Development of a Decision Support System through Modelling of Critical Infrastructure Interdependencies

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In the name of Allah, the Most Beneficent, the Most Merciful.

ABSTRACT

Critical Infrastructure (CI) networks provide functional services to support the wellbeing of a community. Although it is possible to obtain detailed information about individual CI and their components, the interdependencies between different CI networks are often implicit, hidden or not well understood by experts. In the event of a hazard, failures of one or more CI networks and their components can disrupt the functionality and consequently affect the supply of services. Understanding the extent of disruption and quantification of the resulting consequences is important to assist various stakeholders' decision-making processes to complete their tasks successfully. A comprehensive review of the literature shows that a Decision Support System (DSS) integrated with appropriate modelling and simulation techniques is a useful tool for CI network providers and relevant emergency management personnel to understand the network recovery process of a region following a hazard event. However, the majority of existing DSSs focus on risk assessment or stakeholders' involvement without addressing the overall CI interdependency modelling process. Furthermore, these DSSs are primarily developed for data visualization or CI representation but not specifically to help decision-makers by providing them with a variety of customizable decision options that are practically viable. To address these limitations, a Knowledge-centred Decision Support System (KCDSS) has been developed in this study with the following aims: 1) To develop a computer-based DSS using efficient CI network recovery modelling algorithms, 2) To create a knowledge-base of various recovery options relevant to specific CI damage scenarios so that the decision-makers can test and verify several 'what-if' scenarios using a variety of control variables, and 3) To bridge the gap between hazard and socio-economic modelling tools through a multidisciplinary and integrated natural hazard impact assessment.

Driven by the design science research strategy, this study proposes an integrated impact assessment framework using an iterative design process as its first research outcome. This framework has been developed as a conceptual artefact using a topology network-based

approach by adopting the shortest path tree method. The second research outcome, a computer-based KCDSS, provides a convenient and efficient platform for enhanced decision making through a knowledge-base consisting of real-life recovery strategies. These strategies have been identified from the respective decision-makers of the CI network providers through the Critical Decision Method (CDM), a Cognitive Task Analysis (CTA) method for requirement elicitation. The capabilities of the KCDSS are demonstrated through electricity, potable water, and road networks in the Wellington region of Aotearoa New Zealand. The network performance has been analysed independently and with interdependencies to generate outage of services spatially and temporally.

The outcomes of this study provide a range of theoretical and practical contributions. Firstly, the topology network-based analysis of CI interdependencies will allow a group of users to build different models, make and test assumptions, and try out different damage scenarios for CI network components. Secondly, the step-by-step process of knowledge elicitation, knowledge representation and knowledge modelling of CI network recovery tasks will provide a guideline for improved interactions between researchers and decision-makers in this field. Thirdly, the KCDSS can be used to test the variations in outage and restoration time estimates of CI networks due to the potential uncertainty related to the damage modelling of CI network components. The outcomes of this study also have significant practical implications by utilizing the KCDSS as an interface to integrate and add additional capabilities to the hazard and socio-economic modelling tools. Finally, the variety of 'what-if' scenarios embedded in the KCDSS would allow the CI network providers to identify vulnerabilities in their networks and to examine various post-disaster recovery options for CI reinstatement projects.

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1 INTRODUCTION

1.1 Background and rationale

Natural hazards such as earthquakes, volcanoes, tsunamis, landslides, and forest fires can severely impact the well-being and survivability of the residents of a country (Chen et al., 2016; Newman et al., 2017). In densely populated areas, these hazards have the potential to cause devastating social and economic loss. Therefore, accurate and timely acquisition of relevant information is important to enabling populations to respond and recover from an event when a disaster develops rapidly (Zhou et al., 2009). All response and recovery actions have the immediate focus of ensuring that people's lives are out of danger and they have somewhere to live. Most critical services such as electricity, water, natural gas, fuel, telecommunication and transportation enable business continuity, movement of people, goods and information, and facilitate daily activities (Trucco et al., 2012). These critical services or facilities can be termed 'lifeline utility services' or 'critical infrastructure' (CI) networks; risks to these CIs from hazards are increasing globally (Banerjee et al., 2018; Furuta et al., 2016; Zio, 2016). The Sendai Framework for Disaster Risk Reduction from United Nations Office for Disaster Risk Reduction (UNDRR), (formerly United Nations International Strategy for Disaster Reduction (UNISDR)) also considers the damage reduction to CIs as one of the most important global targets for building resilience (UNDRR, 2015). The effects of a hazard can be amplified due to the complex interdependencies between CIs (Rinaldi et al., 2001). Thus, when emergency responders and other relevant stakeholders, such as safety engineers and building owners need to make decisions, they must have ground truth information (that is information collected on location) about the impacts from non-functional or damaged CIs and their interdependencies (Fogli & Guida, 2013).

Rinaldi et al. (2001) argue that interdependency is a bidirectional relationship between two CI networks, where the state of infrastructure *A* is somehow dependent on the state of infrastructure

B, and vice versa. Dependencies can be direct from one infrastructure network to the other and therefore they can be identified quite easily. These dependencies are termed '*first-order dependencies*'. However, dependencies between two infrastructure networks can also be indirect. For example, if infrastructure *A* is dependent on infrastructure *B* and infrastructure *B* is dependent on infrastructure *C*, then a dependency exists between infrastructures *A* and *C*. These types of dependencies are termed '*second-order dependencies*' and are much more difficult to identify. The effects of infrastructure dependencies need to be identified through explicit techniques such as modelling and simulation (Zhang et al., 2016).

Several previous studies have recognised and explained the importance of developing simulation tools for modelling interdependent CIs (see, for example, Johansson & Hassel, 2010; Laprie et al., 2007; Ouyang, 2014; Pederson et al., 2006; Rinaldi et al., 2001; Setola & Theocharidou, 2016). Existing models have been built through numerical computations to provide advanced level modelling of CI interdependencies. However, these models cannot support decision-making functionalities because of the complex nature of uncertainty involved in the decisions. Therefore, due to the changing nature of emergencies, this lack of decision support does not fulfil the requirements of the decision-makers (Filip, 2008). Sànchez-Marrè et al. (2008) defined three complexity levels when modelling and simulation are used with decision-making:

a) The first complexity level deals with the issues that have limited scope. This level involves a single perspective of the models to resolve low uncertainty issues;

b) The second complexity level deals with higher uncertainty systems where the simple models alone are not sufficient to resolve the problems. Therefore, there is a need to involve experts' involvement for a better description of the system; and

c) The third complexity level deals with issues that have conflicting goals. Several perspectives of the same problem make them more complex and need additional support systems to resolve the issues. The higher complexity level in such systems is not associated with multiple components of the systems, but rather due to the epistemological or ethical nature of uncertainty.

