, with the pessimistic $71 billion loss estimate, Δf_i, the overall loss ΔX is calculated to be $160.1 billion, of which $89.1 billion (ΔX – ΔF) is contributed by the cascading and higher order of impacts due to the initial impact. Comparing this with the results from Pulau Bukom fire case study, it is notable that the different industries could have significantly different impacts on their corresponding interconnected sectors. It is noted that when the losses calculated in the “cascading/ indirect losses in all sectors” are significant in amount in comparison to its initial impact, then that sector is critical to the whole country. This is more strongly evident in the Tohoku earthquake case study rather than the Pulau Bukom fire case study. However, it should also be noted that this is not a final conclusion, as ultimately a country needs all sectors to work together so as to supply essential goods and services for the country. The corresponding cascading impacts due to the Tohoku earthquake are ranked in descending order of magnitude in Figure 4-2.

Similar to the Pulau Bukom fire case study, as the input-output model is fundamentally linear, the initial loss/impact ΔF will have a linear relationship with overall impact ΔX and its corresponding cascading impact. The results in terms of optimistic and pessimistic economic losses per day for the top ten significant sectors are summarised in Table 4-2. The results in Table 4-2 illustrate the reduction in economic losses that can be achieved per day of recovery time reduced. The division of the monthly cascading impact (Figure 4-2) by 30 days computes the daily cascading losses in Table 4-2. Similar to the Pulau Bukom fire case study, reducing the number of recovery days is an obvious option for the reduction of economic losses. However, the cost of risk mitigation needs to be further evaluated before the execution of the mitigation process.

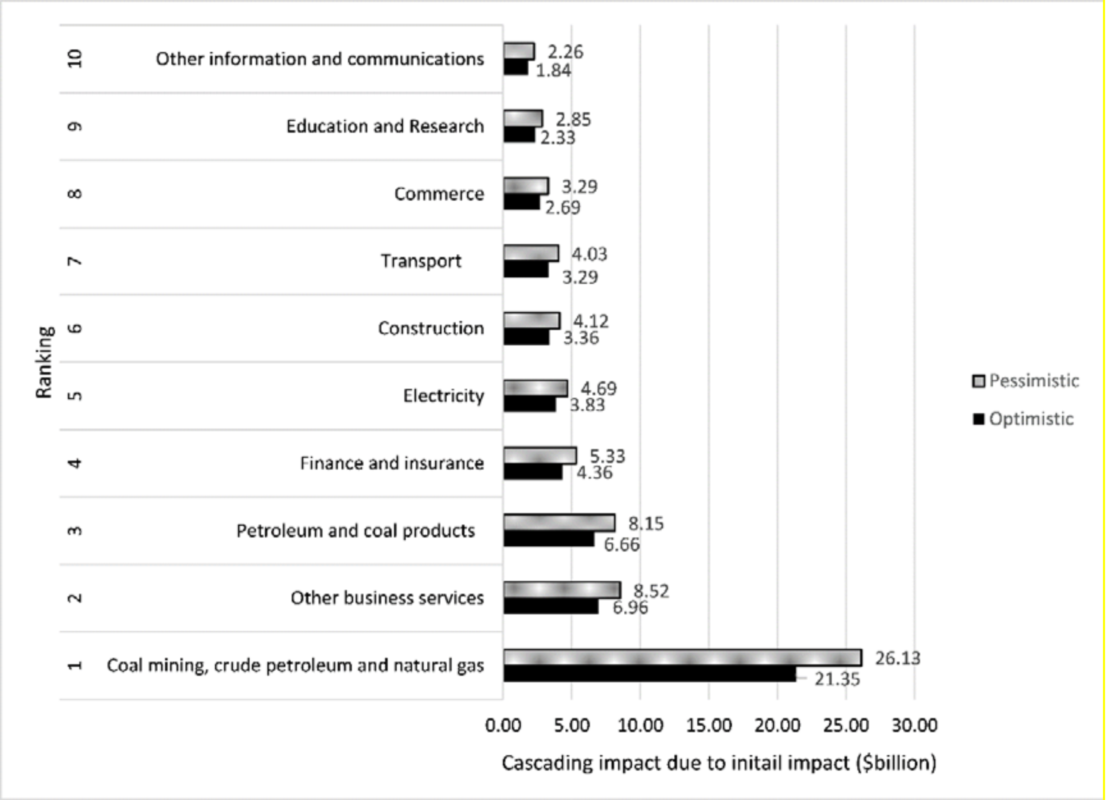


Figure 4-2: Top ten sectors with highest cascading impacts per month due to initial estimated optimistic and pessimistic losses in the electricity sector caused by the Tohoku earthquake

Table 4-2: Cascading economic losses per day for the top ten significant sectors based on the estimation of ΔF for the Tohoku Earthquake

Rank	Sectors	Optimistic loss estimate ($ million)	Pessimistic loss estimate ($ million)
1	Coal mining, crude petroleum and natural gas	712	871
2	Other business services	232	284
3	Petroleum and coal products	222	272
4	Finance and insurance	145	178
5	Electricity	128	156
6	Construction	112	137
7	Transport	110	134
8	Commerce	90	110
9	Education and Research	78	95
10	Other information and communications	61	75

Figure 4-2 presents the top ten resulting cascading impacts as a result of the initial impact, which is calculated as (ΔX - ΔF). Both the optimistic and pessimistic results have the same ranking in terms of the sectors that are most affected by the cascading impact. As shown in Figure 4-2, the coal mining, crude petroleum, and natural gas industry in Japan is ranked first with the highest cascading impact due to initial impact on the electricity sector, while the electricity sector itself is ranked in the fifth position. As the coal mining, crude petroleum, and natural gas industry requires a lot of electrical energy for production, it is thus severely affected. The other business services are ranked in the second position as the electricity disruption caused their production to cease. Overall, as expected, a range of other industries were affected at different levels of severity. Stakeholders will thus be able to note the interdependencies between these relevant sectors and plan relevant actions to safeguard their interests. The indirect cascading losses of $72.8 billion and $89.1 billion obtained here were fairly close to the $51 billion to $91 billion estimated by Daniell et al. (2011) who applied the CATDAT-EQLIPSE models that utilised the socio-economic data in the CATDAT database to formulate fragility and empirical functions so as to estimate the indirect losses in the country due to the earthquake. However, it is important to note that the risk analysis estimate should be treated as a proxy to aid relevant decision-making.

4.3 Summary

The case studies of the Singapore Pulau Bukom fire and Japan Tohoku earthquake had been examined to analyse the impact to the respective countries. The I/O interdependency model was used in this chapter to model interdependencies between economic sectors using the respective country’s I/O table, which was publicly available. Through the use of the I/O interdependency model derived from the I/O table, a risk analysis on the specific industry/sector affected by the disruption can be conducted and the results of the overall and corresponding cascading impact/losses in all other sectors can be evaluated. The case studies in this chapter helped in the understanding of the use and accuracy of input-output interdependency models through the comparison of the results with relevant information sources. The methodology served as a quick and systematic tool to enable stakeholders to understand the scale and severity of the disruption, and to design their own resource allocation strategy to mitigate the potential disruption (Fiedrich et al., 2000; Kunz et al., 2014). This chapter also illustrated the capability of the input-output interdependency model in multi-sectoral analysis. This work had also been extended in Lin et al. (2016a; 2016b) in Chapter 5 & 6 to the analysis of physical infrastructure networks to find the worst possible case scenarios.

Chapter 5 Critical infrastructure interdependencies modelling on one critical infrastructure

This chapter takes the first step towards modelling a physical critical infrastructure system as a critical infrastructure model. In this chapter, a Leontief input-output model of the critical infrastructure system and one physical critical infrastructure network is developed. The input-output model serves to evaluate the interdependencies among the various infrastructure systems, while the physical infrastructure network describes the linkages within one physical infrastructure. An interdependency matrix based on the national input-output table from the Singapore Department of Statistics is formulated to quantify the interdependencies among infrastructure systems. An elementary network of the telecommunication infrastructure of Singapore is constructed and integrated into the infrastructure interdependencies model. This chapter examines the overall impact of any failures within the telecommunication infrastructure using the input-output interdependencies model. By systematically evaluating the impact caused by one or more points of failure in the physical infrastructure, worst case scenarios can be determined, hence enabling the identification of the corresponding most critical/vulnerable points and failure combinations. The study aims to create a general framework for economic impact studies that can be used in any country with a national I/O table and a network structure of the critical infrastructure of concern. The results can provide insight on the fragility of the economic system with respect to different points of disruption, allowing stakeholders to be advised about the risks and magnitude of the potential damage and losses.

5.1 Modelling critical infrastructure interdependency

This study adopted the use of the input-output model described in Section 3.2 and used equations (3.1) – (3.10). Based on the case studies in Chapter 4, the input-output model as a critical infrastructure interdependency model produced results which are in fairly good agreement with those produced by other researchers using other methodologies.

Based on equation (3.9) from Section 3.2, it is noteworthy that ΔF is very crucial in this research as I/O models are based on the assumption that the external demand of a country (or the capability of an economic sector to sell to an external buyer) is the driver for economic activity in a country. The positive changes in final demand, ΔF, stimulate new funding and investment into an economic sector, which increase output X (Liu et al., 2004). Similarly, a negative change in final demand will lead to a decrease in output. This main attribute of the I/O model, where a change to an economic sector will result in an increase or decrease in output X of the other sectors connected within the model, is useful for critical infrastructure analysis (Jonsson et al., 2008). The economic losses in the I/O model are typically estimated on an annual basis. Hence, to estimate the losses of a shorter time frame (e.g. one day), the losses are being assumed to be spread uniformly across the 365 days in a year (Anderson et al., 2007). However, in a typical critical infrastructure analysis, it may take an extended amount of time for the impact to affect the other critical infrastructure sectors, thus the full impact may only be seen after a period of time.

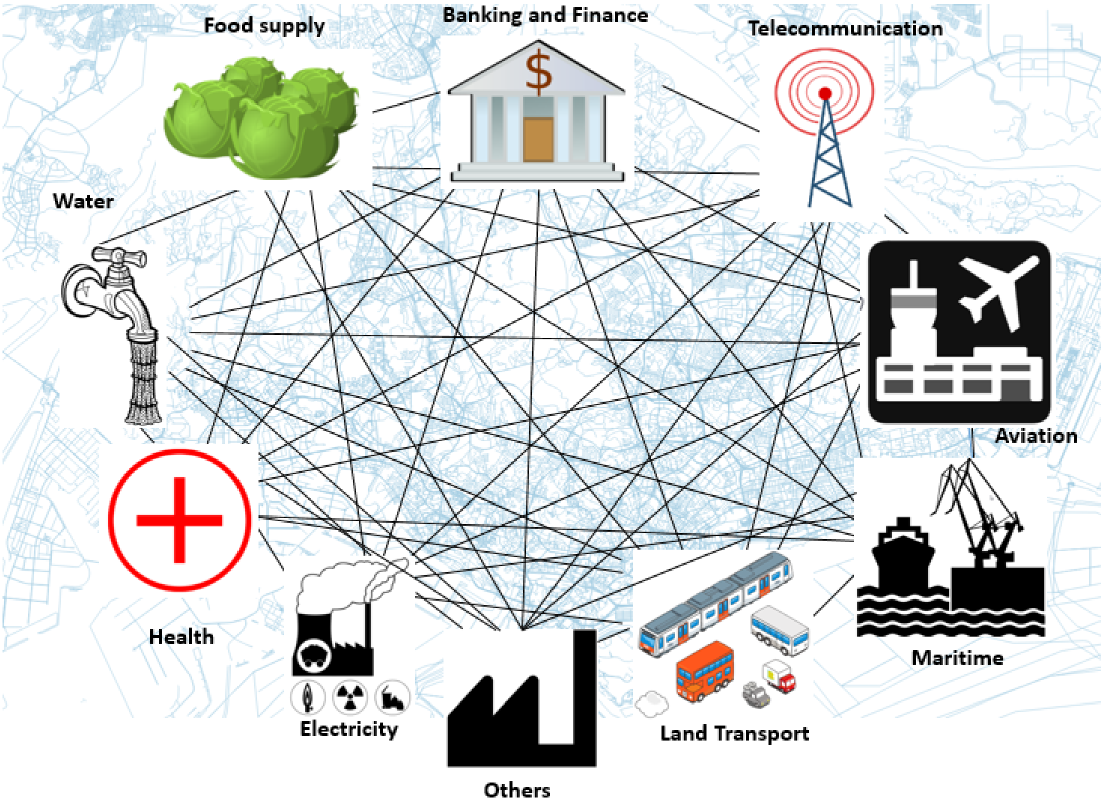


Figure 5-1: Combining physical infrastructure networks with the aggregated input-output interdependency model

The aggregation of the 136 sectors from the 2007 Singapore national I/O table (see Table 5-1) into their respective critical infrastructure sectors (nine main critical infrastructure sectors and one "others" sector that is a combination of the remaining "miscellaneous" economic sectors) is completed with reference to studies from the National Security Coordination Centre (2004) and Ho (2005). The grouping is based on the perception of the various sectors as critical infrastructure in Singapore (Lin et al., 2016a; 2016b), and therefore may not apply to other countries. The new "aggregated I/O table" based on the above aggregation is used to compute the I/O interdependency matrix (Table 5-2), which represents the linkages among all the critical infrastructure sectors as grouped in Figure 5-1. A sensitivity analysis on the different level of aggregation on CI sectors had been done in Appendix D to test on the different of results on different level of aggregation of CI sectors.

Table 5-1: Aggregation of economic sectors into their respective critical infrastructure sectors

No	Main CI sector	Relevant sector in I/O table by ID	Name of the sector
1	Banking and Finance	101	Life insurance
		102	General & other insurance
		103	Banks & finance companies
		104	Other financial services
		105	Fund management
2	Telecommunication	100	Communications
		109	Information technology
3	Electricity	77	Electricity
4	Water	79	Water
5	Land transport	88	Passenger transport by land
		95	Freight transport by land
6	Health	126	Medical & health services
		127	Environmental health services
7	Food supply	1	Nursery products
		2	Other agriculture
		3	Livestock
		6	Food preparations
		7	Bread, biscuits & confectionery
		8	Sugar, chocolate & related products
		9	Oils & fats
		10	Dairy products
		11	Coffee & tea
		12	Other food products
		13	Soft drinks
		14	Alcoholic drinks & tobacco
		29	Food chemicals & additives
		86	Food & beverage services
8	Aviation Security	92	Air transport
		93	Supporting services to air transport
		94	Airport operation services
9	Maritime Security	89	Water transport
		90	Supporting services to water

Note: The classification of industries in the I-O table is based on the 2005 Singapore Standard Industrial Classification

Table 5-2 derives from $(\mathrm{I}-\mathrm{A})^{-1}$ in Equation (3.9) and describes the physical interdependency linkages between critical infrastructures. For example, the value of 1.273 in Table 5-2 represents the self-interindustry relationship of "Banking & Finance" sector and for a \$1 worth of initial effect $\Delta\mathrm{F}$ in "Banking & Finance" sector, it will cause \$1.273 worth of overall effect to "Banking & Finance" sector after taking into

Table 5-2: Critical infrastructure interdependency matrix

	Banking & Finance	Telecommunication	Electricity	Water	Land transport	Health	Food supply	Aviation Security	Maritime Security	Others
Banking & Finance	1.273	0.014	0.030	0.045	0.053	0.032	0.032	0.019	0.017	0.043
Telecommunication	0.064	1.104	0.011	0.012	0.035	0.042	0.022	0.030	0.010	0.027
Electricity	0.005	0.007	1.238	0.072	0.017	0.020	0.030	0.011	0.002	0.015
Water	0.001	0.002	0.005	1.001	0.001	0.002	0.005	0.001	0.000	0.002
Land transport	0.003	0.003	0.001	0.001	1.185	0.003	0.005	0.003	0.002	0.004
Health	0.002	0.002	0.004	0.003	0.006	1.118	0.009	0.004	0.001	0.010
Food supply	0.005	0.004	0.001	0.002	0.003	0.005	1.074	0.017	0.004	0.004
Aviation Security	0.003	0.003	0.001	0.003	0.003	0.004	0.007	1.160	0.001	0.004
Maritime Security	0.005	0.006	0.003	0.004	0.033	0.006	0.010	0.008	1.085	0.023
Others	0.121	0.179	0.163	0.239	0.363	0.267	0.407	0.301	0.114	1.341

account the propagation of initial effect ΔF and the interdependencies of all critical infrastructures. Similarly, the value of 0.014 (right of 1.273) represents the interdependencies of “Banking & Finance” and “Telecommunication” sector and a $1 worth of initial effect ΔF in “Banking & Finance” sector will cause $0.014 worth of overall effect to “Telecommunication” sector after taking into account the propagation of initial effect ΔF and the interdependencies of all critical infrastructures. The other critical infrastructure interdependency matrix in the later chapter can also be described in similar ways.

Using the I/O model for critical infrastructure modelling is advantageous in various ways, namely (1) the data used is easily available from the public domain; (2) the linearity of the I/O model provides speed and flexibility in the calculation of the changes in demand; and (3) the fine representation of the inter-sectoral transactions captures the interdependencies among all economic sectors in a country (William & Thijs, 2009). A disadvantage of solely using the I/O model for critical infrastructure analysis is that the I/O model is inadequate towards describing actual physical infrastructure networks. An attempt to combine a physical infrastructure network and the I/O interdependency model is presented in the following sections.

5.2 Modelling a physical critical infrastructure network

In this chapter, a telecommunication network is used. The telecommunication network model developed here embodies the main interconnections of the telecommunication network in Singapore. It consists of two sets of elements – the central offices and transmission links.

Figure 5-2 illustrates the topology of the elementary telecommunication network (Tiong, 2009) developed in QGIS (QGIS, 2009). QGIS is an open-source geographic information system used to construct the location and linkages of the physical critical infrastructure network. The central offices are simulated as nodes and the transmission links are simulated as the links between the nodes. For example, a link connecting node 0 and node 1 denotes that both nodes are interdependent in their operations. When a disruption to a specific node happens, it will be treated as a node failure, which then detaches all links connected to the node. A sensitivity analysis on the topology representation of physical CI is being done in Appendix D, Section D.2, to test how the overall impact (ΔX) calculated will changes over different network topology.

The network performance for the physical infrastructure is evaluated before and after the occurrence of a failure in the physical infrastructure network (Dalziell & McManus 2004). Two network performance metrics are used in this study, namely (1) the efficiency of network (Crucitti et al., 2004; Wang et al., 2013) and (2) the network average clustering coefficient (Brust & Rothkugel, 2007; Holmgren, 2006; Mao et al., 2009). The ‘efficiency of network’ is used to measure how efficiently resources are exchanged in a network. The network average clustering coefficient is used to measure the average degree to which all nodes are clustered together, which quantify the density of the network composition. As the different performance metrics measure different aspects and characteristics of a network, they are thus both useful in network analysis.

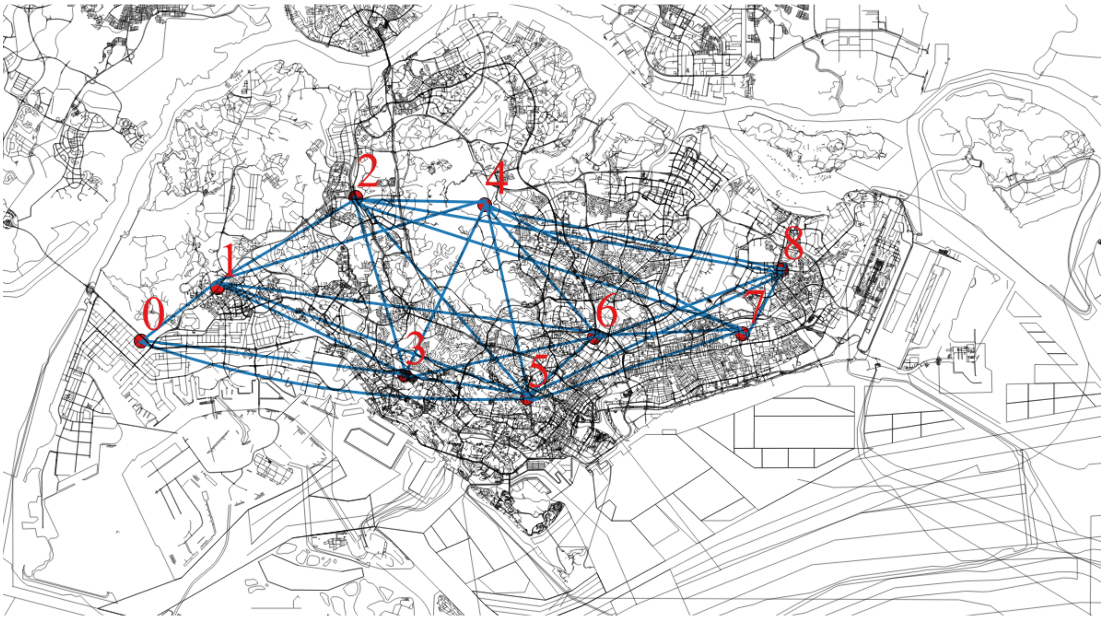


Figure 5-2: Telecommunication network constructed in QGIS

The efficiency, η, of the network (Latora & Marchiori, 2001) is defined as follows:

$$\eta = \frac{1}{n(n-1)} \sum_{i,j \in V} \frac{1}{d_{ij}} \tag{5.1}$$

In the equation, *n* represents the number of nodes in the network, *v* represents the set of nodes, and d_{ij} represents the shortest path length between nodes *i* and *j*.

The average clustering coefficient of a network (Kemper, 2009) is defined as the average of the local clustering coefficient of all nodes in the network, and is formulated as follows:

$$\eta = \frac{1}{n}\sum_{i=1}^{n} \frac{\text{number of triplets (closed) connected to node } i}{\text{number of triplets (both open and closed) centered on node } i} \tag{5.2}$$

The clustering coefficient of a nodes is based on triplets of nodes. A triplet is three nodes that are connected by either two (open triplet) or three (closed triplet) undirected ties. The clustering coefficient of a nodes is the number of closed triplets over the total number of triplets (both open and closed) of a node. The average clustering coefficient is the direct average of the clustering coefficient of all nodes, n, in a network.

Simulations for the individual failed nodes and combinations of failed nodes are conducted and the resultant percentage (e_{loss}) change in network performance is evaluated according to the following:

$$e_{loss} = \left(1 - \frac{\eta_{final}}{\eta_{initial}}\right) \times 100\% \tag{5.3}$$

In the above equation, $\eta_{initial}$ denotes the initial network performance, and η_{final} refers to the final network performance after node failures, and $\eta_{initial}$ and η_{final} are computed based on the respective network performance metrics. It is assumed that when the network performance of a physical critical infrastructure network after a node failure is lower, the removed node is critical, and e_{loss} will be positive to indicate its criticality.

A central office that encounters any disruption in the elementary telecommunication network is modelled as a node failure in the network. Upon any node failure, the impact to the corresponding infrastructure sectors per day can be computed as a monetary loss derived by:

$$w_{loss} = \frac{x_i}{365} e_{loss} \tag{5.4}$$

In the above equation, w_{loss} represents the monetary loss per day for critical infrastructure sector *i* due to the change in its network performance. x_i represents the output of the sector *i* in a year and e_{loss} represents the loss of network performance upon failure in the physical critical infrastructure. w_{loss} is used in $\Delta\mathrm{F}_i$ to estimate the loss due to critical infrastructure sector *i* in the I/O table.

5.3 Integration of one physical critical infrastructure network into the input-output interdependency model

The use of a physical infrastructure network makes the simulation of disruption possible. Node failure in the network is simulated as a disruption that may cause cascading damages to other critical infrastructure sectors linked via the interdependency model. The impact to these sectors as a result of any hazards or failures that affect the physical critical infrastructure can thus be established.

The critical infrastructure network is first constructed in QGIS and then imported into Netlogo, which is a multi-agent programming language and integrated modelling environment (Wilensky, 1999). Netlogo is selected because of its ease of use and its simulation language. The elementary critical infrastructure network constructed in QGIS contains the geographical location of the nodes and links, which provides the possibility of extension to geographical area damage simulation in future work.

The failure scenarios within the physical infrastructure network, comprising of one-node failures, two-node failures and three-node failures, are simulated by assuming different combinations of failed nodes and computing the resulting impact on all critical infrastructure sectors interconnected in the I/O model (Kizhakkedath et al., 2013; Lam et al., 2013; Tai et al.,2013).

Figure 5-3 is a graphical representation created using the Netlogo programme for "one physical network", which in this case is a telecommunication network. The links and geographical locations of the telecommunication network (Tiong, 2009) are imported into Netlogo to construct the network. Details of the links are provided in Table 5-3. For clarity, nodes 0 to 8 are the nodes in the telecommunication network.

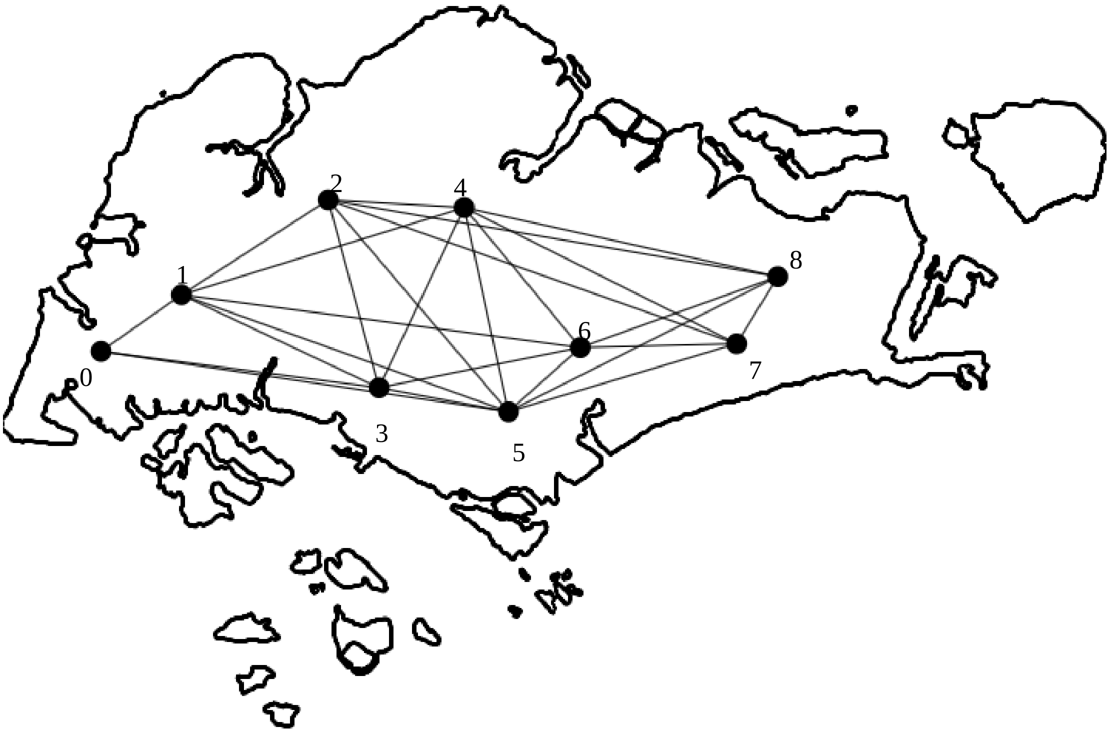


Figure 5-3: Netlogo programme for modelling node failure in one critical infrastructure network

Figure 5-4 describes how network performance losses in a physical infrastructure cascades economic losses across all critical infrastructures through the I/O model. The losses in the network performance (ΔF) in each critical infrastructure network are evaluated by using I/O interdependency matrix $(\mathrm{I}-\mathrm{A})^{-1}$ in Table 5.2 through Equation (3.9) to find the total impact to all sectors (ΔX), which will evaluates the overall losses across all critical infrastructures due to the initial losses calculated through the network performance losses as described in Figure 5-4. In order to find the worst case scenario, a comprehensive exhaustive search via coding for all the possible combinations of failed nodes is conducted for one-node failure, two-node failure and three-node failure scenarios.

Table 5-3: Links of the telecommunication infrastructure network used

	TS	JW	BP	AR	AM	OC	ES	BD	TP
TS	0	1	0	1	0	1	0	0	0
JW	1	0	1	1	1	1	1	0	0
BP	0	1	0	1	1	1	0	1	1
AR	1	1	1	0	1	1	1	0	0
AM	0	1	1	1	0	1	1	1	1
OC	1	1	1	1	1	0	1	1	1
ES	0	1	0	1	1	1	0	1	1
BD	0	0	1	0	1	1	1	0	1
TP	0	0	1	0	1	1	1	1	0
node-id	0	1	2	3	4	5	6	7	8

Note: The abbreviations used in this table are the names of the node locations in Singapore The abbreviations stand for Tuas (TS), Jurong West (JW), Bukit Panjang (BP), Ayer Rajah (AR), Ang Mo Kio (AM), Orchard (OC), Eunos (ES), Bedok (BD), and Tampines (TP) respectively.

The e_{loss} and w_{loss} for the infrastructure networks in this study are calculated and used as the component of ΔF in the I/O model to compute the overall impact over all sectors.

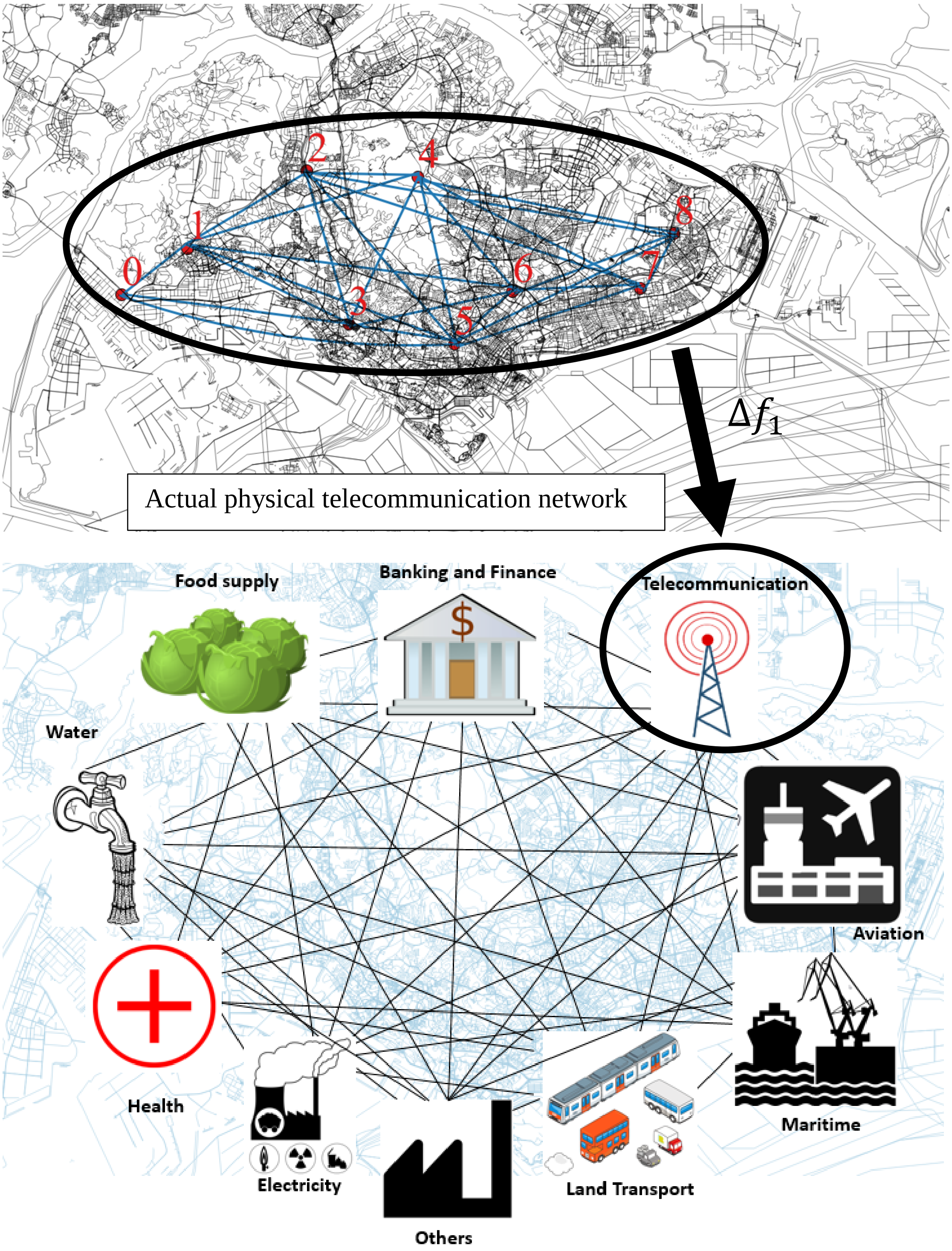


Figure 5-4: Propagation of network performance losses into I/O interdependency model

5.4 Simulation results and discussion for one physical critical infrastructure

The worst case scenario caused by the failure of the most critical node or node combination is the focus for this chapter. All results for all node combinations were recorded and ranked (Apostolakis & Lemon, 2005) accordingly to the analysis of the case scenario for the given one-node failure, two-node failure and three-node failure scenarios.

One physical infrastructure network, namely the telecommunication network, is being simulated in Netlogo. Tables 5-4, 5-5 and 5-6 present the results of the corresponding case scenarios for one-node, two-node and three-node failures, respectively, based on each of the two network performance metrics.

Table 5-4: Results for all case scenarios based on a one-node failure in one physical infrastructure network

Network performance metric	Failed Node	η_{initial}	η_{final}	e_{loss}	Overall impact, ΔX/day ($ Millions)
Efficiency of network	(0)	1.28	1.18	7.76	6.94
	(7)	1.28	1.25	2.17	1.94
	(8)	1.28	1.25	2.17	1.94
	(1)	1.28	1.29	-0.621	-0.555
	(2)	1.28	1.29	-0.621	-0.555
	(3)	1.28	1.29	-0.621	-0.555
	(6)	1.28	1.29	-0.621	-0.555
	(4)	1.28	1.32	-3.42	-3.05
	(5)	1.28	1.43	-11.8	-10.5
Network average clustering coefficient	(5)	0.793	0.717	9.64	8.62
	(4)	0.793	0.73	7.99	7.14
	(7)	0.793	0.796	-0.342	-0.306
	(8)	0.793	0.796	-0.342	-0.306
	(1)	0.793	0.802	-1.17	-1.04
	(3)	0.793	0.802	-1.17	-1.04
	(0)	0.793	0.824	-3.87	-3.46
	(2)	0.793	0.836	-5.37	-4.80
	(6)	0.793	0.836	-5.37	-4.80

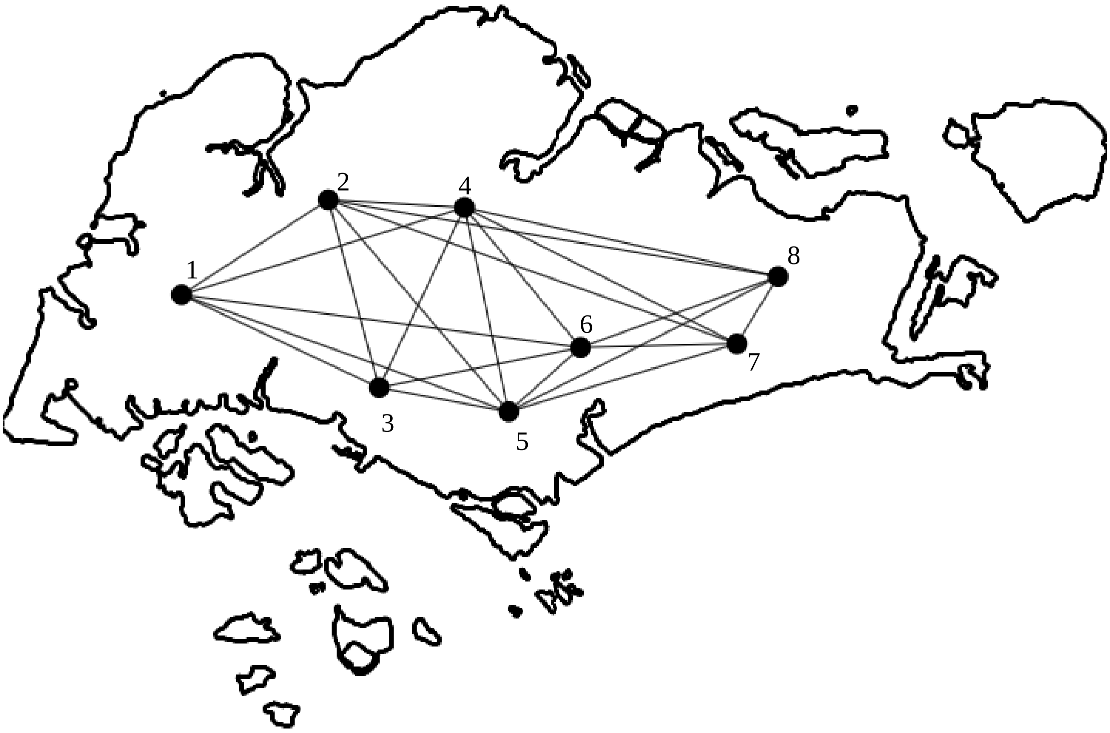


Figure 5-5: Example of node 0 failure under the efficiency of network metric in Table 5-4

As described in Section 5.3, the overall impact for each case scenario is computed by applying Equation (3.9) using the critical infrastructure interdependency matrix in Table 5-2. In Table 5-4, which shows the results of all case scenarios for one-node failure, node 0 is discovered to be the most critical node under the efficiency of network metric (Figure 5-5), while node 5 is the most critical node under the network average clustering coefficient metric. Node 7 under average clustering coefficient metric receives a negative value for the calculated overall impact for its failure under the network average clustering coefficient metric. The negative overall impact results observed for node 7 and the rest of the node under average clustering coefficient metric and efficiency of network could be explained as a phenomenon where the failure of a node actually increases the network performance of the critical infrastructure. From the viewpoint of network performance analysis, this situation is possible because there are some nodes that are less crucial, and their removal thus increases the performance of the infrastructure (e.g. the flow of goods and service in the network becomes more efficient due to the removal of node). However, a node failure in a physical infrastructure in the real world would definitely still cause some undesirable impact on the critical infrastructure and to the overall economy and hence it may be necessary to remove and disregard those instances of negative e_{loss} from the analysis and results.

Table 5-5: Results for the top ten worst case scenarios based on a two-node failure in one physical infrastructure network

Network performance metric	Failed Nodes	η_{initial}	η_{final}	e_{loss}	Overall impact, ΔX/day ($ Millions)
Efficiency of network	(0 1)	1.28	1.14	10.6	9.44
	(0 3)	1.28	1.14	10.6	9.44
	(0 7)	1.28	1.14	10.6	9.44
	(0 8)	1.28	1.14	10.6	9.44
	(0 2)	1.28	1.19	6.83	6.11
	(0 6)	1.28	1.19	6.83	6.11
	(7 8)	1.28	1.19	6.83	6.11
	(0 4)	1.28	1.24	3.11	2.78
	(0 5)	1.28	1.24	3.11	2.78
	(2 7)	1.28	1.24	3.11	2.78
Network average clustering coefficient	(4 5)	0.793	0.571	28.0	25.0
	(1 5)	0.793	0.576	27.4	24.4
	(3 5)	0.793	0.576	27.4	24.4
	(5 7)	0.793	0.700	11.7	10.5
	(5 8)	0.793	0.700	11.7	10.5
	(4 7)	0.793	0.714	9.94	8.89
	(4 8)	0.793	0.714	9.94	8.89
	(1 4)	0.793	0.719	9.34	8.35
	(3 4)	0.793	0.719	9.34	8.35
	(0 4)	0.793	0.743	6.34	5.67

The top ten worst case two-node failures under the efficiency of network metric as seen in Table 5-5 are the node pairs (0 1), (0 3) and (0 7), and they all include node

0 which happened to be the most critical node under the same metric for one-node scenarios (as seen from the results in Table 5-4). Similarly, the top ten worst node pairs

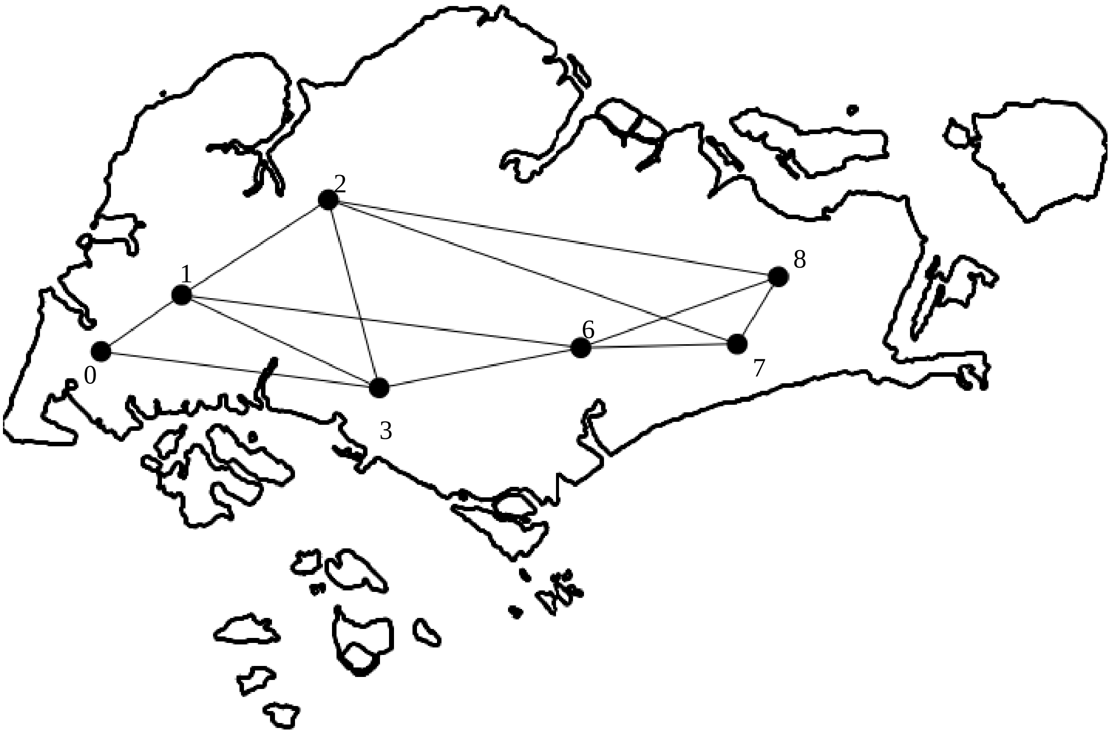


Figure 5-6: Example of node pair (4 5) failure under the network average clustering coefficient metric in Table 5-5

under the network average clustering coefficient metric from Table 5-5 are (4 5), (1 5), (3 5), and they all include node 5, which was also the most critical node under the same metric from Table 5-4. Node pair (4 5) is illustrated as an example in Figure 5-6. Intuitively, it should not be surprising that the worst case node pairs included the most critical node from the one–node scenarios under the same metric since the metric quantifies the network performance in similar manner in one-node and two node failure scenario. However, the anticipation of the interactions when two or more nodes fail is not straightforward, and their combined impact may not simply be the sum of the individual impacts. This is because the evaluated results, w_{loss}, are based on equation (5.1) and (5.2) which are non-linear. When w_{loss} is used in Δf_i, the overall result, ΔX, evaluated from equation (3.9) will be non-linear. For example, failure of node pair (0 1) causes \$9.44 million in overall losses under the efficiency of network metric in Table 5-5. However, for one-node failures in Table 5-4, node 1 is not found in the most significant node, and in fact, the \$9.44 million worth of damages caused by (0 1) is actually slightly larger than the summation of the top two overall impacts under the efficiency of network metric in Table 5-4 (amounting to SGD\$8.88 million if we sum up the overall impact of node 0 and node 7). This implies that a combination of node failures can potentially cause damages that are higher than expected, and becomes more significant as the number of failed nodes increase, as presented in Table 5-6. As the I/O model is fundamentally linear, any change to the input loss $\Delta \mathrm{F_i}$ will have linear relationship to the output predicted overall loss ΔX. However, $\mathrm{w_{loss}}$, which is used in Δf_i, is non-linear as they are calculated based on efficiency of network and average cluster coefficient of a network. The calculated network performance metrics depends on the CI network construction uniquely and a complete thorough search for all possible scenario for 1,2,3 nodes failure are done in Chapter 5 & 6 to avoid missing out any cases. There will only be variability of results if the CI network change (and the linkages too). With the evaluation of physical CI network performance based on node failure and applying them into the input-output model, this makes the system nonlinear.