Modelling of CI network interdependencies is related to the second and third levels of complexity, and therefore needs the involvement of experts for a better understanding of the uncertainty levels (Hasan & Foliente, 2015). Furthermore, a need to build new systems for supporting the decision-making of experts is also evident from the complex nature of CI interdependency modelling (Klashner & Sabet, 2007). After reviewing the existing literature, it was found that through modelling and simulation it is possible to develop a computer-based Decision Support System (DSS) to understand the functionality of interdependent CI networks (Mitsova, 2018; Zografos et al., 2000). The DSS in this case should be appropriate and sophisticated enough to analyse and process a large amount of information to enhance the decision-making process for the various stakeholders engaged in large and complex emergency response and recovery activities (Vivacqua et al., 2016). Therefore, a DSS supported by modelling and simulation techniques can be a very useful tool for CI network providers and relevant emergency managers to understand the behaviour of a region after a hazard event (Kiel et al., 2016).

1.2 Research gaps

DSSs can resolve higher levels of complexities associated with the integration of multiple frameworks, software architectures, tools and techniques (Aleskerov et al., 2005; Asghar et al., 2005). The need for decision support in CI interdependency modelling is widely recognized in the literature (see, for example, Choraś et al., 2010; Filip, 2008; Rosato et al., 2016), and several DSSs or decision support tools have been developed to resolve the associated issues and to support decision-making in the field of CI interdependency modelling (see, for example, Alutaibi, 2017; Anzaldi et al., 2014; Rutledge et al., 2007).

However, most of these DSSs are models or tools that have been used for data visualization or better description of the research problems, but they cannot provide a variety of customizable options to the decision-makers through which they can create and test their desired damage and recovery modelling scenarios. Furthermore, the majority of these DSSs focus on addressing the overall CI interdependency modelling process but do not involve experts' feedback in the form of elicited knowledge for solving the real-world CI interdependency problems that are region-specific (McCarthy et al., 2016; Müller et al., 2019). Although it is argued that a model or related information system can be used for decision support, there is a strong need for CI interdependency modelling using DSS to adopt a knowledge-based approach (see, for example, Anzaldi et al., 2014; Arain, 2015; Inan & Beydoun, 2017; Osatuyi & Andoh-Baidoo, 2014; Singhaputtangkul et al., 2013). Recently, several DSSs have been developed to incorporate elicited knowledge in the knowledge-bases to support more transparent and justifiable decision-making (Anzaldi et al., 2014; Duah & Syal, 2016; Zaraté & Liu, 2016). Even with the involvement of experts, the management of these decisions needs a robust decision-making framework that can integrate the different models, experts' knowledge and problem-solving tools into a single intelligent support system.

At present, the use of modelling and simulation techniques with the DSSs has proven to be an efficient way of integrating different CI network models and analysing CI interdependencies. A comprehensive review of the literature indicates that various approaches have been adopted by researchers to model interdependencies between CI networks, including mathematical modelling approach by Haimes and Jiang (2001); system dynamics approach by Canzani et al. (2017) and Cavallini et al. (2014) ; agent-based modelling approaches by Casalicchio et al. (2010), Haghnevis et al. (2016), Nan and Sansavini (2016) and Panzieri et al. (2004); and network modelling approaches by Dueñas-Osorio, Craig and Goodno (2007), Ouyang and Dueñas-Osorio (2011b), Lam and Tai (2018) and Dunn et al. (2013). However, after reviewing these techniques for modelling and simulation of CI, it is evident that they lack one or more key capabilities including:

- Most of the simulation models concentrate on a single perspective of interdependency, for example, physical interdependency, and cannot, therefore, incorporate multiple perspectives in a single system (Ventura et al., 2010);
- More often a CI is modelled as a single node using spatial characteristics which ignores its component-level hierarchy and connectivity (Dueñas-Osorio & Hernandez-Fajardo, 2008);

- Most of the existing models cannot model the temporal interactions of the systems to predict the behaviour of recovery and, therefore, there is a need for a time-stamped simulation so that stakeholders can visualize the cascading effects of a disaster and do a prediction of how much a geographical region or area of interest would be recovered in different periods (Wang et al., 2014);
- Most of the simulation approaches focus only on one CI and its impact on the other CIs, without considering the characteristics of subsystems, elements, or components. In the case of interdependency analysis, one component of a CI can be different from another, and their characteristics should, therefore, be defined separately (Lee et al., 2018);
- Finally, limited effort has been made to link models relevant to different domains to achieve more realistic results. For example, an end to end linkage of hazard and economic models could enable decision-makers to effectively understand the economic loss to a region by using appropriate hazard models (Kelly, 2015; Syed et al., 2021).

The above limitations and research gaps clearly show the need to develop a robust DSS that can integrate a CI interdependency modelling framework with experts' feedback in the form of elicited knowledge for solving the real-world CI interdependency problems. The identified research gaps led to the formulation of the following research questions:

1. What are the requirements and challenges for understanding CI interdependencies and issues of decision-making during an emergency scenario?
2. What form would a framework take for a better representation of CI components and the assessment of their functionality?
3. What functional features should a DSS have to support decision-making during the recovery of CI networks?
4. What attributes must be considered for evaluating the functionality of the DSS?

1.3 Research aim and objectives

To successfully answer the above questions, this study aims to design and develop a Knowledge-centred Decision Support System (KCDSS) using a computer-based impact assessment framework that can assess the functionality of CI networks by modelling their interdependencies. To achieve this, the proposed KCDSS will make use of the elicited knowledge from the experts to provide various optimization options, scenario-driven comparative analysis and customizable recovery strategies for CI assets or components. Furthermore, this study will answer the above research questions by successfully achieving the following research objectives:

1. Exploring fundamental concepts, requirements, existing methods, and current techniques of understanding the CI interdependencies;
2. Development of a conceptual CI performance framework to generate disruption measures in spatial and temporal context and to generate time-stamped outage maps;
3. Development of an interactive DSS that hosts the processes of the conceptual framework and enables 'what-if' analysis for various scenarios within a simulation-based environment; and
4. Evaluating the KCDSS from a list of experts and identify areas for future development.