Based on Table 5-6, which shows the results of the top ten worst case scenarios for three-node failures, nodes (0 1 3) and nodes (0 7 8) are the two worst case scenarios for overall impact under the efficiency of network metric while nodes (1 4 5) and nodes (3 4 5) are the two worst case scenarios for overall impact under the network average clustering coefficient metric. Nodes (1 4 5) are illustrated as an example in Figure 5-7. Overall, simulations for multiple node failures do produce some unexpected results. For example, the emergence of nodes (0 1 3) as the worst case scenario under efficiency of network metric was unexpected, as nodes 1 and 3 were not among the top few most critical nodes in the one-node scenarios. One of the potential reasons for this might be due to the topological linkages that have caused the node combination of (0 1 3) to be the overall most critical under the efficiency of network performance metric.

Table 5-6: Results for the top ten worst case scenarios based on a three-node failure in one physical infrastructure network

Network performance metric	Failed Nodes	η_{initial}	η_{final}	e_{loss}	Overall impact, ΔX/day ($ Millions)
Efficiency of network	(0 1 3)	1.28	1.07	16.5	14.8
	(0 7 8)	1.28	1.07	16.5	14.8
	(1 3 5)	1.28	1.10	13.9	12.4
	(0 1 2)	1.28	1.13	11.3	10.1
	(0 1 6)	1.28	1.13	11.3	10.1
	(0 1 7)	1.28	1.13	11.3	10.1
	(0 1 8)	1.28	1.13	11.3	10.1
	(0 2 3)	1.28	1.13	11.3	10.1
	(0 2 7)	1.28	1.13	11.3	10.1
	(0 2 8)	1.28	1.13	11.3	10.1
Network average clustering coefficient	(1 4 5)	0.793	0.333	58.0	51.8
	(3 4 5)	0.793	0.333	58.0	51.8
	(4 5 8)	0.793	0.444	44.0	39.3
	(4 5 7)	0.793	0.444	44.0	39.3
	(1 5 7)	0.793	0.500	37.0	33.0
	(1 5 8)	0.793	0.500	37.0	33.0
	(3 5 8)	0.793	0.500	37.0	33.0
	(3 5 7)	0.793	0.500	37.0	33.0
	(0 4 5)	0.793	0.556	30.0	26.8
	(1 2 5)	0.793	0.611	22.9	20.5

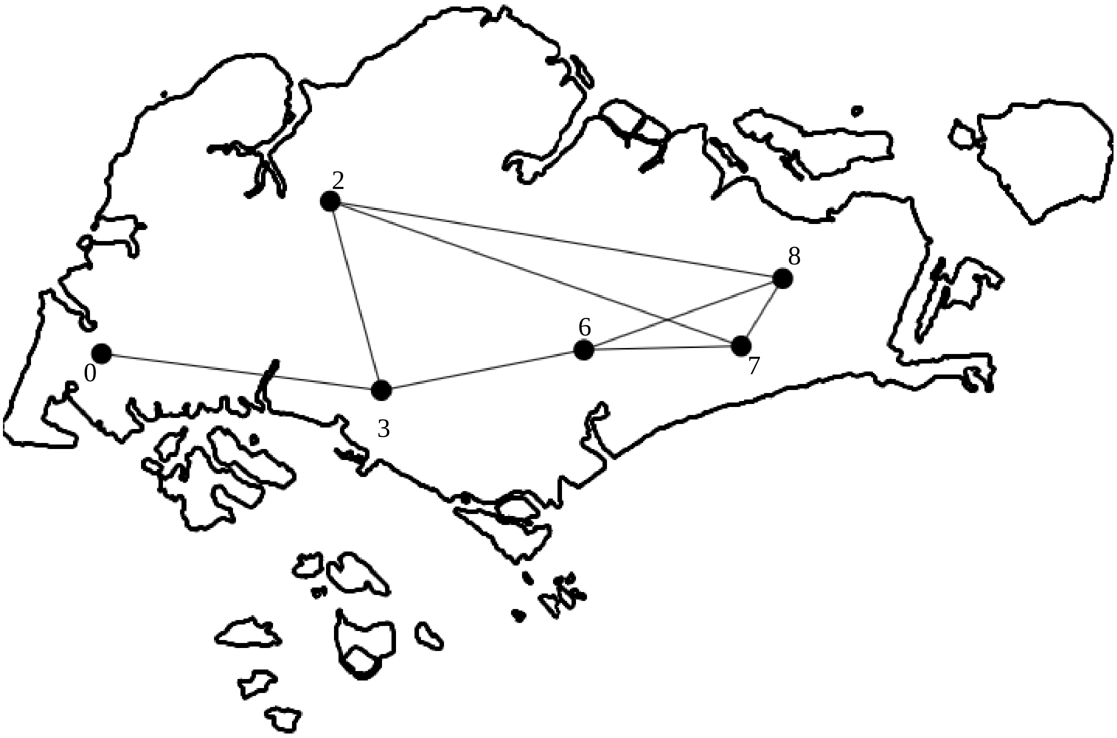


Figure 5-7: Example of node (1 4 5) failure under the network average clustering coefficient metric in Table 5-6

5.5 Summary of this chapter

Critical infrastructures are different in form and are interconnected. This increases the complexity of modelling them all together. By using modelling and simulation, these interdependencies can be captured and analysed systematically. The I/O interdependency model provides a representation of the cascading effect of some failure on one physical critical infrastructure through modelled interdependencies. The network performance metrics used in this chapter serve as a proxy for the full simulation of the network performance based on the assumption that users do not have the detailed info about the network capacity, routing protocol, hierarchy and other data. The current work in this chapter is a generic one and can be used for all countries with a publicly available I/O table, which is a reliable and open-source data. However, there are some limitations to this framework, such as the lack of cross references to some particular critical infrastructure, as the I/O model is an economic based model and some critical infrastructure do not make up a large proportion of monetary output in the national economy (Filippini & Silva, 2014). An example of this is the electricity sector, which holds a smaller economic value as compared to other sectors but is very critical to a nation. Some critical infrastructure, like military defence, which is traditionally classified as critical infrastructure, is not included as a sector in the I/O table as it does not technically contribute to the national economy but is critical to the defence of a nation. The next stage of the research is on the construction of two known critical infrastructure networks and the simulation of disruption via similar methods. The overall damage propagated through the I/O interdependencies could provide valuable insight to the overall economic damage caused to the nation’s critical infrastructure.

Chapter 6 Vulnerability analysis for two critical infrastructure sectors

This chapter takes the second step towards modelling a physical critical infrastructure system into a critical infrastructure model. This chapter is an straightforward extension of the work in Chapter 5, with two critical infrastructure sectors being modelled and integrated into the critical interdependency model discussed in Chapter 3. While the analysis done in Chapter 5 is similar to the analysis done in this chapter, the differences between single and multiple critical infrastructure are being discussed below, and the results of the multiple critical infrastructure sectors are being evaluated in this chapter.

6.1 Modelling electricity grid network

This chapter consists of modelling two critical infrastructure networks. One of the critical infrastructure networks is the telecommunication network, which was discussed in Section 5.2. The telecommunication network is represented by Nodes 1-8 in Figure 5-2. The second network to be modelled is the electricity grid network, which is developed here based on the same rules described in Section 5.2. The nodes and links in the electricity grid network correspond to the main power plants and the main linkages between the power plants. As the finer details of the electricity grid were not available, the electricity grid used in Figure 6-1 was treated as a coarse model.

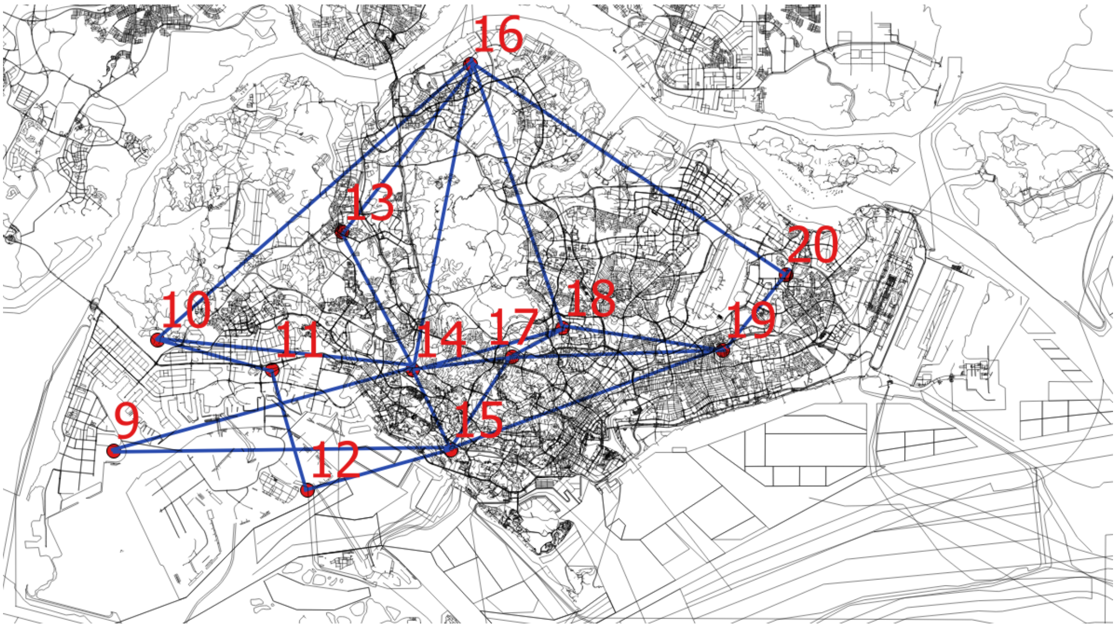


Figure 6-1: Electricity grid network constructed in QGIS

Table 6-1: Links of the electricity grid network used

	Tuas PS	Upper Jurong	Jurong Pier	P Seraya PS	Choa Chua kang	Ayer Rajah	Labrador	Senoko PS	Kg Java	Kallang Basin	Paya Lebar	Tampines
Tuas PS	0	0	0	0	0	1	1	0	0	0	0	0
Upper Jurong	0	0	1	0	0	1	0	1	0	0	0	0
Jurong Pier	0	1	0	1	0	0	0	0	0	0	0	0
P Seraya PS	0	0	1	0	0	0	1	0	0	0	0	0
Choa Chua kang	0	0	0	0	0	1	0	1	0	0	0	0
Ayer Rajah	1	1	0	0	1	0	1	1	1	1	0	0
Labrador	1	0	0	1	0	1	0	0	1	0	1	0
Senoko PS	0	1	0	0	1	1	0	0	0	1	0	1
Kg Java	0	0	0	0	0	1	1	0	0	1	1	0
Kallang Basin	0	0	0	0	0	1	0	1	1	0	1	0
Paya Lebar	0	0	0	0	0	0	1	0	1	1	0	1
Tampines	0	0	0	0	0	0	0	1	0	0	1	0
node-id	9	10	11	12	13	14	15	16	17	18	19	20

Figure 6-1 illustrates the topology of the elementary electricity grid network (Chang et al., 2001) developed in QGIS (QGIS, 2009). Nodes 9 to 20 represent the power plants in the electrical grid, while the linkages (Table 6-1) represent the electricity power lines connecting the power plants. Similar to the telecommunication network in Section 5.2, if a link is connecting two nodes, such as node 9 and node 14, it indicates that both nodes are linked and interdependent in their operations. When a disruption happens to a specific node, a node failure occurs and causes all links attached to this node to fail and disconnect.

The network performance for the multiple physical infrastructure is evaluated before and after a failure occurs in the physical infrastructure network. Again, two network performance metrics are used, namely (1) efficiency of network (Crucitti et al., 2004; Wang et al., 2013) and (2) network average clustering coefficient (Brust & Rothkugel, 2007; Holmgren, 2006; Mao et al., 2009), which were discussed in Section 5.2.

6.2 Combining the I/O model and physical critical infrastructure network

Similar to the telecommunications network developed in Section 5.2, the electricity grid in Section 6.1 is developed in Netlogo. This enables the simulation of disruption, and the node failure in the network is simulated as a disruption that may cause cascading impacts on other critical infrastructure sectors linked via the interdependency model. The impact to these sectors can thus be evaluated for any potential hazards or failures that may affect the physical critical infrastructure. Similar to Section 5.3, the critical infrastructure network is first constructed in QGIS and then imported into Netlogo for the simulation of the disruption.

Figure 6-2 shows the graphical representation from the Netlogo programme for “two physical networks” comprising the telecommunication network (Tiong, 2009) and the electrical grid (Chang et al., 2001). The details of the links are provided in Table 5-3 and Table 6-1 respectively.

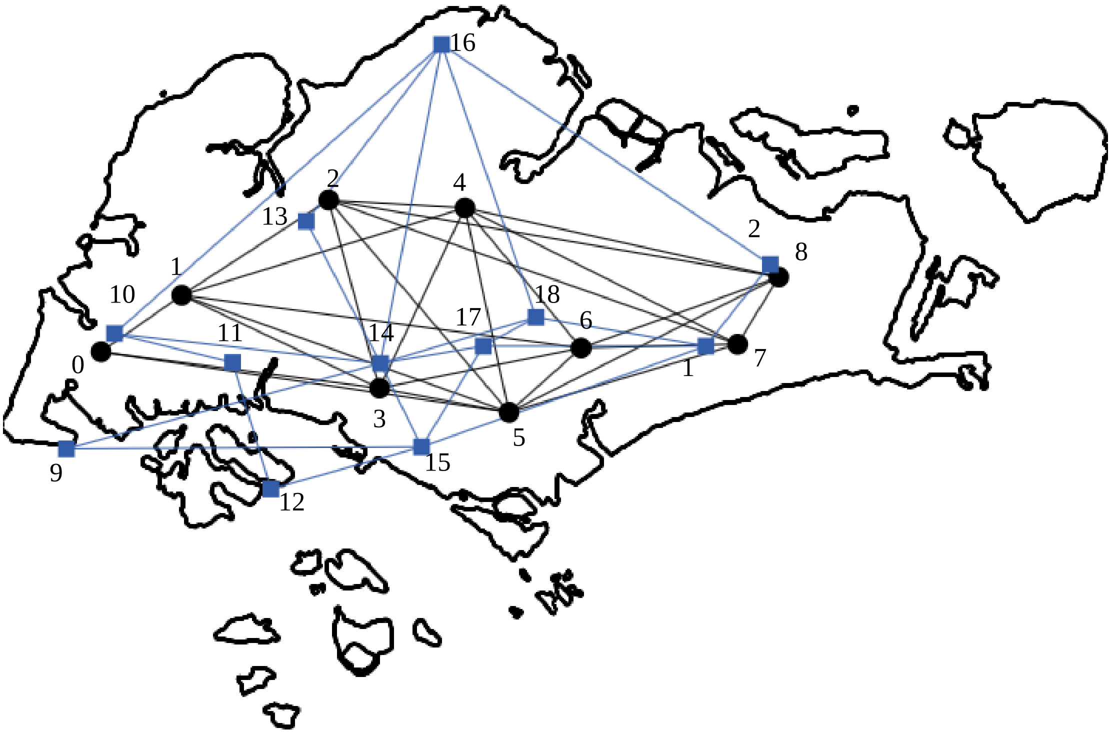


Figure 6-2: Netlogo programme for modelling node failure in two critical infrastructure networks

For the simulation, any node failure and monetary loss w_{loss} is assumed to be for the duration of one full day. The losses of network performance are propagated across the other critical infrastructure sectors and the total impact to all sectors is evaluated. In order to find the worst case scenario, a comprehensive exhaustive search for all possible combinations of failed nodes was conducted for one-node failure, two-node failure and three-node failure scenarios.

The network performance for multiple physical networks is calculated individually as the networks are not connected physically but are connected through the I/O interdependency model as illustrated in Figure 6-3. This is to avoid over-calculating

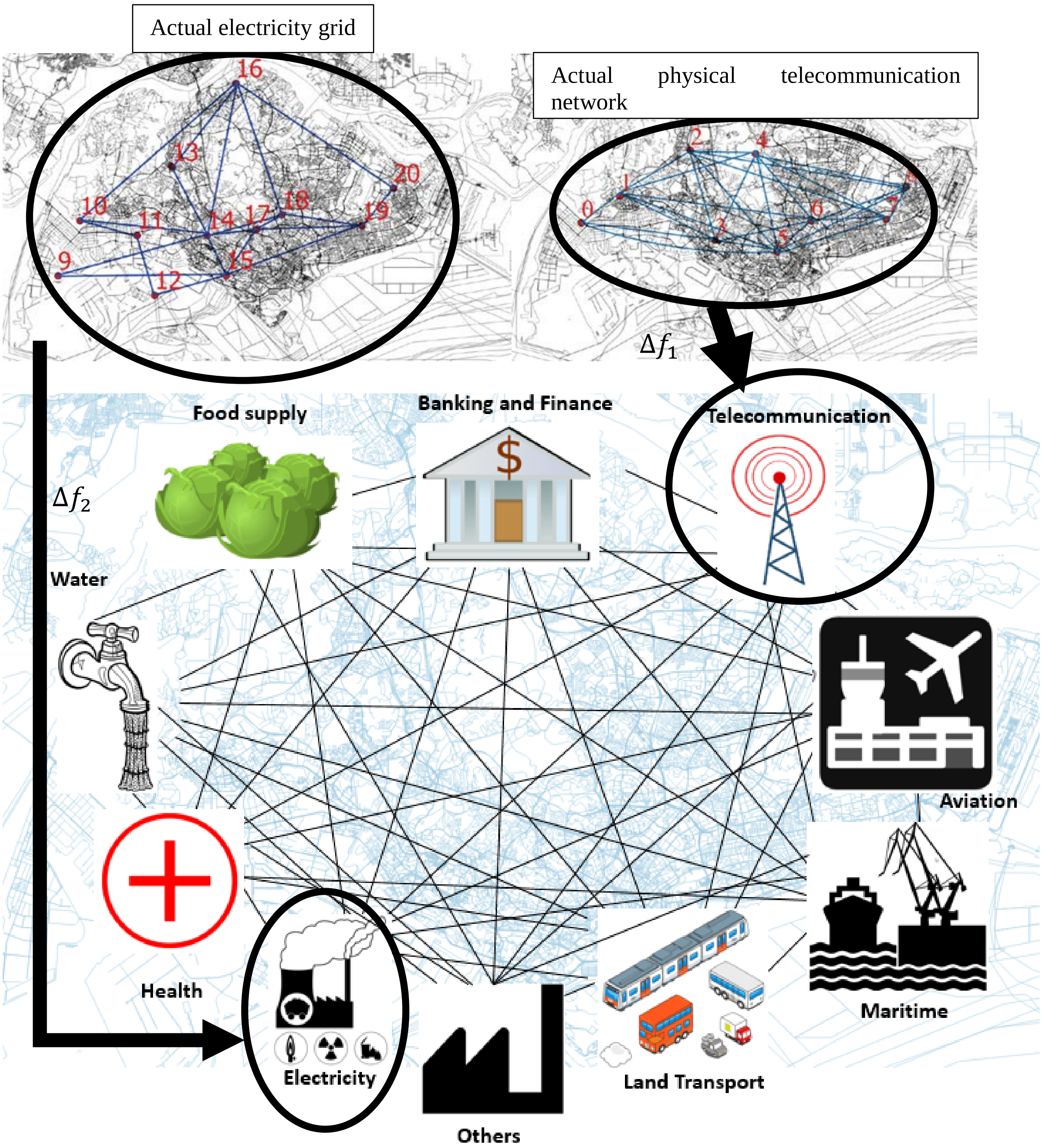


Figure 6-3: Propagation of network performances losses into an I/O interdependency model for two physical critical infrastructure

the impact incurred due to the disruption (Beccuti et al., 2012; Marrone et al., 2013). The reason behind this is that the interdependencies are already established in the input-output interdependencies model and should not be modelled at the physical network level in Figure 6-2. As such there is no physical interdependency link between the two physical networks. The e_{loss} and w_{loss} for each of the two infrastructure networks in this study are calculated individually and used as two non-zero component of ΔF in the I/O model to derive the overall impact on all sectors. For example, both electricity grid and telecommunication network happened to be impacted by an area attack simultaneously. This attack will causes a network performance drop in both networks in the form of $e_{loss(1)}$ for electricity grid and $e_{loss(2)}$ for telecommunication network, and thus $w_{loss(1)}$ and $w_{loss(2)}$ can be evaluated based on Equation (5.4). As the $w_{loss(1)}$ and $w_{loss(2)}$ can be represented as $\Delta \mathrm{F}_1$ and $\Delta \mathrm{F}_2$, the evaluation of the overall impact losses through Equation (3.9) produces ΔX, which is the overall impact losses to all critical infrastructures in the nation as shown in the last column of Table 6-2.