1.4 Research scope

The scope of this study is to demonstrate how CI network recovery performance can be modelled, accounting for interdependencies using a KCDSS and focusing on delivering results that are useful for local- and regional-level stakeholders and CI network providers within their decision-making contexts. This study is supported by core funding from GNS Science (Institute of Geological and Nuclear Sciences) through its Post Disaster Cities (PDC) project. Within this project, this study primarily focuses on CI networks in the Wellington region in Aotearoa New Zealand. The Wellington region is located on the plate boundary of the Pacific and Australian tectonic plates and therefore considered a region of very high seismicity (Mowll et al., 2013). The principal active earthquake faults bisect many CI networks so that any future earthquake could severely affect CI connectivity within the region. The earthquake faults extend into the marine area surrounding the region, creating a significant tsunami hazard from fault movement on the offshore sections of faults, or because of submarine landslides triggered by the earthquake shaking (Get Ready, n.d.).

This study intends to model the interdependencies between electricity, potable water, and road networks as they greatly determine the level of economic stability and continuity of a country, even after a disaster event. The production of electricity requires large volumes of water while the treatment and distribution of water depend on electricity and both electricity and water networks are physically linked through the road network. The impact assessment framework of this study aims to transform the damage information of CIs generated from hazard and risk assessment tools into a measure of the region-wise Level of Service (LOS). The proposed KCDSS intends to collate the decision-making process of various emergency management stakeholders including emergency managers, safety engineers, insurance companies and economic analysts. Also, end-users from organisations like Wellington Region Emergency Management Office (WREMO) (WREMO, 2017), Greater Wellington Regional Council (GWRC) (GWRC, n.d.), Wellington Electricity (WE) (Wellington Electricity, n.d.), Wellington Water (WW) (Wellington Water, n.d.) and Waka Kotahi NZ Transport Agency (Waka Kotahi NZTA, n.d.) may also use the KCDSS for damage assessment of the CIs and its impact on a region through simulated disaster scenarios. One more important aim of this study is to make the KCDSS customizable and applicable to a variety of CI networks of other regions without any dependency on region-specific CI network data. It will support the stakeholders to be proactive and to effectively plan and prepare for response and recovery of a large-scale disaster by designing and developing more appropriate and accurate policy and procedures for their regions of interest.

1.5 Thesis structure

The remaining chapters in this thesis are structured as follows:

Chapter 2 *(Literature Review)*, identifies the current gaps and challenges in the modelling of CI interdependencies and the use of DSS to enhance decision-making capabilities. It also explores the potential influence of recent modelling and simulation technologies to address the challenges associated with understanding CI interdependencies. Then, a detailed investigation of the use of DSS is presented by providing some real-world examples followed by a thorough literature review of the existing methods.

Chapter 3 *(Research Methodology)*, describes the perspectives and strategies that are adopted in this study to answer the research questions and achieve the aim and objectives. This chapter includes the research philosophy, approach, strategy, methodological choice, time horizon and the techniques and procedures of the study. It also specifies the justification of chosen research strategy to assist in answering the research questions.

Chapter *4 (Artefact - I: Framework for Integrated Impact Assessment of Critical Infrastructure Networks)*, outlines the design of the impact assessment framework using four integrated modules to conceptually present the modelling process of CI interdependencies. The conceptual model is demonstrated using the test case scenario of the Wellington region to highlight the integration of the data collection and analysis procedures.

Chapter 5 *(Artefact - II: Development of Knowledge-centred Decision Support System (KCDSS))*, presents the implementation of the KCDSS through the conceptual framework of Chapter 4. It presents the overall implementation architecture of the KCDSS following a layered architecture pattern, which provides a modularization to simplify the implementation process. Additionally, the functional capabilities of the KCDSS are demonstrated through its user interface screens.

Chapter 6 *(Evaluation of the KCDSS)*, provides evaluation of the KCDSS quantitatively through the involvement of experts from various fields of the emergency management domain. In-depth interviews and analysis of the experts’ feedback are the main instruments being used to evaluate the functionality, usability, reliability, performance, and supportability features of the KCDSS.

Finally, Chapter 7 *(Contributions and Future Directions)*, concludes the entire thesis with a reflection on how this study has addressed the original research problem. It acknowledges the limitations and proposes recommendations for the CI networks of Aotearoa New Zealand. This chapter also discusses the value of the study and its contributions to researchers involved in CI network interdependency modelling, DSS development and knowledge management for decision-making.

1.6 Chapter Summary

This chapter has laid the foundations for the thesis. First, a background on the related concepts and existing issues in the interdependent nature of CI networks was provided. Then, the chapter introduced the research problem that the thesis seeks to address, which was followed by stating the aim of the research, the essential questions and the objectives of this study. This chapter ended with delineating the overall structure of this dissertation to guide the reader throughout this document.

The following chapter provides a background to understanding various interdependencies related to the modelling of CI networks, including the underlying principles and concepts of modelling and simulation techniques to facilitate the recovery of CI network data. It also provides a review of the existing literature related to CI interdependencies and DSS as the two main strands of this study.

2 LITERATURE REVIEW

2.1 Introduction

To explore and identify gaps in the existing literature and potential research opportunities, this chapter presents a relevant literature review starting from an introduction to CI networks, followed by the use of modelling and simulation to understand interdependencies between CI networks and finally the need for developing DSS supporting emergency management and more specifically DSS for CI interdependency.

2.2 Critical Infrastructure (CI)

Although CIs are defined differently in various countries, the main concept aims to describe essential infrastructure elements and processes from a government's perspective. For instance, in the USA, the President's Commission on Critical Infrastructure Protection (PCCIP) deals with the hazards, vulnerabilities and associated implementation plans to protect the regional CIs. In its October 1997 report to the U.S. President, the Commission defined infrastructure as "a network of independent, mostly privately-owned, man-made systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services" (PCCIP, 1997, p. 3).