6.3 Simulation results and discussion for two physical infrastructure scenario

In this chapter, two physical infrastructure networks, namely the telecommunication network and electricity grid network, are simulated on Netlogo. Tables 6-2, 6-3 and 6-4 present the results of the top ten worst case scenarios for one-node, two-node and three-node failures, respectively. The failure of nodes can occur in either one or both networks. $e_{loss(1)}$ and $e_{loss(2)}$ represent the percentage losses of network performance in the telecommunication network and electrical grid, respectively.

Table 6-2: Results for the top ten worst case scenarios based on a one-node failure in two physical infrastructure networks

Network performance metric	Failed Node	$e_{loss(1)}$	$e_{loss(2)}$	Overall impact, ΔX/day ($ M)
Efficiency of network	(0)	7.76	0.00	6.94
	(7)	2.17	0.00	1.94
	(8)	2.17	0.00	1.94
	(11)	0.00	4.19	1.41
	(13)	0.00	2.26	0.76
	(20)	0.00	2.26	0.76
	(9)	0.00	1.29	0.44
	(12)	0.00	1.29	0.44
	(18)	0.00	-0.65	-0.22
	(17)	0.00	-1.61	-0.54
Network average clustering coefficient	(14)	0.00	65.3	22.0
	(16)	0.00	26.8	9.04
	(5)	9.64	0.00	8.62
	(15)	0.00	21.4	7.22
	(17)	0.00	21.4	7.22
	(4)	7.99	0.00	7.14
	(9)	0.00	12.2	4.10
	(13)	0.00	12.2	4.10
	(18)	0.00	2.14	0.72
	(8)	-0.34	0.00	-0.31

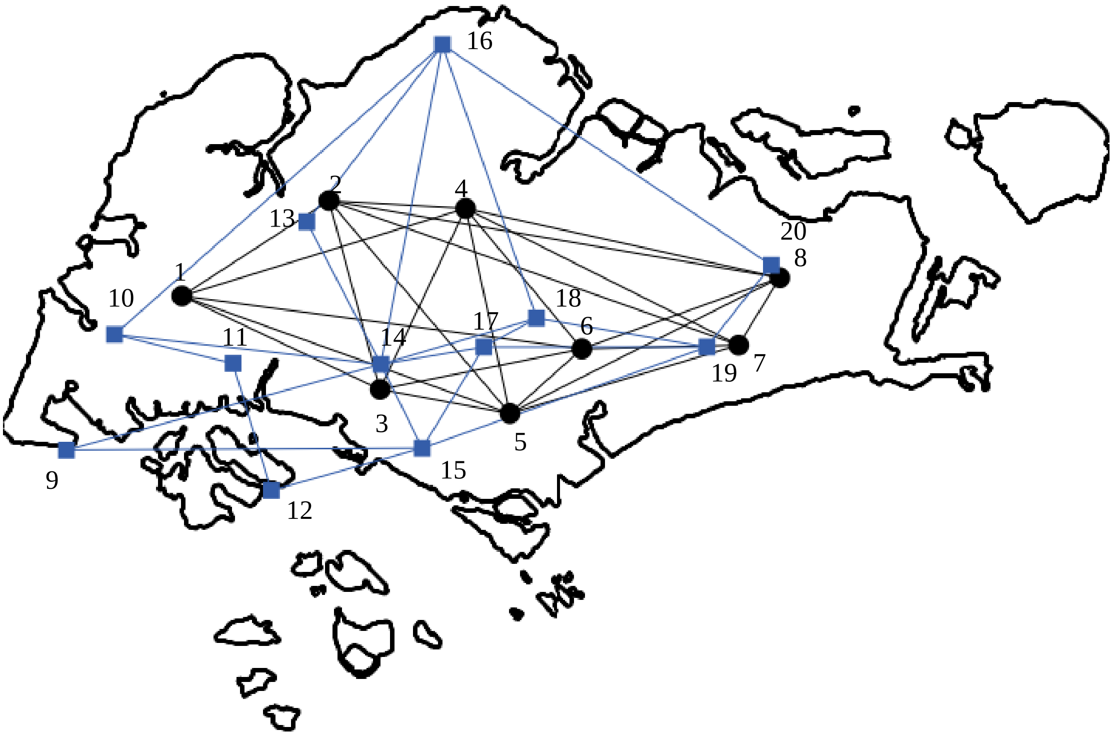


Figure 6-4: Example of node 0 failure under the efficiency of network metric in Table 6-2

Under the efficiency of network metric, all the results in Tables 6-2, -6-3 and 6-4 (i.e. for two physical infrastructure) are the same as those in Tables 5-4, 5-5 and 5-6 (i.e. for the single physical infrastructure). Figure 6-4 shows the worst case scenario of the disruption of node 0 under the efficiency of network metric in a one-node failure scenario due to the evaluation method of efficiency of network in equation (5.1). Under the efficiency of network performance metric, the top ten worst cases for one-node failure, two-node failure and three-node failure scenarios in Tables 6-2, -6-3 and 6-4 as well as Tables 5-4, 5-5 and 5-6 all involve nodes from the telecommunication network only. The efficiency of network performance metric might potentially be highly sensitive to the percentage of nodes removed in a network as the telecommunication network consists of a total of nine nodes, while the electricity grid network consists of twelve nodes in total. The topology of the linkages might also relate to the reason for this phenomenon and therefore, is an area worthwhile to be taken note of. However, the results under the network average clustering coefficient metric are mostly different and Table 6-2 shows that node 14 turns out to be the most critical node under this metric for one-node failure.

Table 6-3: Results for the top ten worst case scenarios based on a two-node failure in two physical infrastructure networks

Network performance metric	Failed Nodes	$e_{loss}(1)$	$e_{loss}(2)$	Overall impact, ΔX/day ($ M)
Efficiency of network	(0 1)	10.6	0.00	9.44
	(0 3)	10.6	0.00	9.44
	(0 7)	10.6	0.00	9.44
	(0 8)	10.6	0.00	9.44
	(0 11)	7.76	4.19	8.35
	(0 13)	7.76	2.26	7.70
	(0 20)	7.76	2.26	7.70
	(0 90	7.76	1.29	7.38
	(0 12)	7.76	1.29	7.38
	(0 18)	7.76	-0.65	6.72
Network average clustering coefficient	(14 17)	0.00	100	33.7
	(14 19)	0.00	100	33.7
	(5 14)	9.64	65.3	30.6
	(4 14)	7.99	65.3	29.2
	(4 5)	28.0	0.00	25.0
	(1 5)	27.4	0.00	24.4
	(3 5)	27.4	0.00	24.4
	(16 17)	0.00	67.8	22.9
	(7 14)	-0.34	65.3	21.7
	(8 14)	-0.34	65.3	21.7

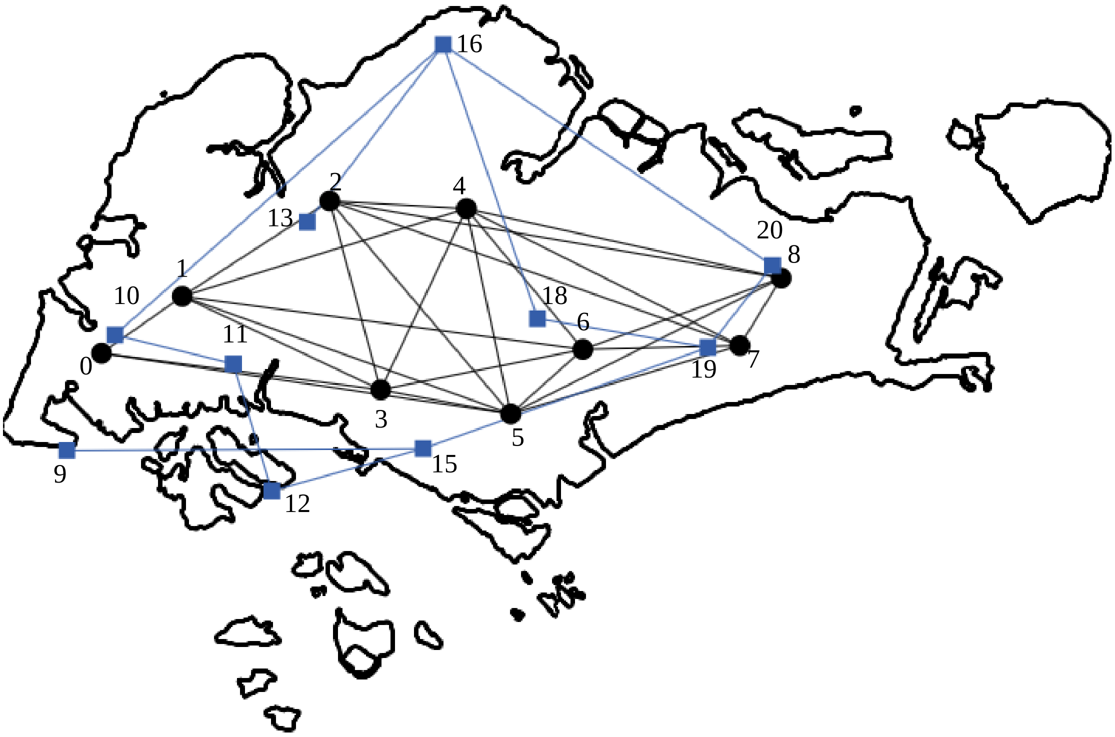


Figure 6-5: Example of node pair (14 17) failure under the network average clustering coefficient metric in Table 6-3

As for two-node failures, the top two worst node pairs as seen in Table 6-3 are (14 17) and (14 19), and both pairs include node 14, which is also the most critical node under the same metric from Table 6-2. Node pair (14 17) is illustrated in Figure 6-5. Note that node pairs (14 17) and (14 19) cause 100% losses in network performance in $e_{loss(2)}$, with the electrical grid having a clustering coefficient of zero for all nodes, and therefore zero network average clustering coefficient for the network. If there is a 100% losses in network performance, $e_{loss(2)}$, under average clustering coefficient, based on average clustering coefficient definition define in Section 5.2, it will means that there is no closed triplet (e.g. there is no three power plant are connected in a triangle) in electricity grid network. Node pair (5 14) is an example of failed nodes from two different critical infrastructures, causing an overall impact of $30.6 million, which is also the sum of the individual impacts of node 5 and node 14, which are respectively ranked third and first under the network average clustering coefficient metric in Table 6-2.

Table 6-4: Results for the top ten worst case scenarios based on a three-node failure in two physical infrastructure networks

Network performance metric	Failed Nodes	$e_{loss\,(1)}$	$e_{loss\,(2)}$	Overall impact, ΔX/day ($ M)
Efficiency of network	(0 1 3)	16.5	0.00	14.8
	(0 7 8)	16.5	0.00	14.8
	(1 3 5)	13.9	0.00	12.4
	(0 10 12)	7.76	14.2	11.7
	(0 1 11)	10.6	4.19	10.9
	(0 3 11)	10.6	4.19	10.9
	(0 7 11)	10.6	4.19	10.9
	(0 8 11)	10.6	4.19	10.9
	(0 11 12)	7.76	11.3	10.7
	(0 1 13)	10.6	2.26	10.2
Network average clustering coefficient	(1 4 5)	58.0	0.00	51.8
	(3 4 5)	58.0	0.00	51.8
	(4 5 14)	28.0	65.3	47.0
	(1 5 14)	27.4	65.3	46.5
	(3 5 14)	27.4	65.3	46.5
	(5 14 17)	9.64	100	42.3
	(5 14 19)	9.64	100	42.3
	(4 14 17)	7.99	100	40.9
	(4 14 19)	7.99	100	40.9
	(4 5 8)	44.0	0.00	39.3

In Table 6-4, which shows the results of the top ten worst case scenarios for three-node failure, nodes (1 4 5) and (3 4 5) are the top two worst case scenarios for overall impact under the network average clustering coefficient metric. The node pairs (14 17) and (14 19) do not appear again as the top ten most critical node in these three-node failures, because there are other combinations of node failures (from the telecommunication network) that caused a higher overall impact. In the top ten case scenario, it can be noted that the case where 100% loss in network performance, $e_{loss\,(2)}$, appeared in 6th ranked under network average clustering coefficient while other case scenarios are more superior in term of overall impact.The combination of nodes (4 5 14) is ranked in third place under the network average clustering coefficient metric in Table 6-4 and caused an overall impact of $47 million in losses. This combination of nodes is of special interest because the nodes are from two different infrastructure sectors, which is indicative that simultaneous failures in two different sectors can cause a substantial impact on the overall critical infrastructure. Moreover, it shows that the overall impact is not merely a summation of the overall impact caused from each individual node failure. As seen from the one-node failure results in Table 5-4 and 6-2, when nodes 4, 5 and 14 each fail alone, the sum of their individual impacts add up to $7.14 + $ 8.62 + $22 = $37.8 million, which is significantly lower than the $47 million impact resulting from the corresponding three-node failure of (4 5 14) in Table 6-4 shown in Figure 6-6. This is an example of a perfect storm (Pate, 2012), where a combination of failures happening simultaneously in different physical infrastructure networks can cause unexpected damages. The result shows that this model is useful for multiple infrastructure analysis where there is an overlap of different infrastructure networks.

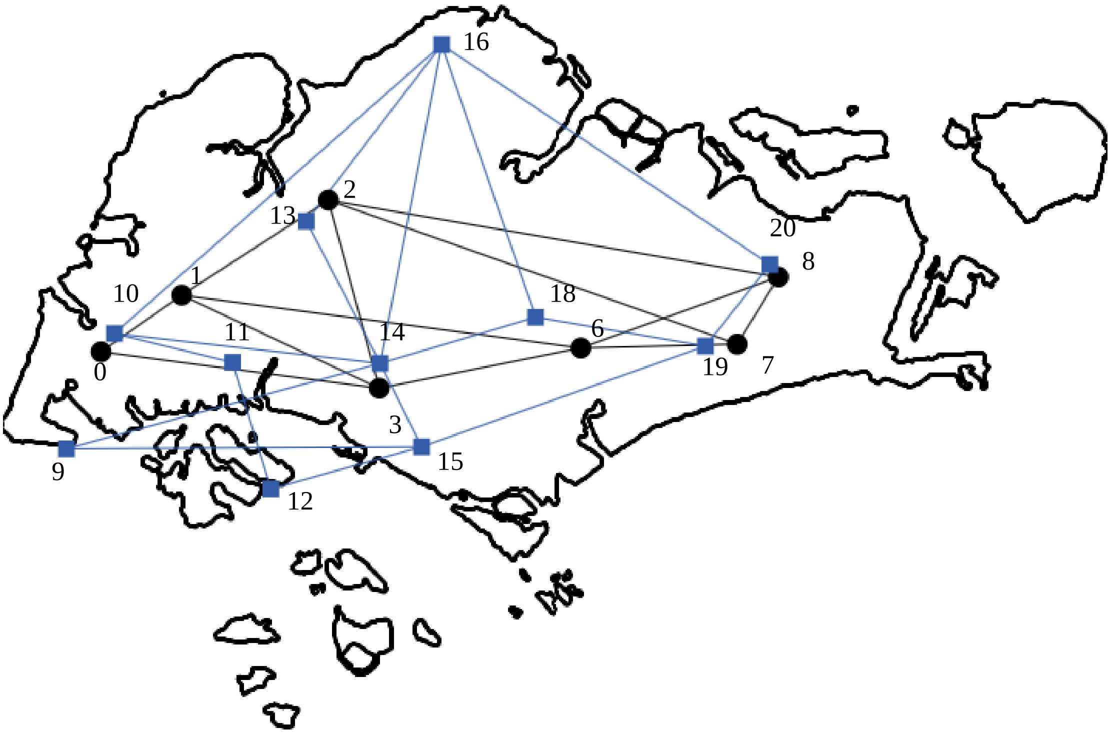


Figure 6-6: Example of nodes (4 5 14) failure under the network average clustering coefficient metric in Table 6-4

Based on this, it can be noticed that the node causing the greatest damages in one-node or two-node failure does not always correspond with those that appear in the worst three-node failures. Using the results, it is logical to protect the node combination that can cause the greatest impact if resources are limited.

Based on this simulation, researchers and stakeholders are able to quickly perform case studies of various scenarios to aid in their decision-making in resource allocation to enhance the reliability, protection and security of their critical infrastructure networks (Billinton & Allan, 1992). This simulation helps to provide insight on the vulnerability of the system to different types of disruption, allowing stakeholders to be made aware of risks and be prepared for potential disruptions due to hazards such as terrorist or cyber-attacks on critical infrastructure.

6.4 Summary of this work

Critical infrastructure is complex and when multiple physical critical infrastructures are put together, interesting results can be seen. This work not only provides additional insight on multiple critical infrastructures, but the model also proved to be functional and serves as an example of how the modelling can be done and how the results can be evaluated if data of two or more physical infrastructure networks is included. The worst possible consequences of a catastrophic event can thus be examined using this approach. It also shows that in the event of partial failure of more than one critical infrastructure, the economic impact can be significant, which should be of interest to relevant stakeholders and policy-makers. The combination of failures across nodes in different physical infrastructure networks may cause an impact that is higher than the expected impact for the same number of failed nodes within a single network. This is a good example of what is termed a perfect storm (Pate, 2012), whereby a combination of unfavourable circumstances that happen simultaneously can cause unexpected and unimaginable damages. The availability and sharing of information and complete data on critical infrastructure can hopefully be done so that black swan events like the 9/11 terrorist attacks or some cyber-attack targeting critical infrastructure can be mitigated, or that the awareness of stakeholders can be enhanced, enabling preparation against the potential risks.

Chapter 7 Analysing impact on a national network of critical infrastructure system

In this chapter, Singapore is used as a case study for analysing all major critical infrastructure assets using the critical infrastructure interdependency model developed in Chapter 3. Singapore was chosen because of its small size as a city state, its ability to be used as a general case model, its strong interdependencies between infrastructure sectors and the data availability of some of the critical infrastructure discussed in this chapter. In general, this research simulates a geographically-based hazard (e.g a dirty bomb explosion) and examine its area of impact on Singapore’s critical infrastructure and its cascading impact. Based on this multi-sectoral analysis, the results can be used in area planning to enable adequate allocation of resources, preventing catastrophic events from happening and allowing the identification of potential “black swan” events in the city state.

7.1 Critical infrastructure in Singapore

Different countries define critical infrastructure differently. Critical infrastructure is a term used to identify infrastructure that are critical with context to a particular country. One example is nuclear power, which is a separate and independent entity listed as “critical infrastructure” in the United States of America (The President’s Commission on Critical Infrastructure Protection, 1997), but is not listed in Singapore as such due to the non-utilisation of nuclear power in the country. Therefore, the list of critical infrastructure is unique to each country. According to the 2012 Singapore National Input-Ouput Table (see Table 7-1), there are 71 economic sectors in the country while there are 136 economic sectors in the 2007 Singapore National Input-Output Table. The research done in Chapter 4, 5 and 6 are done in the earlier stage of research with only the 2007 Singapore I/O table available. The 2012 Singapore I/O table reduces the economic sectors from 136 to 71. These sectors are combined and categorised together into suitable critical infrastructure sectors to facilitate the geographically-based hazard analysis. The 71 sectors in the Singapore input-output table are categorised into ten main critical infrastructure sectors and one “others” sector (which is a combination of the remaining “miscellaneous” economic sectors that are not used in Table 7-1), referencing the studies of the National Security Coordination Centre (2004) and Ho (2005), which define the Singapore critical infrastructure context in this manner. It is also noteworthy that there is an additional critical infrastructure – the petrochemical critical infrastructure – among the ten main critical infrastructure sectors as petrochemical should also be considered critical based its economic size in Singapore context and the fundamental uses of petrochemical product for other critical infrastructure like electricity sector. The petrochemical critical infrastructure sector includes petroleum product, petrochemical and gas economic sectors. The grouping is completed based on how they are viewed in Singapore (Lin et al 2016a; Lin et al 2016b), which makes the grouping used in this research unique to Singapore only. The new “aggregated I/O table” based on the above aggregation is used to compute the I/O interdependency matrix (Table 7-2), which represents the linkages among all critical infrastructure sectors. The 2012 Singapore input-output table is based on the Singapore Industrial Classification 2010 (SSIC 2010), while the IO product codes are based on the World Customs Organization Harmonized Product Description and Coding System Nomenclature 2012 (HS 2012) for goods and the United Nations Central Product Classification Version 2 (CPC Ver.2 2008) for services.