In Aotearoa New Zealand, the National Infrastructure Unit (NIU) within Treasury draws on the same definition as the Civil Defence Emergency Management (CDEM) Act 2002 (MCDEM, 2002). Referred to as lifeline utilities or simply lifelines, there are twelve CIs in Aotearoa New Zealand. These CIs can be grouped into the energy sector (gas, electricity, petroleum supply), water sector (water supply, wastewater, stormwater), transportation sector (road, rail, airports, shipping ports), and communications sector (telecommunications, broadcasting).

CIs, therefore, consist of interconnected interdependent networks or systems which we can also term as ‘system of systems’ that are essential for a continuous flow of critical services to end-users (Luiijf et al., 2003; Tolone et al., 2009; Ventura et al., 2010). During emergency and disaster situations such as earthquakes, tsunamis, floods or forest fires, these CIs are critical to providing a continuous flow of services to emergency relief so if they are damaged there is a serious threat to the resilience of a community (Meduri, 2016; Orchiston et al., 2018). These CIs need to be recovered as quickly as possible to enable the regional community to face any challenges with the changing conditions and recover rapidly (Mendonça et al., 2001). Past hazard events can be useful to identify the existing vulnerabilities in the individual CI networks to make better preparations for future hazards. Their empirical data can also be utilized to demonstrate the importance of dependencies and interdependencies among multiple CIs of a region (Alcaraz & Zeadally, 2015; Masucci et al., 2016; Ouyang, 2014).

Dependency, as termed by Rinaldi et al. (2001, p. 14), is “a linkage or connection between two infrastructures, through which the state of one infrastructure influences or is correlated to the state of the other”. Rinaldi defined interdependency as “a bidirectional relationship between two infrastructures through which the state of each infrastructure influences or is correlated to the state of the other. More generally, two infrastructures are interdependent when each is dependent on the other” (Rinaldi et al., 2001, p. 14).

Identification and analysis of CI dependencies and interdependencies is a complex process. These interdependencies are characterised by Rinaldi et al. (2001) into different: (i) interactions i.e. upstream, internal and downstream), (ii) classes (that is, physical, cyber, logical and geographic) and (iii) dimensions (that is the operating environment, coupling and response behaviour, type of failure, infrastructure characteristics and state of operation). They influence vulnerability, resilience and any consequences associated with the resilience of the CIs and lead to the propagation of cascading and escalating failures (Dueñas-Osorio & Vemuru, 2009; König & Schauer, 2019).

Due to the interdependent CI networks being complex, many existing studies emphasize the need to enhance interdependency analysis (Bloomfield et al., 2017; Chou & Tseng, 2010; Mitsova, 2018). With the range of complexities involved in the integration of dependencies and interdependencies of CIs, it is impossible to analyse the behaviour of a CI in isolation from the environment or other CIs. Failure to understand the dynamics of the dependencies and interdependencies of CIs will result in an ineffective recovery process, and poor coordination between decision-makers that will further affect the management of personnel and resources (Hasan & Foliente, 2015). Additionally, with a variety of stakeholders being involved in the management of CIs, it is not easy to handle their diverse planning and design concerns. Therefore, it is vital to understand the decision-making contexts and the objectives of the stakeholders to evaluate their capabilities and challenges. One such technique is to use computational modelling and simulation (Rodríguez et al., 2012). The following section elaborates on modelling and simulation along with a comparison of some of the existing simulation tools.

2.3 Modelling and simulation

The purpose of developing a model is to predict the effects of modifications in a system. The model analysts can incorporate most of the salient features of the system into a model (Tolk et al., 2013). The model should be simpler than the system it represents because complex models are very difficult to handle and can lose their purpose (Maria, 1997). An important aspect of modelling is model validation, as such, it is important to ensure that the model effectively depicts a real-world scenario (Çagnan & Davidson, 2003; Eusgeld et al., 2008). Model validation is also important to test a model under predefined input conditions and comparing the results generated by a model with real system outputs. Simulation of a model is the most popular technique for model validation and has been adopted by several researchers in the past (see, for example, Brown, 2006; Canzani et al., 2017; Eusgeld et al., 2008; Haghnevis et al., 2016; Johansen & Tien, 2017; Tolk et al., 2013). Specifically, a computer model is the combination of algorithms and equations used to capture the behaviour of the modelled system (De Nicola et al., 2016). Simulation is the visual representation of a computer-based modelling program that contains equations or algorithms during runtime. Therefore, simulation is the process of conducting experiments with a model to meet predefined conditions through an optimized system performance and to eliminate unexpected bottlenecks to prevent mismanaged utilization of the resources (Maria, 1997). More specifically, simulation modelling and analysis should be used in situations where:

- There is a challenge with handling real-world processes, which are otherwise too expensive or impossible to predict, for example, a natural hazard or the testing of newly developed aircraft;
- Difficulties with handling complicated analytical problems of the complex systems, for example, stock market and large-scale queuing models; and
- Validation of mathematical problems due to their extreme cost and complexity of measurements, for example, due to an insufficient amount of available data.

Applications of simulation modelling abound in the areas of defence (Ventura et al., 2010), computer and communication systems (Borshchev et al., 2002; Macal & North, 2008), manufacturing (Porcellinis et al., 2008), transportation (air traffic control) (Markus et al., 2004), business analysis (Tolk et al., 2013) and health care (Cheng et al., 2016) and emergency management (Hosseininezhad et al., 2012). In the emergency management domain, preliminary work by Kellner et al. (1999), Maria (1997) and Jain and McLean (2003) focused on modelling a major disaster event itself. Current technological developments during emergency management allow a system-level approach that includes modelling of all the key aspects of a CI, its impact on population and resources and the response by concerned authorities (Aung & Watanabe, 2009; Hasan & Foliente, 2015). During the past few years, several simulation-based models have been developed to support the process of understanding the behaviour of a CI network and to identify potential weaknesses (for example, Erdener et al., 2014; Galbusera et al., 2018; Haghnevis et al., 2016; Hasan & Foliente, 2015; Panzieri et al., 2005; Portante et al., 2017; Zhang & Peeta, 2011; Zhang et al., 2016).

Most of the existing studies for CI network modelling focus on reproducing network disruptions that cause service outages. They assess system vulnerabilities or the impact of network parameters, such as the load and demand of modelled networks in the presence of disruptions. Similarly, there are software systems or simulators developed to simulate CI interdependencies to varying degrees. One such example is AIMS (Agent-based Interdependency Modelling and Simulation), which is a multi-agent modelling and simulation suite that allows its users to create models of infrastructure and observe the behaviour of the modelled system through simulations (Bagheri et al., 2007). AIMS provides its users with a set of predefined templates for the CI components. The modelled infrastructure is then built through the instantiation of these templates into software agents. ASPEN (agent-based simulation model of the U.S. economy) is another example, which is an agent-based microanalytic simulation model designed specifically at the SANDIA national laboratories to simulate the US economy (Basu et al., 1998; Haghnevis et al., 2016). ASPEN can simulate the behaviour of simple decision-making agents of the economy. The CIMS (Critical Infrastructure Modelling System) is developed at Idaho National Laboratory (Dudenhoeffer et al., 2006). In CIMS, an agent represents each physical infrastructure and the interdependencies between infrastructures and their relationships are represented as connected graphs. CISIA (Critical Infrastructure Simulation by Interdependent Agents) is also a popular simulation model proposed by Panzieri et al. (2004). It models the behaviour of various interacting infrastructures through a set of non-linear interdependent agents. In CISIA, the agents' dynamic behaviour is described by fuzzy logic.

A variety of above-mentioned software systems and simulators have addressed the fundamental issues related to a CI such as its organisation, behaviour, risks, threats and vulnerabilities. Although these simulation tools have made significant efforts to represent, simulate, and model the CI interdependencies, there is still a need for further investigation to provide new or innovative models and techniques that can meet the practical needs of decision-makers. A review of existing simulation-based approaches reveals the following merits:

- The use of simulation for CI network modelling can provide an insight into various disaster situations and can capture the network interdependencies and economic flows in the CI networks;
- They are simple to use even for large-scale problems through a little effort in avoiding complicated theoretical or mathematical limitations;
- Through integration with DSSs, they can provide support for what-if analysis to deal with various types of hazard scenarios and their recovery strategies;
- They can capture the behaviour and strategies of decision-makers through a knowledge-base of rules or cases representing different scenarios; and
- They can provide a user-friendly graphical interface to facilitate ease of use and better visualisation for interpretation of the results.

Apart from the above merits, simulation-based approaches have the following limitations:

- Most of the simulation-based tools cannot produce statistical analysis or analyse the numerical or mathematical properties of the underlying models;
- Most of the simulation-based tools concentrate on a single perspective of interdependencies, for example, their physical or geographical aspects, and therefore, all the aspects of the interdependencies are not modelled in the same simulation-based study;
- The modeller's initial assumptions about the behaviour of the software components can greatly affect the quality of the simulation. In most cases, the modellers cannot justify these assumptions theoretically; and
- Most of the simulation tools cannot calibrate the simulation parameters through a comparison with realistic benchmark data.

To develop a simulation-based framework that can model the CI interdependencies by resolving the limitations mentioned above, it can be argued that each CI need to be modelled starting from its macro components that have specific and easily recognisable roles. There needs to be a consistent description of the capabilities and behaviours of these components and fuzzy numbers should be used to code parameters and values to avoid any vague statements about their characteristics. Finally, there should be a provision for command and control systems to be integrated with real-time decision support to consider the impact of dependencies and interdependencies among the different CIs (Ani et al., 2019; Griot, 2010; Raskob et al., 2015).

2.4 Techniques for modelling and simulation of CI interdependencies

In the last two decades, several studies have been published in the literature that used a variety of techniques for modelling CI interdependencies (for example, Bloomfield et al., 2017; Griot, 2010; Ouyang & Dueñas-Osorio, 2011a; Panzieri et al., 2004; Pederson et al., 2006). In the context of Aotearoa New Zealand, Zorn et al. (2020) presented a methodology to combine functionally interdependent CI networks with geographic interdependencies by simulating complete component failures across a national-scale grid of spatially localised hazards, making it a critical assessment of 'what-if' failure scenarios. The methodology has demonstrated the ability to quantify the consequences of failure in terms of the potential user disruptions in a fixed time frame (that is average daily user disruptions); however, the study highlighted the need for future developments to model the temporal changes in disruption should recovery processes be further considered, which becomes more important when considering a specific natural hazard (such as earthquakes, flooding, volcanic eruptions) or multi-hazard scenarios.

Several review papers have been published during this time to summarize developments and to present state-of-the-art modelling and simulation techniques classified in a range of taxonomies (for example, Eusgeld et al., 2008; Ouyang, 2014; Pederson et al., 2006). However, many of the articles review the existing techniques without explicitly considering their modelling objectives and stakeholder concerns. As noted by Rinaldi et al. (2001), the diverse set of stakeholder concerns drive the principal requirements of a model. Hasan and Foliente (2015) presented a stakeholder-oriented framework focused on modelling the CI interdependencies. This framework provides opportunities to analyse different modelling approaches that deal with direct and broader socio-economic impacts of an extreme event to a CI network.

Given the inherent complexities of CI networks, no single technique or approach can answer all questions for any CI and no universal model can completely model the CI interdependencies (Eusgeld & Nan, 2009; Murray et al., 2008). Indeed, a growing body of literature over the last two decades highlights the variety of perspectives and approaches that can be adopted for analysing interdependent CI networks. A review of the literature shows that the existing studies have adopted one of the five different methodological approaches, namely, (i) empirical, (ii) agent-based, (iii) system dynamics, (iv) economic theory and (v) a network-based approach. A summary of these approaches is given below.