Table 7-1: Aggregation of economic sectors into respective critical infrastructure sectors

No	Main CI sector	Relevant sector in I/O table by ID	Name of the sector
1	Banking and Finance	48	Banking & finance
		49	Insurance, reinsurance & pension funds
		50	Fund management activities
		51	Other financial & insurance services
2	Telecommunication	46	Telecommunications
3	Electricity	29	Electricity
4	Water	31	Water & Sewerage
		32	Waste collection, treatment, disposal & material recovery services
5	Land Transport	24	Land transport equipment
		37	Land transport & supporting services
6	Healthcare	66	Medical and health services
7	Food supply	1	Agriculture and fishing
		2	Food products
		3	Beverages & tobacco products
		43	Food & beverage services
8	Air transport	26	Aircraft & related machinery
		39	Air transport & supporting services
9	Sea transport	25	Ships, boats & oil rigs
		38	Water transport & supporting services
10	Petrochemical	7	Petroleum products
		8	Petrochemicals & its products
		30	Gas

Note: The classification of industries in I-O tables is based on the 2010 Singapore Standard Industrial Classification

However, as it is not possible for the "food supply" critical infrastructure to be modelled in the scenario of a geographically-based hazard, it is not be included in the analysis. One of the main reasons relates to the fact that food supply in Singapore is highly dependent on imports from external countries. Also, the storage of the food supply is highly distributed with no available open data source for reference. Therefore, only the critical infrastructure in Table 7-2 are being investigated in this study:

Table 7-2: Critical infrastructure interdependency matrix

	Banking & Finance	Telecommunication	Electricity	Water	Land Transport	Healthcare	Food supply	Air transport	Sea transport	Petrochemical	Other industry
Banking & Finance	1.226	0.049	0.023	0.029	0.050	0.044	0.031	0.018	0.027	0.009	0.051
Telecommunication	0.024	1.241	0.003	0.008	0.015	0.013	0.007	0.012	0.007	0.002	0.012
Electricity	0.005	0.023	1.104	0.066	0.021	0.021	0.035	0.013	0.007	0.030	0.015
Water	0.001	0.002	0.001	1.181	0.003	0.009	0.009	0.002	0.002	0.005	0.005
Land Transport	0.006	0.007	0.001	0.007	1.121	0.003	0.008	0.009	0.008	0.005	0.007
Healthcare	0.001	0.002	0.000	0.002	0.002	1.085	0.002	0.001	0.001	0.001	0.008
Food supply	0.007	0.008	0.001	0.003	0.004	0.008	1.239	0.031	0.010	0.001	0.007
Air transport	0.005	0.005	0.001	0.006	0.005	0.008	0.009	1.094	0.002	0.002	0.009
Sea transport	0.007	0.014	0.003	0.018	0.018	0.010	0.014	0.005	1.192	0.005	0.028
Petrochemical	0.004	0.007	0.062	0.046	0.062	0.023	0.032	0.050	0.025	1.202	0.010
Other industry	0.156	0.350	0.073	0.344	0.268	0.364	0.334	0.133	0.192	0.095	1.332

Each critical infrastructure sector from Table 7-3 is identified and associated with a set of physical entities with their corresponding geographic position in the Singapore map, all these critical infrastructure entities are first mapped in QGIS (QGIS Development Team, 2009) before their GIS location are exported into Matlab for further analysis. A total of 297 critical infrastructure entities are modelled and illustrated in Figure 7-1.

Table 7-3: Critical infrastructure investigated in the geographically-based hazard scenario

No	Main critical infrastructure sector
1	Telecommunication
2	Electricity grid
3	Water
4	Healthcare
5	Banking & Finance
6	Sea Transport
7	Air Transport
8	Petrochemical
9	Land Transport

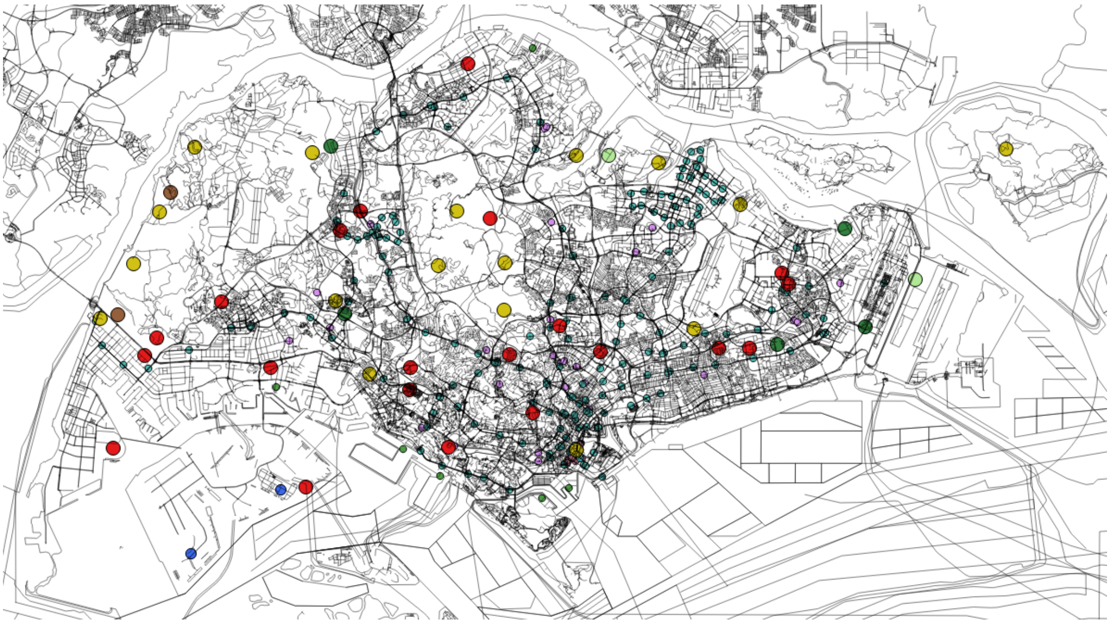


Figure 7-1: A total of 297 critical infrastructure nodes modelled in QGIS

Table 7-4 describes the 297 nodes modelled for the various critical infrastructure sectors and their respective node number range (e.g. nodes 9 to 20 are all electricity critical infrastructure entities).

Table 7-4: Critical infrastructure node entities and their node range

Critical infrastructure sector	No. of Nodes	Node range
Telecommunication	9	0-8
Electricity	12	9-20
Water	24	21-44
Healthcare	29	45-72
Banking and Finance	32	73-103
Sea transport	6	104-109
Air transport	2	110-111
Petrochemical	2	112-113
Land Transport	183	114-296

Each of the main critical infrastructure sectors in Table 7-4 is modelled according to its major significance in the country and geographical location. Minor features of the critical infrastructure sector are not modelled due to data availability constraints and the main idea of creating a coarse model, instead of a very detailed model for each critical infrastructure sector. In this manner, the amount of time required for analysis are being reduced while quick overall results of prediction through the analysis is achieved. The modelling of each of the critical infrastructure sector entities is described in the following chapters.

7.1.1 Telecommunication sector

The telecommunication sector is modelled using its major central office (Figure 7-2) that connects the Singapore telecommunication network (Tiong, 2009). The telecommunication sector consists of 9 main central offices that handle telecommunication coverage in the Singapore geographical area, and is represented by nodes 0 to 8 (also listed in Appendix C).

Figure 7-2: Telecommunication central office modelled in QGIS

7.1.2 Electricity sector

The electricity sector is modelled (Figure 7-3) as the power generating plants situated in Singapore (Chang et al., 2001) and represented by nodes 9 to 20 in Appendix C. The power plants distribute electricity across Singapore and any major impact to these plants will cause significant impact to the economy and society. The details of the electricity grid were not modelled, as there was too little available open source information (Rosas-Casals et al, 2015). Therefore, it has been excluded in this analysis.

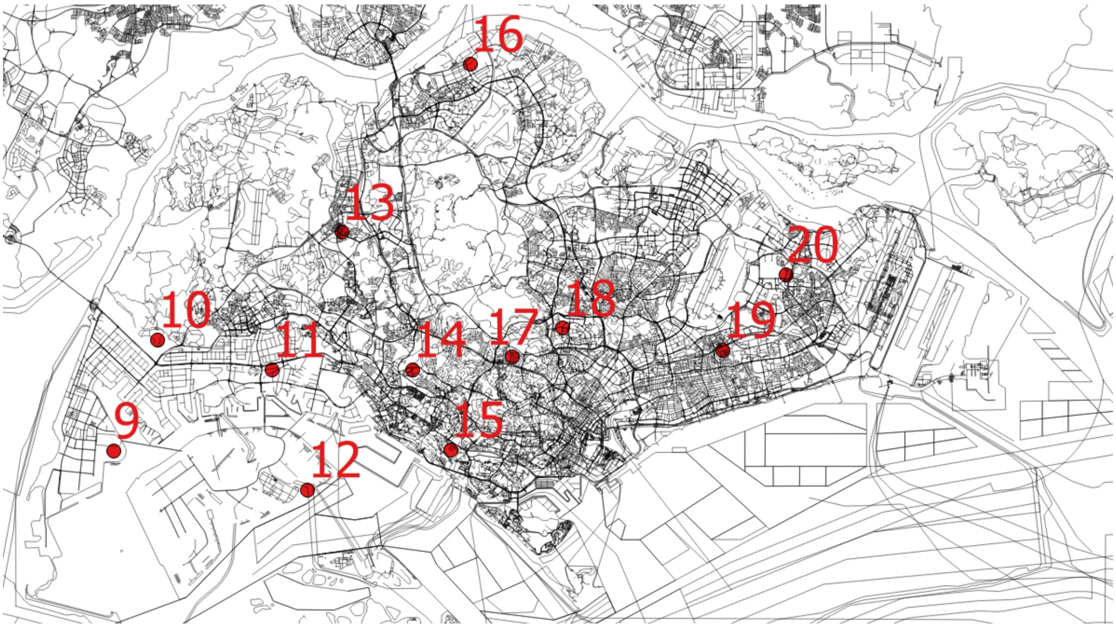


Figure 7-3: Electricity sector modelled in QGIS

7.1.3 Water sector

The water critical infrastructure sector is modelled as three parts in this analysis. Nodes 21 to 25 represent the NEWater plants (Jean, 2010), plants that use a reclaimed water technology incorporating dual-membrane technology to purify water for human consumption; nodes 26 to 27 represent the desalination water plants (Public Utilities Board, 2017a) in Singapore; and nodes 28 to 44 represent the reservoirs (Public Utilities Board, 2017b) in Singapore (Appendix C). The water critical infrastructure sector is modelled with the water sources of Singapore only and the water grid network is not included in the analysis.

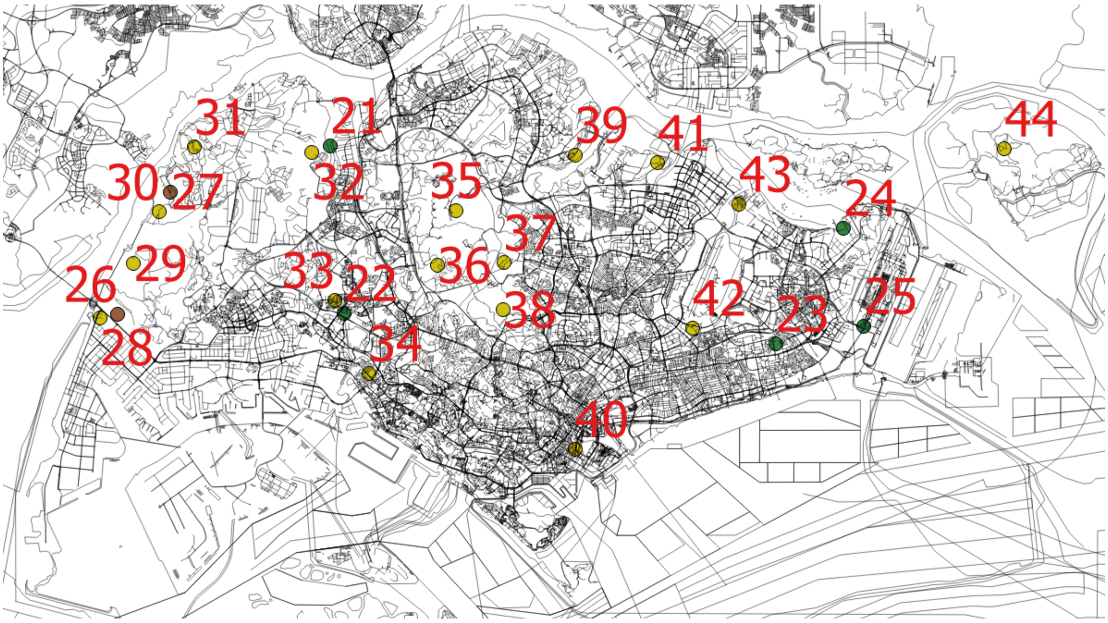


Figure 7-4: Water supply critical infrastructure modelled in QGIS

7.1.4 Healthcare sector

The healthcare critical infrastructure sector is modelled based mainly on the major hospitals (including public and private hospitals) in Singapore, and represented by nodes 45 to 72 (Appendix C). Polyclinics and other private clinics that do not have 24 hours emergency services departments are excluded from the analysis. The geographical locations of the hospitals are based on the Ministry of Health directory in the OneMap website (Ministry of Health, 2016).

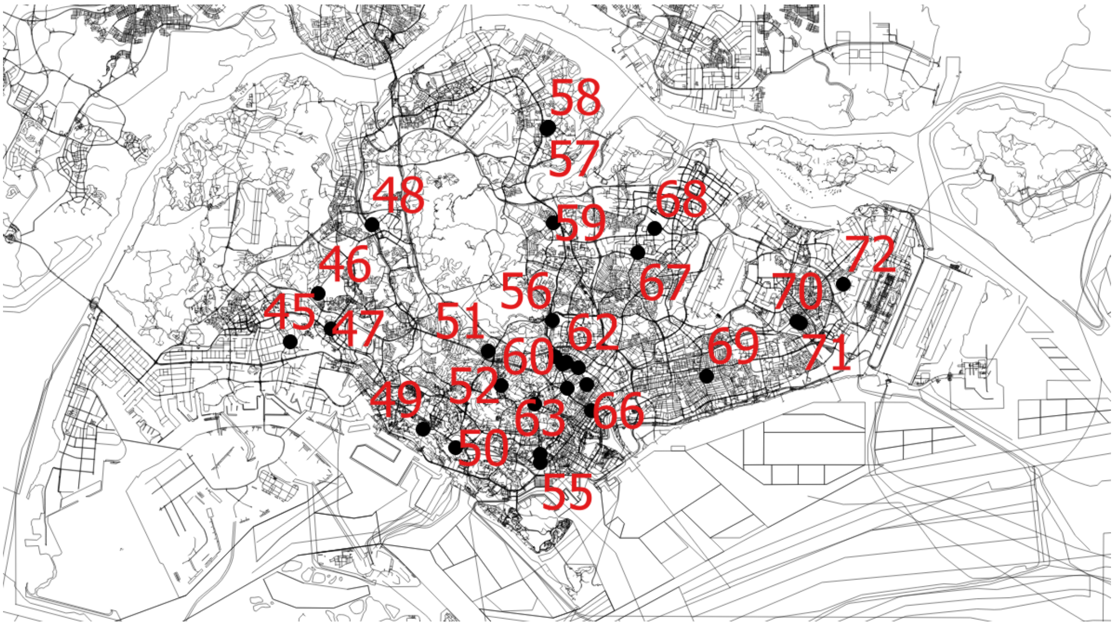


Figure 7-5: Healthcare critical infrastructure modelled in QGIS

7.1.5 Banking and finance sector

The banking and finance sector in Singapore is modelled (Figure 7-6) based on the major banks that possess full bank features in Singapore (MAS, 2017). According to Monetary Authority of Singapore, a full bank provides the whole range of banking services permitted under the Banking Act. Only the banks' main offices are modelled in this analysis, their branches are not included. Nodes 73 to 77 mark local banks, while nodes 78 to 103 indicate foreign banks situated in Singapore (Appendix C). Bank branches are not added into the analysis. Based on historical news reports, in short time period, bank branches closure do not incur any significant losses, thus not reported at all in their financial report. Instead, banks' back offices are quite important as they provide the operation centre of the bank. There are difficulties in adding banks' back offices in this chapter as there are many unknowns in identifying the banks' back offices. A test analysis as done similarly in this chapter had been added in Appendix E to show the differences in the results between "banking and finance" sector that added banks' back office versus “banking and finance” sector that did not add banks’ back office. In this chapter, as all the banks are clustered in the central business district of Singapore, it will become a major issue if something happens in that area. As such, the area is an obvious target even before the analysis is conducted.

Figure 7-6: Banking and finance critical infrastructure modelled in QGIS

7.1.6 Sea transport sector

The sea transport sector in Singapore is modelled based on the seaports of Singapore. The seaports are the only avenues of sea trade. Maritime business entities that are involved in sea transport services are not modelled in the analysis. The sector comprises of six major ports, namely the Tanjong Pagar, Keppel, Brani, Pasir Panjang, Sembawang and Jurong seaports (Figure 7-7), which are featured as nodes 104 to 109 (Appendix C).

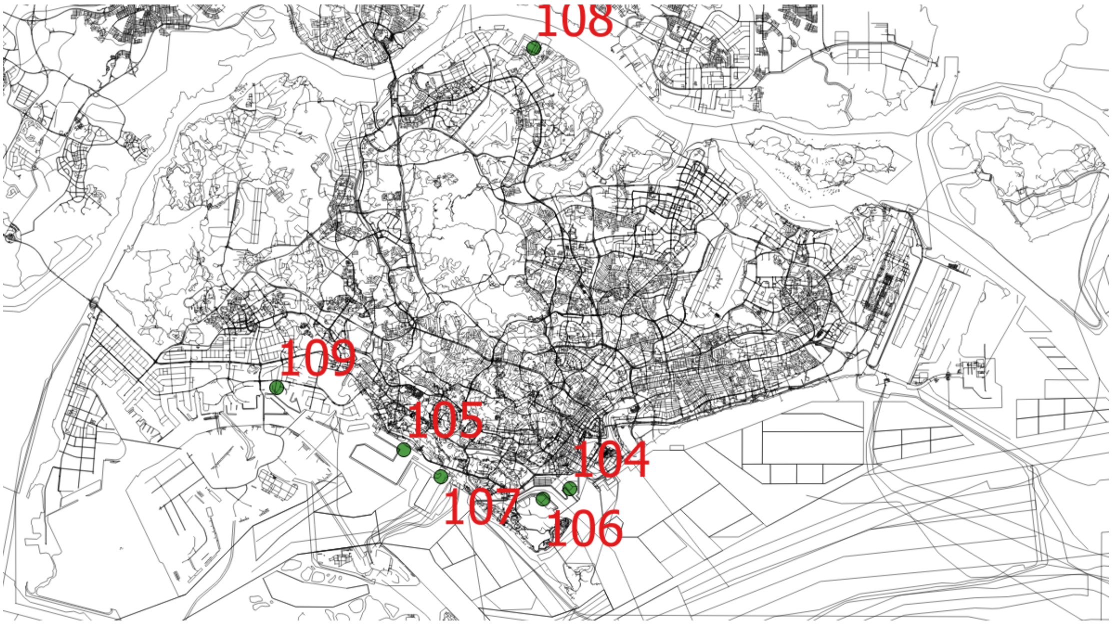


Figure 7-7: Sea transport critical infrastructure modelled in QGIS

7.1.7 Air transport sector

Singapore is a small country. Therefore, there are not many airports in the country. Figure 7-8 shows the only two airports in the country, namely the Changi Airport and Seletar Airport, which are represented by nodes 110 to 111 in Appendix C. However, although there are few airports in the nation, the Singapore Changi airport is named as one of top 20 busiest airports in the world in terms of passenger traffic (The Port Authority of NY & NJ, 2017) and one of the best airports in the world. Therefore, any hazards to these airports will incur heavy losses and their protection should be a top priority for Singapore.

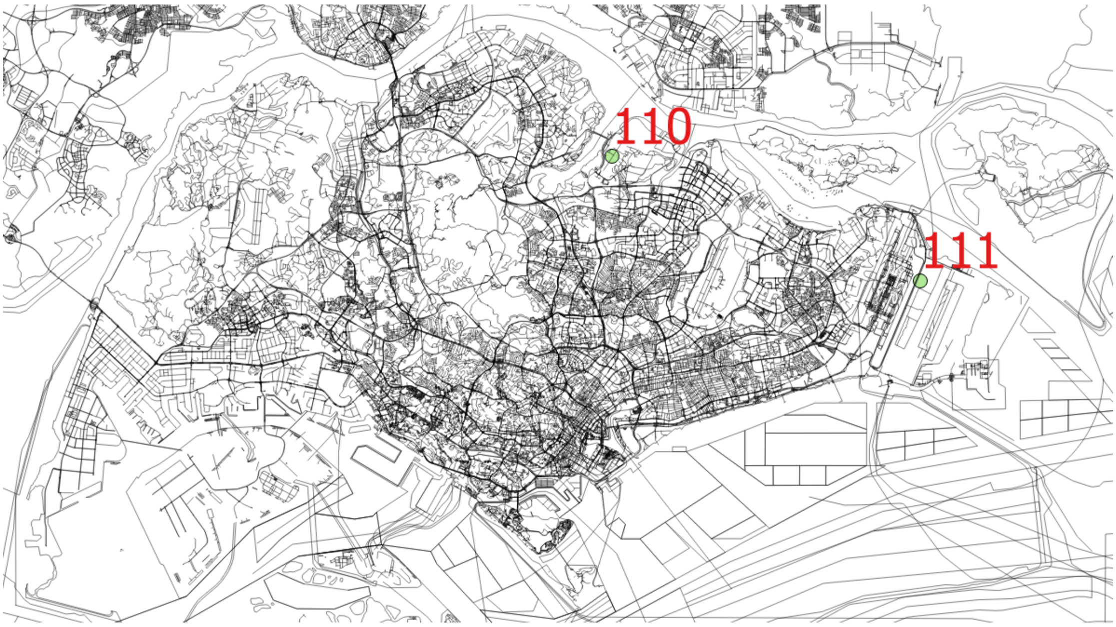


Figure 7-8: Air transport critical infrastructure modelled in QGIS

7.1.8 Petrochemical sector

The petrochemical sector in Singapore makes up approximately 5% of its GDP (Contact Singapore, 2011). This alone is indicative of the importance of this industry sector to Singapore, and also its importance as a critical infrastructure for the nation. The establishments of the petrochemical industry are mainly situated at Jurong Island and the offshore islands to protect the rest of the nation in the case of an emergency. Figure 7-9 reflects nodes 110 to 111 (Appendix C), which are the main connecting access ports for the import and export of petrochemical products in Singapore. The petrochemical companies are not listed as their locations were not readily available in open source data. Therefore, the connecting access points (e.g. the ports for the import and export of crude oil and refined products) are used in this analysis.

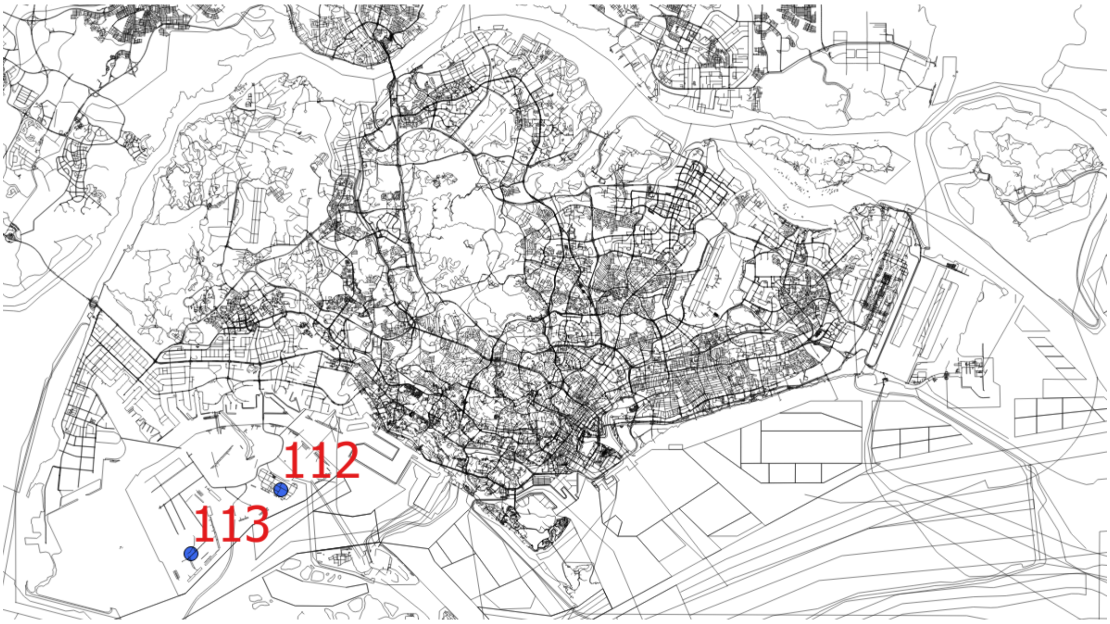


Figure 7-9: Petrochemical critical infrastructure modelled in QGIS

7.1.9 Land transport sector

Land transport is a very large sector on its own as it normally contains all the transportation modes in a nation. Singapore is known for its good public transportation system where the need for a self-owned vehicle is reduced due to the accessibility of the public mass rapid transit system (MRT system). With more stations in the process of being built and various future plans to build more stations, the system provides greater accessibility for residents. In this analysis, the transportation mode is limited to the MRT system in Singapore. The road systems are not included in this analysis as they cannot be modelled as nodes in the analysis. Therefore, the MRT system are being modelled as a proxy for the land transportation system in Singapore. There are 191 land transport nodes (MRT/LRT stations) modelled in Figure 7-10, represented by nodes 114 to 296 (Appendix C).

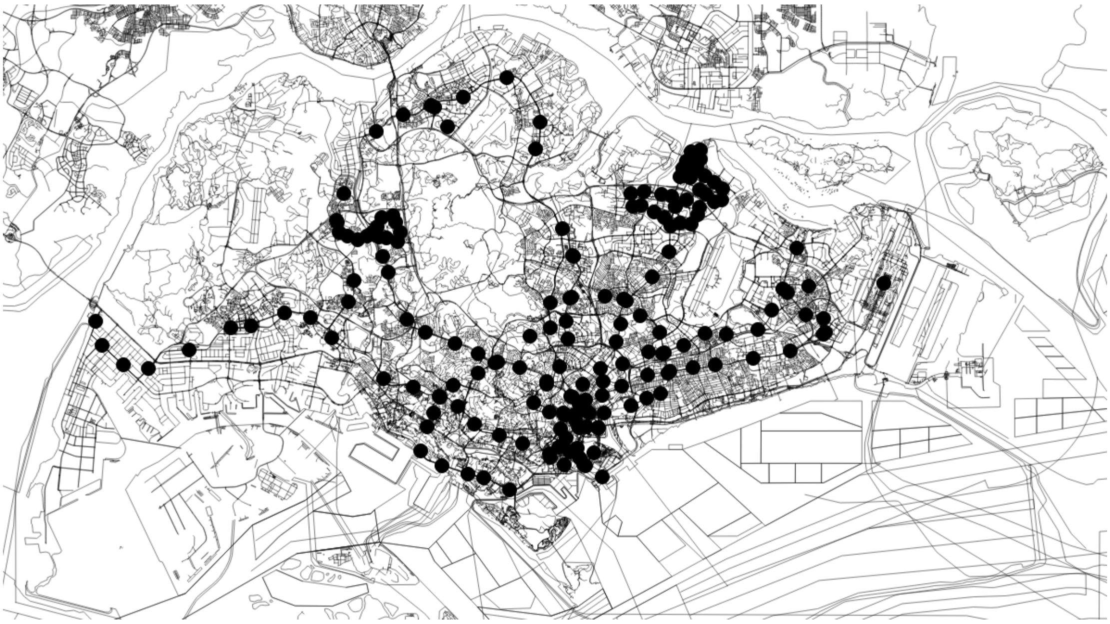


Figure 7-10: Land transport critical infrastructure modelled in QGIS

7.2 Geographically based hazards

Based on the disaster statistics recorded under the United Nations Office for Disaster Risk Reduction (UNISDR), which also utilises disaster databases like the “GAR Risk Data Viewer” and “EM-DAT: The International Disaster Database”, there has been an increase in the frequency of man-made and natural hazards in the present day (Heaslip et al., 2010; Dorbritz, 2011). As such, analyses on critical infrastructure with respect to their geographical locations have become increasingly important and applicable. Many critical infrastructure are located in close proximity to each other, especially in the context of a densely populated city like Singapore (Freckleton et al., 2012). This analysis focuses on various hazards, from naturally occurring hazards such as flash floods to man-made hazards like terrorist attacks, large-scale accidents (e.g. fire outbreaks), infrastructure failures (failure of an infrastructure entity) and civil disturbances. These types of hazards are important, as they have significant economic impact and cause societal disturbance.

With the capability to analyse geographically-based hazards, stakeholders have the ability to evaluate the projected impact of a disturbance on the critical infrastructure of concern, as well as its cascading impact on the interconnecting critical infrastructure.

7.3 Simulation process

This analysis involves the simulation of a geographically-based hazard (e.g. bomb explosion) and its impact on the surrounding critical infrastructure. The objective is to search for all critical infrastructures (e.g. central offices that are within a stipulated radius X km) from the target point of a geographically-based hazard. For this analysis, all hazards are simulated to occur directly at the location of a critical infrastructure for simplicity in the analysis (Shen, 2013). Different radii of impact from the hazard are simulated in the analysis, specifically, for 100 metres, 250 metres, 500 metres and 1 kilometre due to the projected size (Freckleton et al., 2012) of the various hazards (e.g. flash flood, terrorist attack).

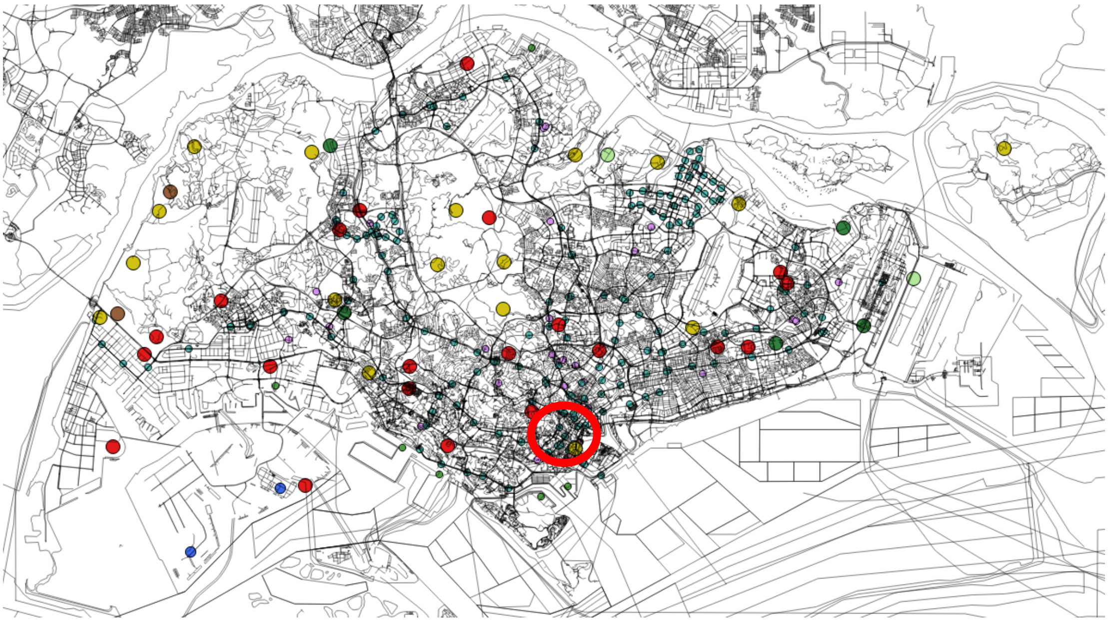


Figure 7-11: An example of the simulation of the hazard (red circle) at a particular critical infrastructure entity

The analysis was conducted systematically. After all critical infrastructure entities were modelled in the QGIS map, a thorough simulation test within the radius of 100 metres, 250 metres, 500 metres, and 1 kilometre from the point of impact on a specific critical infrastructure entity were being evaluated. All 297 cases of the attack radius above were simulated. The method used to compute all nodes that fall within the radius of the hazard is known as the haversine formula method (Sinnott, 1984), and is used to calculate the great-circle distance between two points on a sphere. As the Earth is spherical, the shortest distance between two points on the Earth's spherical surface can be evaluated using this method. The haversine formula is included as follows:

$$\begin{aligned} a &= \sin^2\left(\frac{(\varphi_2-\varphi_1)}{2}\right)+\cos(\varphi_1)\cos(\varphi_2)\sin^2\left(\frac{\lambda_2-\lambda_1}{2}\right) \\ c &= 2\arctan 2(\sqrt{a},\sqrt{(1-\mathrm{a})}) \\ d &= R\cdot c \end{aligned} \tag{7.1}$$

where φ_1 and φ_2 denote the latitude of point 1 and 2 on the map; λ_1 and λ_2 represent the longitude of point 1 and 2 on the map; R refers to the Earth's radius (mean radius = 6,371km); and *c* is the angular distance in radians. Arctan2 is an arctangent function with two arguments. Arctan2 (y, x) is the angle in radians between the positive x-axis of a plane and the point given by the coordinates (x, y) on it. The calculated d will be the distance between two points on the Earth's surface. Using the haversine formula, the distances between the point of impact and all surrounding critical infrastructure can be computed. For the context of this analysis, as Singapore is a small city state, simplification of calculation can actually be done by using Pythagorean Theorem to calculate the direct direction between two points on a map. However, these calculation will not be appropriate in the context of big cities (e.g. China, United States) due to their geographical size.

With the disruption of the computed nodes by the geographically-based hazard for all 297 cases within the different radii, the critical infrastructure interdependency model used in Chapter 3 is then used to calculate the initial impact, ΔF, based on the disrupted nodes for each case. As the computed nodes can involve infrastructure entities of various critical infrastructure sectors, any node affected by the disruption is assumed to incur a percentage performance loss to its respective critical infrastructure sector. For example, as the telecommunication critical infrastructure sector contains nine nodes, if one node was involved in the disruption, it will be assumed that at that point of time, a performance loss of 1/9*100% = 11.11% (e_{loss}) will be incurred by the telecommunication critical infrastructure sector. With the performance losses (e_{loss}), the w_{loss} can be evaluated based on equation (5.4) as mentioned in Section 5.2. w_{loss} is used in $\Delta\mathrm{F}_i$ to propagate the cascading impact loss due to critical infrastructure sector i to all sectors in the I/O table represented by Table 7-3. The overall impact to all critical infrastructure, ΔX, is being evaluated per day that the hazard continues to affect the various infrastructure. Based on the overall impact, ΔX, the worst case scenario can then be deduced based on the different impacts within the various radii.

7.4 Simulation results

The results for the evaluation of the impact within the radii of 100 metres, 250 metres, 500 metres and 1 kilometre from the geographically-based hazard are being discussed in this chapter. Some of the results are expected, but there are also interesting findings in this analysis.

7.4.1 Within 100 and 250-metre radii of geographically-based hazard

For the scenario that simulated the impact within the radii of 100 and 250 metres of a geographically-based hazard, nodes 112 and 113 (Figure 7-12) are ranked jointly as the nodes that induced the worst overall impact, amounting to S$165.5 million dollars per day of disruption. Due to the fact that the simulated radius of impact is small and isolated from other nodes in terms of distance, nodes 112 and 113, which are the petrochemical critical infrastructure, constitute the worst case scenario if a hazard occurs within 100 or 250 metres in radius of these node locations. Based on local knowledge of the location and the type of critical infrastructure being affected, it is not difficult to understand why the petrochemical industry constitutes the worst case scenario for the 100 metres and 250 metres range, as the petrochemical industry makes up about 5% of the Singapore GDP and any disruption to this critical infrastructure will affect the economy significantly. However, as the radius of impact increases, nodes 112 and 113 are no longer be ranked the worst cases as later discussed in Section 7.4.2 on the 500-metre range of impact.

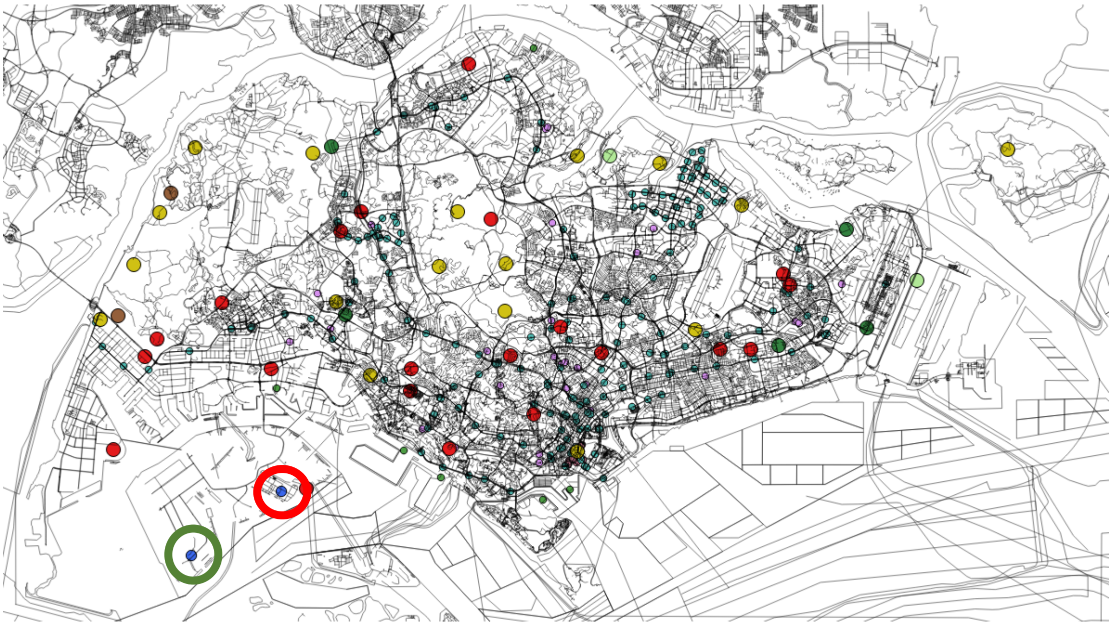


Figure 7-12: Worst case scenario based on a 100 metre radius from the hazard, with the node circled in red indicating node 112 and the node circled in green indicating node 113

7.4.2 Within a 500-metre radius of geographically-based hazard

For 500-metre radius scenario, node 94 is ranked as the worst case scenario (Figure 7-13), incurring a total of S$229.5 million dollars in economic losses due to impact from the simulated hazard. Node 94 is a banking and finance critical infrastructure entity situated at the heart of the Singapore central business district. The impact on the banking and finance sector is usually substantial as these sectors sustain a large amount of economic output and any disruption to them will cause significant economic impact, which will also cascade to other sectors (Table 7-5) through the critical infrastructure interdependency model (Scala et al., 2015). Node 40, 84, 91, 92, 93 are ranked jointly as the second worst overall impact, incurring a total of S$220.4 million dollars in economic losses due to impact from the simulated hazard. The result here is different compared to the 100-metre and 250-metre range, which shows that as the radius from geographically based hazard increases, the analysis will tend towards areas in the country where the critical infrastructure are more densely situated, and this is also dependent on the economic contribution of the critical infrastructure entities affected.

Table 7-5: List of critical infrastructure entities affected by the 500-metre radius hazard situated at node 94

Critical infrastructure sector	No. of Nodes affected	List of affected nodes
Telecommunication	0	
Electricity	0	
Water	1	40
Healthcare	0	
Banking and Finance	25	73-78, 80, 82-87, 91-94, 96-101, 103
Sea transport	0	
Air transport	0	
Petrochemical	0	
Land Transport	3	228, 291, 295

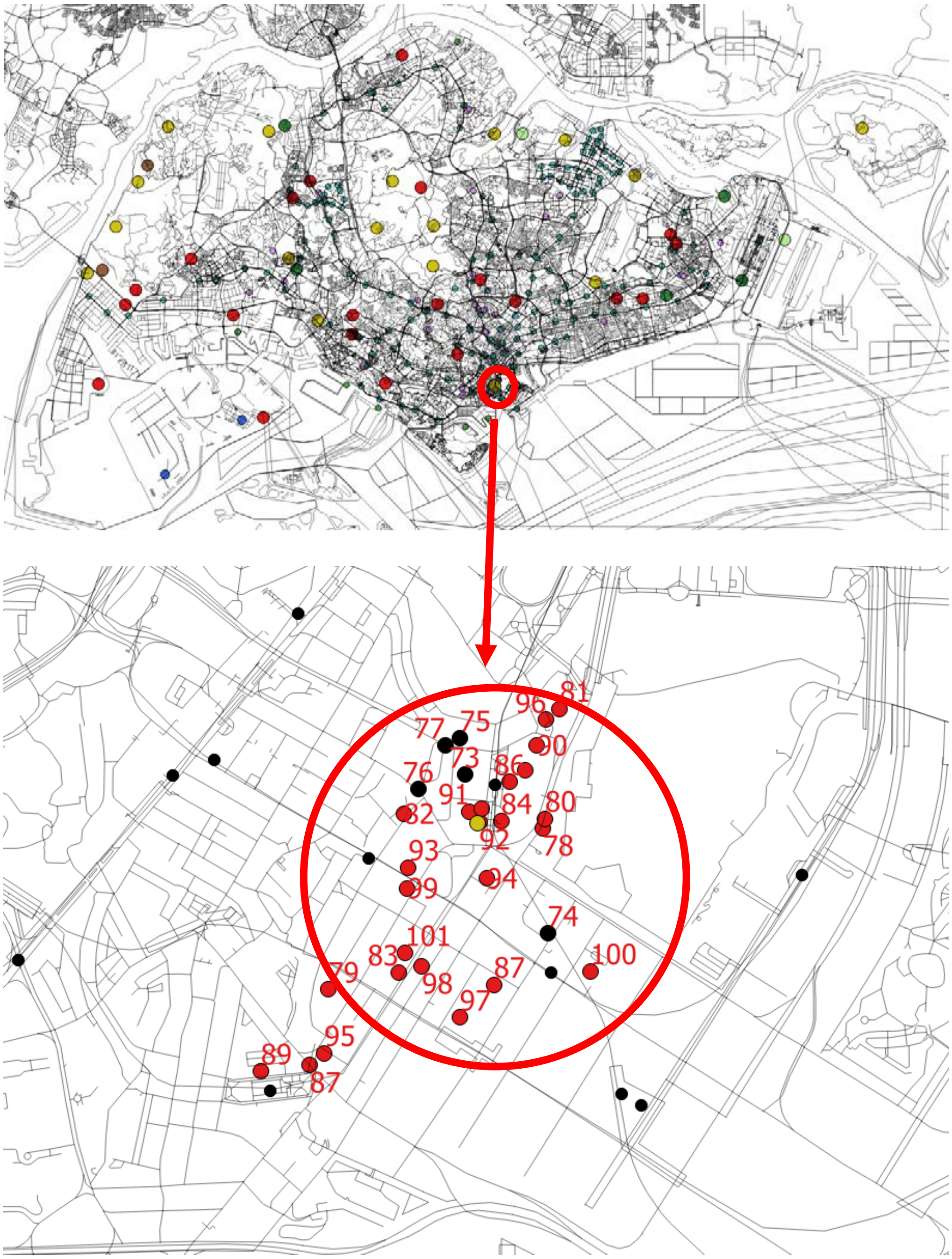


Figure 7-13: Worst case scenario depicting a 500-metre radius from the hazard situated at node 94, with the red circle representing the area of critical infrastructure that are being affected

7.4.3 Within a 1-kilometre radius of geographically-based hazard

For the scenario simulating a 1-kilometre radius from the geographically-based hazard, nodes 40, 84, 91, 92, 94 and 103 are ranked jointly as the worst case scenarios for a geographically-based hazard within a 1-kilometre range, incurring S$277.0 million dollars in economic losses per day due to the simulated hazard. These nodes are situated in the central business district area, with node 40 showcased as an example in Figure 7-14 and the corresponding affected nodes in Table 7-6. Node 40 is a water critical infrastructure while nodes 84, 91, 92, 94 and 103 are banking and finance critical infrastructure nodes. Based on local knowledge, these scenarios are highly likely to occur as the banking and finance sector contributes to a big percentage of the Singapore economy, and also because the banking and finance critical infrastructure are mostly situated in the central business district area, thus any hazards that occur in that area will incur huge economic losses.