2.4.1 Empirical approaches

The empirical approaches analyse CI interdependencies and provide better situation awareness for decision-makers. They provide alternative risk mitigation strategies according to historical disaster data and experiences gained by experts in the field (Ani et al., 2019; Ouyang, 2014). Empirical studies often utilize historical data to identify similar patterns in the failure of CI. Past studies have created databases for different types of patterns. For example, McDaniels et al. (2007) created a database for societal impacts, Luiijf (Luiijf et al., 2009) created a database of various CI related incidents in selected European countries to show cascading failures, whereas Chou and Tseng (2010) created a database through a knowledge discovery process of CI failures of similar types at the component level. Another way to represent CI interdependencies is through common factors to indicate better plans for mitigation and emergency-based decision-making. These factors can be quantified using statistical analysis techniques such as frequency analysis or time-series analysis (Dueñas-Osorio et al., 2007; Mendonça et al., 2001). The findings from empirical studies may be biased because of the small-scale data acquired from specific cases (Ouyang, 2014). The bias can be reduced by enhancing the size of the empirical/observational data. As these approaches depend on the availability of past data, they become challenging to use the data for future scenarios or 'what-if' analyses. Another problem with empirical approaches is that there is no certainty that all the historical data was collected for the past event without missing any important information, making the data unreliable (Luiijf et al., 2009). Also, as disasters are mostly unpredictable, damage patterns can change even in similar situations, even accurate data may not apply to future events (Lin et al., 2014). These weaknesses suggest that the combination of empirical approaches should be applied with other modelling and simulation approaches, like agent-based modelling or network theory, for additional decision support.

2.4.2 Agent-based approaches

Agent-based modelling (ABM) approaches support bottom-up analysis to analyse the complex architecture and adaptive behaviours of the CI network components (Bagheri et al., 2007). The bottom-up analysis provides a capability to model down to the level of individual CI components, as well as the behaviour of a decision-maker. Several previous studies have used ABM for simulation of CIs (for example, Hosseininezhad & Alidoosti, 2017; Lee et al., 2018; Nan & Sansavini, 2017, 2017; Oliva et al., 2010). The drawback of ABM approaches is that they may need a lot of parameters, can be time-consuming and need repetitive simulations in some cases to avoid uncertainties. The decision-makers using ABM also need to be very careful to specify all required information for the simulations, because even slight changes in input can change the results (Bagheri et al., 2007). Like the empirical approach, ABM works better when integrated with other techniques to address multiple behaviours and aspects of the CIs in the modelled framework.

2.4.3 System dynamics approaches

System dynamics approaches are widely used to analyse and understand the behaviour and structure of a complex system over time (Canzani et al., 2017). Based on the non-linear theory and feedback controls, they represent a top-down approach to analyse complex systems. System dynamics has three central concepts, which include *stocks* that deals with the accumulation of resources in a system, *flows* that is concerned with the rates of change that alter those resources, and *feedback* that deals with the information that determines the value of the flows (Eusgeld et al., 2008; Ouyang, 2014). The simulation of a CI network based on a system dynamics approach gives a better understanding of the dynamic behaviour of the system through an insight into the changing nature of the causes and effects. As part of the limitations of the approach, it requires a huge amount of data that can only be validated at the conceptual level and therefore this approach lack the capability to capture CI component level dynamics (Cavallini et al., 2014).

2.4.4 Economic theory based approaches

Economic theory based approaches adopt two models: (i) the input-output (I-O) model and (ii) the CGE (Computable General Equilibrium) model; both are heavily used in the 'economics' context (Jonkeren et al., 2012; Santos, 2006). In the I-O model, the 'inoperability' of the CI networks can be quantified in terms of the percentage of loss of function to the system's original production level. A few limitations of the I-O model as used in CI network analysis include: (i) CI networks cannot be represented spatially in the modelling framework and (ii) The interdependencies existing at the individual level of the CI components or economic sectors cannot be handled by this approach (Haimes & Jiang, 2001). Therefore, these models cannot provide any useful guidance for improving CI network resilience through investment decisions. CGE models extend the capabilities of I-O models and enable the capture of interdependencies in a single and multi-layer CI network (Kelly, 2015; Oliva et al., 2010).

2.4.5 Network-based approaches

CIs can be treated as networks that are spatially spread with different components linked together to function and provide desired levels of services (Ani et al., 2019; Cheng, 2017; Kim & Kang, 2013). In the network modelling approach, nodes or vertices represent different components of a CI network and links or edges represent connectivity and relationships among them (Dueñas-Osorio & Hernandez-Fajardo, 2008). To understand the performance of an entire CI network under a given hazard, damage to individual components are to be modelled first, then cascading failures in the CI network can be simulated based on the dependencies in terms of physical connectivity and functional relationship among the interconnected components within a CI network or with the components from more than one CI networks (Dunn et al., 2013). Network-based approaches can be divided into two groups: (a) topology-based approaches and (b) flow-based approaches.

2.4.5.1 Topology-based approaches

Topology-based or structural approaches generally identify discrete states for each component (node or link) as failed and normal, i.e. each component is either completely out-of-work or fully working, respectively (Dueñas-Osorio et al., 2007). These approaches require basic information on the topological structure of a CI, which is generally easy to obtain. The basic information could include structural properties of the CI network components in terms of their geographical locations and connectivity among the components. These approaches usually examine failures at the node or link level, considering their vulnerabilities, and then examine cascading failures to other nodes or links (Zhang et al., 2016).

The topology-based approach is further divided into analytical-based and simulation-based. Analytical-based methods are applied for randomly constructed networks of large or infinite size with no spatial constraints and with assumptions of equal probabilities of failure for their network components. Hence, they are not suitable for modelling the performance of real CI networks where spatial constraints and different probabilities of failure of the network components under a hazard need to be modelled (Ouyang, 2013). On the other hand, simulation-based methods provide capabilities to model features of real networks with a desirable level of granularity and variations in failure probability of the components (Hosseininezhad et al., 2012). This method can model performance metrics related to their topological structure, such as the number of failed components (representing physical vulnerability of the network), availability of connectivity and redundancy in the network. In addition, the method can incorporate metrics for functional properties of the network, including the duration of loss of service at the component and system levels. Such metrics are highly useful in understanding the resilience of CI networks and guide decision-makers to achieve improved performance (Rosato et al., 2016).

2.4.5.2 Flow-based approaches

Flow-based approaches are developed by equipping the topological structure with some flow-dynamic models that communicate information on the LOS that each node can deliver to, or consume from another node (Dueñas-Osorio & Hernandez-Fajardo, 2008). This method not only provides useful and quantified estimates of a LOS that is closer to reality but is also used to identify critical components in a network. However, tuning such flow-dynamic models requires a lot of data, is hard to obtain and the computational cost becomes very high as the network grows (Brown, 2006).