Table 7-6: List of critical infrastructure entities affected by the 1-kilometre radius hazard situated at node 40

Critical infrastructure sector	No. of Nodes affected	List of affected nodes
Telecommunication	0	
Electricity	0	
Water	1	40
Healthcare	0	
Banking and Finance	30	73-103
Sea transport	0	
Air transport	0	
Petrochemical	0	
Land Transport	10	212, 220, 228, 233, 234, 236, 237, 262, 291, 295

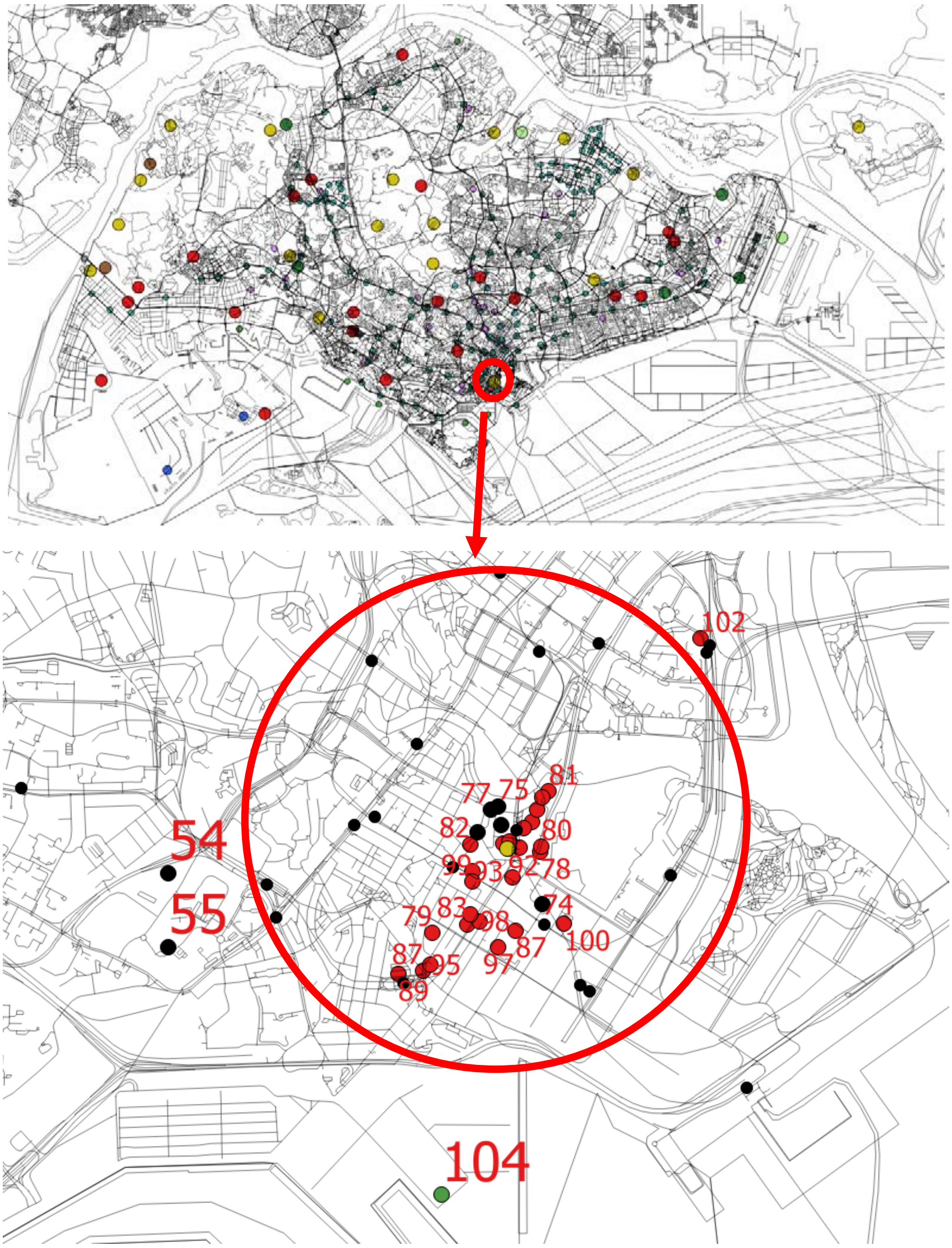


Figure 7-14: Worst case scenario within a 1-kilometre radius of the hazard occurring at node 40, with the red circle representing the area of critical infrastructure that is affected

7.5 Implications from this analysis

The results suggest that the outcome of a thoroughly computed analysis on all critical infrastructures in a nation might yield interesting results. For example, as the radius of impact from the hazard increases, the petrochemical industry may no longer be the sector that incurs the worst impact. Within a certain threshold of distance from the hazard, a shift of the worst case scenario from the petrochemical critical infrastructure to the banking and finance critical infrastructure might occur. The location of critical infrastructure entities in Singapore and the location of the geographically-based hazard are also important to consider, as different countries manage their critical infrastructure differently. This analysis is a basic and straightforward means to analyse the economic impact on all critical infrastructure sectors due to a geographically-based hazard, and is very useful as a multi-sectoral critical infrastructure analysis as interdependencies are taken into account. This analysis is also useful for area planning as well as adequate allocation of resources to prevent catastrophic events from happening.

Chapter 8 Conclusion

This chapter provides a summary of the work done and results that aim to answer the research questions and highlights the original contributions in this thesis. The chapter concludes with suggested topics for future work, to enable the continuation of the development and study of critical infrastructure interdependencies. The idea of modelling interdependencies has been a big topic in the modern era due to the interconnectedness of critical infrastructure and densely populated cities in the world. The contents of this thesis highlight the challenges of the integration and collaboration of physical infrastructure systems with an economic model, and demonstrates its uses through the work done.

8.1 Research summary

Chapter 1 posed several research questions that guided the work in this thesis. This chapter revisits these questions to summarise the completed research.

1) What is the network relationship (interdependence) between critical infrastructures?

As discussed in Chapters 2 and 3, the notion of interdependency depends on the definition used by the researcher. In this thesis, the interdependency is defined as the economic interconnection of the critical infrastructure that links them together. It can be seen as a physical flow of goods and services that individual critical infrastructure sectors buy and sell to all other critical infrastructure sectors in a nation’s economy through the input-output table. Based on the input-output table, the interdependency strength can be computed using Leontief’s input-output model, which forms the foundation of the critical infrastructure interdependency model in Chapter 3. The interdependency strength represents how closely any two critical infrastructure sectors are connected to each other, and the degree of effect if some disruption happens. In Chapter 4, the critical infrastructure interdependency model was tested with case studies of the Singapore Bukom fire accident and the Tohoku Earthquake, and the results were compared with relevant sources for benchmarking. The work in Chapter 4 enhances the confidence about the use of the input-output model as a critical infrastructure interdependency model.

2) How do we simulate the impact of a hazard within a critical infrastructure network system, and how does this impact propagate to other critical infrastructure?

As discussed in Chapter 5, the critical infrastructure interdependency model is inadequate for this genre of research, as it lacks the capability of analysing a physical critical infrastructure network. Therefore, the inclusion of a physical critical infrastructure network was proposed and this physical critical infrastructure was embedded within the critical infrastructure interdependency model to provide a more accurate analysis on the potential scenarios that might happen (e.g. a hazard or disruption occurring in one of the critical infrastructure entities). The network analysis technique and the performance metrics, namely the efficiency of network and average network clustering coefficient metrics, were introduced to evaluate the disruptions that might happen. Based on the performance metrics, the initial impact, ΔF, could be evaluated, thus enabling the initial impact that is being propagated to other critical infrastructure with overall impact, ΔX, to be computed through the interdependency model.

3) How do we analyse two or more critical infrastructures that happen to fail simultaneously?

Chapter 6 attempts to apply scenarios where two or more physical critical infrastructure systems are incorporated into the critical infrastructure interdependency model. The method used was similar to the work done in Chapter 5, except that there were some careful considerations to be made in the handling of two or more physical critical infrastructures. The two physical critical infrastructures do not interconnect in term of physical connection in the network model again, as their interdependencies are already being modelled in the critical infrastructure interdependency model. Based on the work done in Chapter 6, the simulation of two or more different critical infrastructure entities becomes possible for analysis.

4) How do we analyse and simulate the worst case scenario, and thereby identify the most critical parts of a critical infrastructure network?

The work discussed in Chapter 3 is applied to Chapters 5, 6 and 7 in the simulation of the worst case scenario possible using various types of analysis. In Chapters 5 and 6, the worst case scenarios of the failure of one, two and three nodes in the physical critical infrastructure were simulated and their results evaluated. The failed one, two or three nodes that resulted in the worst loss/impact can therefore be considered as the most vulnerable or most critical nodes in the infrastructure network. In Chapter 7, the work was shifted onto a larger scale to cater to the analysis of all critical infrastructure sectors affected by some geographically-based hazards, and through the analysis, the worst case scenario was isolated and the corresponding critical infrastructure entities at which the hazard directly occurs can be considered the most critical entities.

8.2 Original Contributions

This thesis makes the following original contributions:

1) Prior research using the I/O model for the modelling critical infrastructure interdependencies has allowed us to analyse how disruptions propagate throughout multiple critical infrastructure sectors in the system. However, such models alone do not enable the analysis of the impact on the system due to the effect of physical hazards on particular physical entities in a particular critical infrastructure system/network. There has also been prior research that analyse how disruptions in some particular physical entities impact one or at most two physical critical infrastructure sectors simultaneously. However, to the author’s knowledge, there was no prior work that analysed how the disruption in particular physical critical infrastructure assets impacts and propagates to the multiple critical infrastructure sectors in the whole economic system. Through the combination of physical critical infrastructure networks with an I/O interdependency model in our framework, we were able to accomplish that.

2) It was difficult to verify the accuracy of the I/O interdependency models in the computation of the impact of any particular disruptions in the critical infrastructure systems, and there was little published literature that compared results with real-world case studies. In this work, we have examined two real-world case studies to compare and benchmark the results with those of relevant available sources.

3) There is no prior work that demonstrated the use of critical infrastructure interdependency models to search for or discover the worst case scenarios (i.e. which physical entities will cause the largest impact on the whole economic system in the event of failure or disruption).

4) No prior studies have attempted to analyse the impact on a complete multi-sectoral critical infrastructure system of a city/state resulting from some particular physical hazards. In this work, we have developed a complete (although coarse) critical infrastructure model of a city state, and analysed the impact of a geographically-based hazard affecting a small and localised area on the whole economic system.

8.3 Recommendation for future work

Based on the current critical infrastructure interdependency model used in this thesis, more work can be done through the incorporation of a sensitivity analysis and other risk/uncertainty quantifications to make the I/O interdependency model more relevant to the real world and enable more realistic applications. Based on the I/O model discussed in Chapter 3, work can be done in looking for the possibility of restructuring the economy based on the input-output table. For example, the impact to a certain sector (e.g. petrochemical sector) can be huge when a hazard or disruption happens, thus more research can be done into the ways that this sector can be impacted and actions that can be taken to mitigate the loss. The real criticality of some critical infrastructure might also be underestimated as this thesis emphasize on the use of economic input-output table of a nation. For example, electricity critical infrastructure that do not make up a large monetary output in the nation economy as compared to other sector might be overlook due to its smaller economic value as compared to other economic sector. Some critical infrastructure, like military defence, is not included in the analysis as they are not an economic sector in economic input-output table. More research on the limits of the simulation of critical infrastructure failure might also be required. This is due to the fact that based on the underlying assumption of the Leontief's input-output model is essentially a linear model. As such, a disruption cannot be too drastic till it changes the input-output table structure and violates input-output model. Therefore, the amount of disruption possible till it violates I/O model assumption will be of research interest. Analyses on real critical infrastructure failures with test examples and their respective recovery time cycles might also prove to be interesting. Such work will require information regarding the timeframe of the failure and recovery process of the critical infrastructure failure. The analysis of geographically-based hazards and their areas of impact can also be extended through more in-depth analyses of the hazards on the affected areas of impact. For example, although a flash flood may affect businesses, telecommunication services may not be part of the affected industries. Therefore, a more complete and detailed analysis can enhance the research completed in this area.

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Appendix A. 136 Sectors in 2007 Singapore I/O table

Sector	Description	Final demand, F	Total output,X
1	Nursery products	30.0	32.7
2	Other agriculture	22.9	24.1
3	Livestock	19.0	60.4
4	Aquarium fish	87.2	91.5
5	Other fisheries	27.1	28.5
6	Food preparations	348.3	547.8
7	Bread, biscuits & confectionery	345.8	498.7
8	Sugar, chocolate & related products	273.9	322.6
9	Oils & fats	458.4	537.9
10	Dairy products	213.7	316.5
11	Coffee & tea	276.2	324.5
12	Other food products	1,032.1	1,433.6
13	Soft drinks	267.4	312.5
14	Alcoholic drinks & tobacco products	624.1	705.2
15	Yarn, fabrics & textile articles	185.3	214.5
16	Wearing apparel	555.3	687.0
17	Footwear, leather & fur products	183.9	213.1
18	Wood & wooden products (except furniture)	69.3	265.0
19	Paper & paper products	700.5	1,005.8
20	Newspapers, books & magazines	1,117.5	1,675.6
21	Other printing	361.4	903.4
22	Petroleum & petroleum products	41,530.6	42,952.2
23	Industrial chemicals & gases	807.2	1,064.7
24	Petrochemicals	16,616.4	20,968.4
25	Pharmaceutical products	16,061.3	16,446.1
26	Perfumes, cosmetics & toiletries	419.8	474.2
27	Cleaning & polishing preparations	87.5	97.4
28	Paints	514.5	763.0
29	Food chemicals & additives	238.7	272.0
30	Other chemical products	2,850.1	3,309.6
31	Rubber & rubber products	372.5	523.6
32	Plastic precision products	585.6	1,133.9
33	Other plastic products	822.4	1,328.2
34	Glass & glass products	255.9	410.8
35	Fibreglass & fibreglass products	101.4	149.2
36	Bricks, cement & concrete products	37.7	535.9
37	Non-metallic mineral products	105.7	233.4
38	Basic metals	657.3	1,008.8
39	Structural metal products	421.9	1,084.5
40	Metal stampings	846.7	1,362.5

Sector	Description	Final demand, F	Total output, X
41	Metal precision components	1,070.1	1,385.5
42	Non-insulated cable products	891.4	1,236.8
43	Metal containers	238.8	558.6
44	Treatment & coating of metals	222.2	478.9
45	Other metal products	1,488.3	2,143.5
46	Computers & computer peripheral equipment	13,447.5	14,093.4
47	Data storage	17,246.5	17,602.5
48	Audio & video equipment	1,172.0	1,221.4
49	Semiconductors	29,687.3	31,934.9
50	Electron tubes & electronic display devices	1,096.2	1,123.7
51	Printed circuit boards	5,356.5	6,266.6
52	Communication equipment	6,981.6	7,150.0
53	Other electronic products	2,242.2	2,347.4
54	Lifting & hoisting machinery	687.3	952.4
55	Other industrial machinery & equipment	4,511.4	4,979.0
56	Refrigerators & air-conditioners	1,206.7	1,330.9
57	Oil rigs & oilfield machinery	4,358.4	4,559.6
58	General engineering works	132.8	331.0
59	Electrical industrial apparatus	2,081.4	2,206.5
60	Recorded media	239.3	296.0
61	Household appliances	262.4	269.7
62	Storage & primary batteries	248.0	260.9
63	Electrical wires & cables	341.1	462.0
64	Lamp & lighting fixtures	51.2	55.3
65	Land transport equipment	1,067.1	1,276.2
66	Building of ships & boats	1,108.8	1,563.4
67	Repairing of ships & boats	1,643.0	3,148.0
68	Marine engines & ship parts	154.0	694.1
69	Aircraft	3,862.0	5,277.9
70	Medical instruments	2,065.9	2,131.2
71	Scientific instruments (including watches & clocks)	1,313.0	1,351.4
72	Photographic & optical goods	543.4	564.4
73	Furniture (except of stone)	407.6	600.3
74	Jewellery	282.9	385.4
75	Other manufacturing	181.7	194.6
76	Scrap	445.4	761.5
77	Electricity	1,204.4	6,908.2
78	Gas	251.8	424.4
79	Water	323.0	906.9
80	Building construction	12,341.4	23,810.8
81	Other construction	4,003.6	6,419.1

Sector	Description	Final demand, F	Total output, X
82	Wholesale trade of computer products	4,209.9	5,791.1
83	Wholesale trade of other products	41,769.0	51,178.6
84	Retail trade of computer products	50.5	109.0
85	Retail trade of other products	5,367.2	8,990.3
86	Food & beverage services	5,022.9	6,808.1
87	Accommodation services	2,149.5	2,684.8
88	Passenger transport by land	2,871.8	4,275.4
89	Water transport	14,226.6	27,192.8
90	Supporting services to water transport	1,285.4	2,463.2
91	Port operation services	1,477.7	2,467.0
92	Air transport	11,570.8	14,159.2
93	Supporting services to air transport	373.7	502.2
94	Airport operation services	781.5	1,563.2
95	Freight transport by land	193.7	1,198.0
96	Logistics service providers & courier services	1,227.0	3,255.5
97	Other transport services	22.7	318.2
98	Warehousing services	725.5	1,303.1
99	Sight-seeing & tourism	135.7	1,785.2
100	Communications	2,602.1	8,303.1
101	Life insurance	2,393.6	3,285.4
102	General & other insurance	2,385.9	3,404.0
103	Banks & finance companies	10,540.6	24,917.5
104	Other financial services	5,772.8	11,021.8
105	Fund management	80.2	2,619.1
106	Real estate	6,297.0	13,955.2
107	Legal services	640.9	1,380.1
108	Accounting & secretarial services	202.1	1,088.8
109	Information technology	6,034.1	11,908.7
110	Publishing	38.3	775.0
111	Architectural & engineering services	2,311.7	5,019.6
112	Industrial design services	7.3	332.7
113	Petroleum & mining consultants	74.2	677.5
114	Employment & labour contracting	15.6	1,201.1
115	Advertising	587.7	1,822.0
116	Exhibitions	178.1	506.0
117	Leasing of machinery & equipment	1,002.8	2,452.7
118	Management consultants	2,271.6	3,133.7
119	Hotel management services	119.5	285.5
120	Research & development	390.7	1,045.7
121	Business representative offices & HQ activities	1,724.1	4,667.3
122	Other business & technical services	1,127.0	3,550.8

Sector	Description	Final demand, F	Total output, X
123	Producers of government services	23,005.2	25,908.7
124	Security services	33.0	596.1
125	Education	1,732.5	1,798.1
126	Medical & health services	4,441.2	5,761.4
127	Environmental health services	257.5	1,588.9
128	Media entertainment	835.2	2,465.1
129	Museums, parks & performing arts	118.5	365.7
130	Sports & recreation	1,217.2	1,915.2
131	Personal & household services	1,156.5	1,613.7
132	Repairs of household goods	95.5	202.9
133	Repairs of road transport equipment	211.1	915.8
134	Domestic services	1,856.1	1,856.1
135	Non-profit bodies	3,496.5	4,613.4
136	Ownership of dwellings	6,342.4	6,342.4

Note: Final demand F, and Total output, X are in SGD million dollars unit.