From the above discussion about different approaches to model interdependencies between the CI networks, it can be argued that each approach has its merits for specific objectives and the scope of a relevant study. The empirical approach is useful to predict damage consequences across different CI networks, ABM is beneficial for studies that intend to model multiple relationships between multiple components of a CI network, economic theory based approach is useful to capture market and economic interdependencies among different CIs, system dynamics approach is more useful because it predicts the dynamics of a system, topological network-based approach mainly represents the topological structures of the interdependent CI network through the identification of their subcomponents, and to provide additional flow-based characteristics of CI networks, flow-based network approach can be useful.

A study by Hasan and Foliente (2015) emphasised that it is essential to identify the decision-making context before choosing an appropriate modelling approach for CI network modelling. The study further suggests that the appropriateness of a modelling approach also depends on its capabilities, features, and an understanding of the types of decisions to be made by different stakeholders as per their job roles. It can also be noted that not many studies have investigated CI network interdependency issues at a local scale to model disruptions to the services. Roles for national, regional and local government stakeholders could include (i) CI network investment and development about asset management and disaster resilience, (ii) CI network services and supply provisions and (iii) CI network management and operations. Their specific decision-making contexts could be described as:

a) providing services delivered through CI network components (for example, the supply of electricity, water, fuel, natural gas and provision of transportation facilities roads, bridges, railway tracks, airports, and wharves, etc.)

b) identification of the number of endangered CI network components due to the risk of major disruptions and development of appropriate mitigating strategies in a major region of interest, and

c) development of action plans and risk assessment strategies to handle the vulnerabilities in CI networks.

The above discussion shows that it is not possible to develop one 'super tool' to address all the key issues of CI interdependency modelling and the related decision-making contexts. Instead, there is a need for a more pragmatic and integrated approach to building and linking CI network models. The integrated approach can be useful to build a platform that will allow the use of different methodological approaches depending on the stakeholder concerns, geographical concerns and regional characteristics of the CI networks to be modelled. It is reported in earlier studies by Brown (2006), Panzieri et al. (2004) and Eusgeld and Kröger (2008) that agent-based and system dynamics models were applied to develop regulation and policy guidelines for the design and management of resilient CIs to assist the decision-makers in national and central government organisations. This is because these methods can perform 'what-if' analyses to understand CI network performance and support decision-making at the conceptual level without requiring actual ground-truth data of real CI networks.

A network-based approach is increasingly becoming preferred for situations in which the stakeholders from local government and CI network providers need to understand the potential level of disruption to services, prepare emergency plans, identify vulnerable parts of the CI networks and choose suitable mitigation approaches (Pant et al., 2017). The network-based approach enables to model the topological structure of a CI network by providing their component-level connectivity while accounting for their interdependencies to help decision-making. Applying this approach can prove valuable if the relevant data and information from CI networks are available. Representation of CIs using a topology network-based approach is beneficial to extract the topology of each CI component and to establish connectivity among them using network generation algorithms (Yao et al., 2018). The choice of a suitable modelling approach leads to choosing an appropriate decision support tool to address the stakeholders' diverse concerns related to the planning, design, development, and management of interdependent CI networks.

2.5 Decision Support Systems (DSSs)

DSSs are a specific class of computer-based Information Systems (IS) that provide a variety of alternative solutions to a problem to support managers in their decision-making activities (Rutledge et al., 2007). Properly designed DSSs are interactive software-based systems that can quickly compile and analyse useful information from raw data, documents, personal knowledge, and business models (Alutaibi, 2017). The concept of DSSs emerged from two main areas of research: theoretical studies that focus on organisational decision-making, and technical works based on interactive computer systems (Shafinah et al., 2010). The evolution of DSSs can be divided into four generations: the first generation focused on data; the second generation focused on improving the user interface; the third generation focused on models, and the fourth generation introduced new analytical web-based applications (Arnott & Pervan, 2014). DSSs have been developed to support multidisciplinary domains including database research (Asghar et al., 2005), artificial intelligence (Tolone et al., 2009), human-computer interaction (Rickenberg et al., 2013), simulation methods (Zhang et al., 2014) and software engineering (Zlatev et al., 2013).

The concept of DSSs was first introduced by Morton (1971) in his book "Management Decision Systems." He presents DSS as an intelligent, human-computer interactive system. These systems are based on management science, operational research and behavioural science which can be applied using computer science, simulation, and information technology to assist the decision-making of both unstructured and semi-structured decision problems. In this way, DSSs are different from Management Information Systems (MIS), which primarily focus only on structured decisions. Sprague and Carlson (1982) also hold the same understanding of DSSs as systems that can help decision-makers solve semi-structured or unstructured problems using data and models. Sprague and Carlson (1982, p. 9) defined a DSS as “a class of information system that draws on transaction processing systems and interacts with the other parts of the overall information system to support the decision-making activities of managers and other knowledge workers in organisations”. Mittra (1986) suggests that DSSs are systems using databases and mathematical models to help users generate the information they need and assist with decision-making. Keen (1987) asserts that DSSs are the combination of “decision”, “support” and “systems”, which means that computer technology can be used to develop the systems that can support to achieve a better decision. Power (2002, p. 1) defined DSSs as “interactive computer-based systems that help people use computer communications, data, documents, knowledge, and models to solve problems and make decisions. DSSs are ancillary or auxiliary systems; they are not intended to replace skilled decision-makers”.

As evident from the various definitions discussed above, there is still no generally accepted definition of a DSS and various technologies can help to achieve the goal of decision support and can be used to construct a DSS. The structure for different types of DSSs may differ significantly due to the varying situations of their usage, their purposes, and the technologies to build the system. However, one thing that is common to all DSSs is that they all should be able to provide decision-making support to their end-users.

DSSs have experienced progressive development over the past few decades because of academic research and industry development (Arnott & Pervan, 2018; Klashner & Sabet, 2007). Due to the easier access to computers with progressive efficiency in the data processing tools, the DSSs have become more popular for the benefits of relevant industries. Furthermore, software technology is continuously evolving over the past couple of decades that has also produced more knowledge and learning platforms for software developers to design and develop state of the art systems (Filip, 2008; Neville et al., 2018; Vitoriano et al., 2015).