Singapore Department of Statistic, (2010). *Singapore Input-Output Tables 2007,* National Accounts, Singapore Department of Statistic, Singapore.

Appendix B. 53 Sectors in 2011 Japan I/O table

Sector	Description	Final demand, F	Total output, X
01	Agriculture, forestry and fishery	1,864,394	12,656,764
02	Mining	-3,344,522	619,457
03	Coal mining , crude petroleum and natural gas	-20,104,182	170,367
04	Beverages and Foods	21,957,081	35,499,817
05	Textile products	261,972	1,600,394
06	Wearing apparel and other textile products	168,143	1,689,030
07	Timber , wooden products and furniture	-702,562	3,743,985
08	Pulp, paper, building paper	145,653	7,465,683
09	Printing, plate making and book binding	64,809	4,919,717
10	Chemical basic products	209,629	11,423,172
11	Synthetic resins	409,363	2,755,089
12	Final chemical products, n.e.c.	2,755,846	6,911,362
13	Medicaments	-591,143	7,221,457
14	Petroleum and coal products	4,470,430	20,575,902
15	Plastic products	1,262,391	10,098,151
16	Ceramic, stone and clay products	623,057	5,979,308
17	Iron and steel	2,307,236	31,279,917
18	Non-ferrous metals	-739,508	8,991,777
19	Metal products	631,227	10,319,287
20	General industrial machinery	16,883,328	23,894,564
21	Machinery for office and service industry	2,249,258	3,055,707
22	Electrical devices and parts	3,783,155	7,075,055
23	Other electrical equipment	3,645,747	5,423,278
24	Household electric appliances	1,972,852	2,328,023
25	Household electronics equipment	4,050,383	4,622,220
26	Electronic computing equipment and accessory equipment of electronic computing equipment	2,123,666	2,252,628
27	Electronic components	2,286,561	12,956,259
28	Passenger motor cars	11,843,614	11,843,614
29	Other cars	2,935,801	2,965,608
30	Motor vehicle parts and accessories	3,227,386	26,002,498
31	Other transportation equipment	3,618,387	6,687,157
32	Precision instruments	2,526,975	3,542,497
33	Miscellaneous manufacturing products	2,471,924	6,787,273
34	Reuse and recycling	349,740	1,058,488
35	Construction	41,768,568	51,541,795
36	Electricity	5,201,953	16,330,456
37	Gas and heat supply	1,933,780	3,851,383
38	Water supply and waste management service	2,546,233	7,584,607
39	Commerce	64,459,947	96,477,782

Sector	Description	Final demand, F	Total output, X
40	Finance and insurance	9,040,584	33,311,024
41	Real estate	11,996,431	19,855,229
42	House rent (imputed house rent)	47,227,915	47,227,915
43	Transport	18,046,707	39,957,659
44	Other information and communications	11,467,572	28,339,680
45	Information services	8,920,996	17,037,650
46	Public administration	26,640,963	27,752,192
47	Education and Research	21,009,338	32,955,804
48	Medical service, health, social security and nursing care	60,981,732	62,798,754
49	Advertising services	-134,906	7,736,325
50	Goods rental and leasing services	780,331	7,827,368
51	Other business services	6,593,422	42,370,554
52	Personal services	44,858,321	47,014,860
53	Activities not elsewhere classified	-587,300	5,181,541

Note: Final demand F, and Total output, X are in JPY million dollars unit.

METI, (2014). *The 2011 Updated Input-Output Tables.* Research and Statistics Department, Minister's Secretariat, Japan Ministry of Economy, Trade and Industry (METI), Japan.

Appendix C. Geographical location of 297 critical infrastructure entities in Singapore

Node number	Longtitude	Latitude
0	103.6588366	1.325307275
1	103.6929737	1.349284545
2	103.755152	1.389517592
3	103.7766909	1.309864287
4	103.81286	1.386266437
5	103.8315542	1.299704427
6	103.8620338	1.326932852
7	103.9282761	1.32855843
8	103.945751	1.357006039
9	103.6445583	1.284041483
10	103.6643292	1.333215207
11	103.7150237	1.320034621
12	103.730739	1.266805332
13	103.7459474	1.380868095
14	103.777378	1.320034621
15	103.7941072	1.284548429
16	103.8027253	1.455389099
17	103.8214823	1.325611023
18	103.8437879	1.338284663
19	103.9147603	1.328652697
20	103.9426423	1.362111107
21	103.7417579	1.418707326
22	103.7480272	1.343873845
23	103.9406836	1.330240618
24	103.9709354	1.381987174
25	103.9800906	1.338201626
26	103.6466238	1.343475795
27	103.6705068	1.398008704
28	103.6388618	1.341684568
29	103.6539878	1.365965644
30	103.6655312	1.389052569
31	103.6810552	1.41811025
32	103.7335978	1.415721948
33	103.7439472	1.349645576
34	103.7590731	1.317005441
35	103.798082	1.38984867
36	103.789723	1.365169543
37	103.8191787	1.366363694
38	103.8187806	1.345267021
39	103.8510227	1.414527796
40	103.8510227	1.283171154

41	103.8880414	1.410945343
42	103.9035654	1.337306013
43	103.924264	1.392635023
44	104.042883	1.417314149
45	103.7231361	1.332009231
46	103.7356462	1.353142741
47	103.7414761	1.337596251
48	103.7594517	1.383749894
49	103.7822856	1.29290009
50	103.7968605	1.284641017
51	103.8109495	1.327879694
52	103.8167794	1.312333203
53	103.8318401	1.30407413
54	103.8342692	1.281968964
55	103.8342692	1.278325256
56	103.8396741	1.341239959
57	103.8371842	1.426381286
58	103.8377915	1.427231485
59	103.8400384	1.384660821
60	103.8410101	1.325207641
61	103.8442287	1.32204976
62	103.8459291	1.32283923
63	103.8462935	1.311118634
64	103.8512125	1.320288634
65	103.8547347	1.313001217
66	103.8570424	1.301159163
67	103.8776901	1.371361285
68	103.8849775	1.382049497
69	103.9080543	1.316705654
70	103.948378	1.340997045
71	103.9498355	1.340268304
72	103.9690257	1.357515192
73	103.8506945	1.284374187
74	103.8527593	1.280426836
75	103.850573	1.285285115
76	103.8495406	1.284009816
77	103.8502087	1.285102929
78	103.8526378	1.283038161
79	103.8472937	1.279030081
80	103.8526985	1.283281075
81	103.8530629	1.286013856
82	103.8491763	1.283402532
83	103.8490548	1.279455181
84	103.8516054	1.283220346
85	103.8522127	1.284495644
86	103.851818	1.284192002

87	103.8514232	1.279151538
87	103.8468382	1.277147498
89	103.8456237	1.276995677
90	103.852486	1.285102929
91	103.8508159	1.28346326
92	103.8510589	1.283189982
93	103.8492977	1.282066505
94	103.851241	1.281793227
95	103.8472026	1.277451141
96	103.8527289	1.285740578
97	103.850573	1.278331704
98	103.8496317	1.279607002
99	103.8492674	1.281550313
100	103.853822	1.279485545
101	103.8492066	1.279941008
102	103.8605325	1.293574552
103	103.8511196	1.283523989
104	103.8477492	1.266064551
105	103.7740248	1.283554353
106	103.8359678	1.261692101
107	103.7903	1.271408657
108	103.8316561	1.462217537
109	103.7172437	1.311185811
110	103.8656641	1.414424224
111	104.00121	1.35952568
112	103.7194299	1.265760909
113	103.679592	1.236125411
114	103.9032525	1.319778952
115	103.7325967	1.342352821
116	103.8329799	1.41738337
117	103.7621654	1.425177699
118	103.8168167	1.289562726
119	103.7474051	1.397535018
120	103.6973215	1.337586882
121	103.7983045	1.302438735
122	103.8930604	1.318112082
123	103.9533717	1.343202895
124	103.9451487	1.353301356
125	103.800988	1.440585001
126	103.835005	1.429443081
127	103.9492681	1.372983774
128	103.7652989	1.314954492
129	103.882906	1.316432612
130	103.849933	1.369347304
131	103.9615482	1.334549778
132	103.7443409	1.385361693

133	103.7422865	1.33315262
134	103.8058843	1.294860933
135	103.6368787	1.340463766
136	103.660553	1.319505215
137	103.7864851	1.436875128
138	103.6490755	1.321026553
139	103.8713865	1.31148891
140	103.6396141	1.329989089
141	103.7901915	1.307183467
142	103.7786378	1.311405293
143	103.8200461	1.449050821
144	103.9129494	1.321038249
145	103.7495668	1.349034109
146	103.8495581	1.369933175
147	103.7060646	1.338604055
148	103.7518935	1.358761857
149	103.7740715	1.432514421
150	103.9299845	1.323979969
151	103.6783751	1.327717173
152	103.7209493	1.344259249
153	103.9463465	1.327187135
154	103.8449473	1.381756046
155	103.9127274	1.402286677
156	103.9048316	1.409612685
157	103.8893048	1.397170196
158	103.8812562	1.398212828
159	103.8905394	1.386723922
160	103.7630136	1.377909898
161	103.7708086	1.384520796
162	103.9024119	1.405194701
163	103.9021563	1.415901719
164	103.9003138	1.411870458
165	103.8972097	1.405088585
166	103.9164867	1.399584853
167	103.9125809	1.393909226
168	103.8756352	1.397318155
169	103.7490555	1.378602766
170	103.9086035	1.405234836
171	103.9059619	1.399281985
172	103.9161661	1.394524496
173	103.7623672	1.382692296
174	103.7645033	1.386703025
175	103.766669	1.377750334
176	103.7537122	1.376684679
177	103.7445537	1.38483636
178	103.7452918	1.380298287

179	103.8800296	1.392079839
180	103.902174	1.383978902
181	103.9089502	1.396912053
182	103.8937972	1.396277631
183	103.9066508	1.41684852
184	103.8985585	1.408452426
185	103.8763086	1.391885888
186	103.8858441	1.389347953
187	103.7712702	1.376142883
188	103.9065776	1.412770894
189	103.7726491	1.380017897
190	103.9054391	1.388092704
191	103.9059736	1.391468497
192	103.9004925	1.394493046
193	103.7601398	1.380321008
194	103.8971947	1.384233561
195	103.7580341	1.378618844
196	103.7695984	1.387772131
197	103.8954426	1.391609364
198	103.8506674	1.296861687
199	103.890287	1.326345372
200	103.8525859	1.292936243
201	103.9546345	1.356191483
202	103.938437	1.345515305
203	103.8719006	1.321505838
204	103.862978	1.313672233
205	103.8503843	1.29886427
206	103.8214431	1.26547264
207	103.860853	1.292891552
208	103.8568683	1.299550746
209	103.7846314	1.293462633
210	103.8893506	1.326076883
211	103.9020726	1.404546728
212	103.8458642	1.276521247
213	103.7874575	1.299759879
214	103.8491544	1.35130868
215	103.8753503	1.30284063
216	103.8557064	1.300465076
217	103.8390752	1.300260055
218	103.8322415	1.303981012
219	103.855477	1.305403642
220	103.8590798	1.281873788
221	103.8954847	1.391694626
222	103.8306896	1.333728882
223	103.8825281	1.306201905
224	103.8850649	1.360179171

225	103.8443283	1.292478928
226	103.8075861	1.317510612
227	103.9623757	1.335382137
228	103.8528404	1.27944619
229	103.7906534	1.306491669
230	103.8555041	1.293321608
231	103.863637	1.299766835
232	103.8395298	1.337674508
233	103.8545978	1.276427355
234	103.855094	1.276150637
235	103.8029396	1.272332732
236	103.8434268	1.284359578
237	103.8444512	1.284748969
238	103.837811	1.313607102
239	103.8073222	1.325883209
240	103.8270194	1.286193393
241	103.7674183	1.362344869
242	103.7838067	1.335665121
243	103.8832475	1.326876715
244	103.8992525	1.329956826
245	103.7757943	1.341223176
246	103.9084597	1.334967302
247	103.9430605	1.355077429
248	103.9179783	1.334742117
249	103.8461152	1.298701307
250	103.8723681	1.350595256
251	103.8708183	1.339190046
252	103.8438256	1.320440791
253	103.8735748	1.349707875
254	103.9322346	1.33660783
255	103.8628598	1.271336711
256	103.8541771	1.31235984
257	103.8921788	1.317430268
258	103.8797589	1.342828338
259	103.8886626	1.308382639
260	103.7913503	1.276213523
261	103.8395747	1.279764543
262	103.8465552	1.288386024
263	103.848144	1.350838988
264	103.8161317	1.322423979
265	103.8394231	1.348707263
266	103.7818105	1.282542157
267	103.8641519	1.351612171
268	103.8628292	1.30735702
269	103.8454882	1.299705459
270	103.8462391	1.298842816

271	103.8881949	1.335433322
272	103.8524217	1.303916484
273	103.8485846	1.307198223
274	103.849647	1.306800025
275	103.8260244	1.320065557
276	103.7615351	1.379002117
277	103.7646944	1.369369831
278	103.7972463	1.330786387
279	103.8475018	1.332628987
280	103.7938509	1.427259979
281	103.8690557	1.331379525
282	103.8923805	1.371292292
283	103.8616865	1.319395706
284	103.9614718	1.341737484
285	103.9883647	1.357314545
286	103.7879308	1.436066981
287	103.8467978	1.340471684
288	103.8931216	1.382877858
289	103.8609992	1.293218051
290	103.8149828	1.322110193
291	103.8514617	1.284125611
292	103.7961918	1.31183479
293	103.8391265	1.281404978
294	103.8097486	1.270753211
295	103.8483028	1.282289536
296	103.8379853	1.3123201

Appendix D. Sensitivity analysis of critical infrastructure interdependency model and network analysis

One key assumption being made in Chapter 5 is that each critical infrastructure is well-represented by the sum of the economic outputs of their corresponding sectors in the I/O table. The other assumption is that the spatial representation of the physical infrastructure uses the physical location and the physical linkages between centre offices might be too simplistic. This appendix aims to use sensitivity analysis to test the above assumption made in critical infrastructure interdependency model.

D.1 Sensitivity analysis on aggregation of I/O table for analysis

Based on the aggregation of critical infrastructures in the I/O table, sensitivity analysis can be done to assess the overall impact losses by adjustment of the aggregation of critical infrastructures. Three different cases were compared in Table D-1, where the aggregations are being differentiated as the following.

Case 0: Aggregated I/O table done in Table 5-1, with 10 sectors in total

Case 1: No aggregation except telecommunication sectors, with 135 sectors in total

Case 2: Modification of aggregation done in Case 0 by adding petrochemical & gas critical infrastructure, with 11 sectors in total

The sensitivity analysis was done using the 136 sectors from the 2007 Singapore national I/O table and with the use of the worst case scenario based on a 1, 2 and 3-node failure in one physical infrastructure network under efficiency of network. As such, the telecommunication network will be simulated to fail based on Case 0, 1 and 2 under efficiency of network and the overall impact losses evaluated in Table D-1 using the model in Section 3.2.

Table D-1: Overall impact losses with different aggregation on I/O table

Worst case scenario under efficiency of network	Overall impact losses in Case 0 ($ Millions)	Overall impact losses in Case 1 ($ Millions)	Overall impact losses in Case 2 ($ Millions)
1 Node failure	6.940	6.945	6.946
2 Node Failure	9.439	9.446	9.447
3 Node Failure	14.769	14.780	14.781

The 3 cases in Table D-1 had shown the insensitivity to the level of aggregation. The results show that the aggregation of I/O table will have little impact on the overall impact losses calculated for critical infrastructure interdependency analysis. The I/O model is a linear model and therefore aggregation of the I/O table for uses in I/O model will only cause minor changes to the results. The minor changes are due to the change in sectors in different cases which cause changes in the I/O model ($(\mathrm{I}-\mathrm{A})^{-1}$). The increase in sectors in Case 1 and 2 change the interdependencies of telecommunication with other sector slightly.

D.2 Sensitivity analysis on topology representation of physical critical infrastructure

The topology representation of the physical critical infrastructure (e.g. telecommunication network) is being selected to test on the variability of the results under different sets of simplifying assumption. Three different cases were compared in Table D-2, where the network was being differentiated as the following.

Case A: Original telecommunication network linkages used in Table 5-3

Case B: Fully connected network (All centre offices are connected to each other)

Case C: Original telecommunication network linkages used in Table 5-3, with linkages between OM and AM removed

The linkage between OM and AM for Case C is removed as these two nodes are the most connected node in the telecommunication network. The sensitivity analysis was done using the aggregated 10 sectors in Table 5-2 and the overall impact losses evaluated based on Section 5.2. The simulation of 1, 2 and 3 nodes failure in Section 5.4 was being used to find the worst case scenario and compared accordingly in Table D-2.

Table D-2: Overall impact losses with different linkages on physical critical infrastructure network

Worst case scenario under efficiency of network	Overall impact losses in Case A ($ Millions)	Overall impact losses in Case B ($ Millions)	Overall impact losses in Case C ($ Millions)
1 Node failure	6.940	3.929	6.249
2 Node Failure	9.439	6.876	7.879
3 Node Failure	14.769	6.876	14.074

The 3 cases in Table D-2 had shown great sensitivity towards the different spatial representation of the physical infrastructure network. Comparing Case A and Case B, the worst case overall impact is significantly lower in Case B as the physical critical infrastructure are fully connected (all centre offices are connected to each other). Therefore, any node failure will not seriously affect the efficiency of network for Case B as compared to Case A, where Case A is limited by the physical infrastructure network original construction. Comparing Case A and Case C, the worst case overall impact is reduced slightly in Case C due to the change in the topology of the telecommunication network.

Appendix E. Adding banks' back offices in the analysis of impact on a national network of critical infrastructure system

This appendix aims to simulate the scenario where the bank back offices are added to the scope of analysis in Chapter 7 under Section 7.1.5. The banks' back offices are more important than bank branches as they usually provide the operation centre of a bank that rarely comes in contact with the customers, which includes accounting, administration, data processing, document handling and many other functions. The difficulties in this part of the analysis are that the back offices are usually not clearly stated in the bank website, under the directory of the banking ministry of a country (Monetary Authority of Singapore (MAS) in Singapore context) and GPS map services like google maps. Moreover, some banks have resort to the use of centralizing back office services in a region that are not in Singapore or back offices are simply within the main office of the bank due to the size of the bank. An example of this is OCBC bank setting up a subsidiary company called "e2 power PTE LTD" in OCBC main office to handle back offices work of OCBC bank.

Table E-1: Geographical location of banks' back offices

Name of banks' back offices	Node numbering	Longitude coordinate	Latitude coordinate
DBS	297	103.9647	1.333046
Citibank	298	103.9662	1.333959
Standard Chartered Bank	299	103.9669	1.335127
Credit Suisse AG	300	103.9627	1.333706
J.P. Morgan	301	103.9632	1.333756

For this analysis, much local knowledge is required in identifying the back offices of the banks that are in Singapore. The back offices of banks are known to be mainly at Changi Business Park area in Singapore (Table E-1).

The banks' back offices have been added to the "Banking and finance sector" critical infrastructure in the analysis made in Chapter 7 shown in Figure E-1. A total of 37 bank nodes will be used for analysing the impact on a national network of critical infrastructure system. The simulation is done based on the simulation process described in Section 7.3. If any node is affected by a disruption, the nodes in the critical infrastructure are assumed to be of equal importance and the performance loss are equally distributed among the 37 bank nodes. Similar to the simulation done in Chapter 7, the impact within the radii of 100 metres, 250 metres, 500 metres and 1 kilometre from the geographically-based hazard are being evaluated and compared with the results in Chapter 7 (without back offices).

Figure E-1: Additional of banks' back offices in QGIS

E.1 Results from the addition of back offices in the analysis

As expected, the worst case scenario results from 100m, 250m, 500m, and 1000m radii of geographically-based hazard are the same in term of ranking.

Table E-2: Results due to addition of banks' back offices

Size of impact	Worst case node	Worst overall impact ($ Millions)
100m	112, 113 (Ranked jointly)	165.5
250m	112, 113 (Ranked jointly)	165.5
500m	94	198.7
1000m	40, 84, 91, 92, 94, 103 (Ranked jointly)	240.0

Nodes 112 and 113 are ranked jointly as the worst case scenario under 100m and 250m, amounting to S$165.5 million dollars per day of disruption. The result is the same as what that has been concluded in Section 7.4.1. Under 500m radii, node 94 is ranked as the worst case scenario with an overall impact of S$198.7 million dollars as compared to S$229.5 million dollars under the analysis made in Section 7.4.2. Node 40, 84, 91, 92, 93 are jointly ranked as the second worst overall impact, incurring to a total of S$190.8 million dollars as compared to S$220.4 million dollars under the analysis made in Section 7.4.2. Under 1000m radii, nodes 40, 84, 91, 92, 94, 103 are ranked jointly as the worst case scenarios, incurring S$240.0 million dollars in economic losses as compared to as compared to S$277.4 million dollars under the analysis made in Section 7.4.3. The results still point to the fact that the main importance of protection should be made at the city centre where all the bank's main offices are situated. However, the overall impact evaluated in this appendix has been shown to have reduced because of the increase in the asset under "banking and finance sector" (from 32 nodes to 37 nodes). The increase in the amount of asset in a critical infrastructure will further dilute the importance of a node in the critical infrastructure due to the assumption of equal importance among the nodes in a critical infrastructure (e.g. banking and finance sector).