2.6 DSS for supporting emergency management

In complex emergencies, making an intelligent decision is one of the major challenges. A DSS for emergency management is considered a system that is designed to handle disaster situations considering a range of emergency management plans and decisions (De Maio et al., 2011). DSSs supporting emergencies provide additional decision-making prompts and guidance to decision-makers and help to better manage complex and stressful situations (Ariav & Ginzberg, 1985; Zakaria et al., 2015). Table 2-1 summarizes some of the crucial emergency management activities and related specific decision-making needs that are learnt through the existing literature.

Table 2-1. Decision-making needs relevant for different emergency management activities

Activities	**Decision-making needs**
Hazard assessment	Analysis of vulnerabilities in the modelled system and the identification of frequency of hazard occurrences (Zio, 2016)
Risk management	Analysis, evaluation and treatment of the risks associated with the disasters (Kim & Kang, 2013)
Mitigation	Development of a mitigation plan and analysis of required measures (Tang & Zhao, 2012)
Preparedness	Based on the empirical data, more advanced planning and resource management (Rutledge et al., 2007)
Response	Analysis, evaluation and up-gradation of the available emergency response plans (Thompson et al., 2006)
Recovery	Damage assessments, management of resources, recovery plans and re-settlement issues (Neville et al., 2016)

Over the past two decades, many DSSs have been developed based on specific needs, and requirements in the field of emergency and disaster management (Newman et al., 2017). These systems support the various decision-making needs as listed in Table 2-1. Some of the most popular and relevant DSSs to this study include, for example:

- HAZUS-MH, which was developed by the United States Federal Emergency Management Agency (FEMA) for the mitigation and estimation of loss to buildings, critical facilities, CI networks and effects on population due to a range of different types of hazards, such as earthquakes, hurricanes and floods (FEMA, 2003; Jain & McLean, 2003).

- EPEDAT (Early Post-Earthquake Damage Assessment Tool), which is a decision support tool designed by EQE International, Inc. to support decision-making for post-earthquake loss estimation (Eguchi et al., 1997). The output of this system encompasses building and infrastructure damage information based on country-specific housing and demographic data.
- KOERILOSS, which is a scenario-based building loss and casualty estimation tool that makes use of deterministic and probabilistic forecasting methodologies. Similar to HAZUS, this tool estimates fragility calculations based on empirical findings (Erdik & Fahjan, 2006).
- EQSIM (EarthQuake damage SIMulation), which is the rapid earthquake damage estimation component based on the adaptation capacity spectrum method used in HAZUS (Markus et al., 2004).
- RiskScape, which is a software tool developed by GNS Science (GNS Science, n.d.) and NIWA (National Institute of Water and Atmospheric Research) (NIWA, n.d.) from Aotearoa New Zealand, for the quantification of direct and indirect losses due to different types of hazards (Bell et al., 2007; Schmidt et al., 2011).
- MERIT (Measuring the Economics of Resilient Infrastructure Tool), which is developed by the ERI (Economics of Resilient Infrastructure) research programme, funded by the Aotearoa New Zealand Government. MERIT can quantify the economic impacts of CI failure and examine post-disaster recovery options for infrastructure reinstatement projects (Daly et al., 2015).

The DSSs mentioned above can be applied to various domains of emergency management and use different techniques and technologies such as artificial intelligence, network models and simulation strategies to achieve their desired goals (Ariav & Ginzberg, 1985; Choraś et al., 2010;

Wang, 2013). However, it is evident these systems have significant limitations as decision support tools for emergency management:

- Firstly, the most crucial issue with some of these DSSs is a heavy reliance on Geographical Information System (GIS) data which often overloads decision-makers with so much information that decision-making effectiveness is reduced (Aleskerov et al., 2005);
- Secondly, some of the DSSs are highly complex, require a high level of expertise, and need well-trained personnel at all levels of management to provide precise and reliable information (Zografos et al., 2000);
- Thirdly, some of the DSSs rely more on observational methods which are feasible in some situations but not recommended because those systems require a very high level of engagement and interpretation from the decision-makers (De Maio et al., 2011);
- Fourthly, some DSSs are dependent on human inference methods to extract useful information about the behaviour and interdependencies of a CI, which is impractical because this information can be huge and the analysis can take years to complete (Hormdee et al., 2007); and
- Finally, some DSSs are designed for macro-level estimation, and any modifications related to analysis have to be made to the configuration to meet the differing organisational requirements (Tinguaro Rodríguez et al., 2010).

A properly designed DSS can compile useful information from the personal knowledge of the experts, planning documents, business models and all the other raw data to solve the problems (Rolland et al., 2010; Vivacqua et al., 2016). To develop a DSS that is capable of effectively extract and organise information from a huge amount of data, the researchers need to go through the key steps of selection, design and implementation of efficient computational techniques and tools capable of dealing with the unstructured nature of the user-generated contents (Ariav & Ginzberg, 1985).

2.7 Types of decision support systems

Bonczek et al. (1980) classified DSSs according to their capabilities to handle different types and amounts of data handling and ability to process simpler or complex levels of modelling. Keen (1987) classified DSSs according to their capability to provide personal level, group level or organizational level support. The classification of different types of DSSs by Power (2002) is the most comprehensive and up to date, and categorises the DSSs into five groups:

- **a) Model-driven DSSs** support complex analysis and the capability to choose between different options through simulation or optimization models. Some earlier DSSs that deal with the accounting, financial, representational and optimization problems have been model-driven. Model-driven DSSs do not consider data collection methods as they primarily aid the decision-making in those situations where the empirical and structural data is already available;
- **b) Data-driven DSSs** are developed to overcome the issues related to model-driven DSSs. They can do real-time manipulation of large amounts of structured data. They utilize query-processing tasks to find solutions for the specific needs of the users. Some examples of data-driven DSSs include data warehousing, EIS and Online Analytical Processing (OLAP);
- **c) Communication-driven DSSs** use network and communications technologies integrated with the associated decision-making models in a hybrid manner to facilitate decisions relevant to information sharing, face-to-face meetings and other forms of communication and collaboration between decision-makers separated by a geographical distance. These types of DSSs intend to support group decision-making, which generally includes user forums, whiteboard communication, message boards and audio/video conferencing by facilitating problem inference and information sharing. Communication-driven DSSs are developed by using advanced communication and computer science technologies;
- **d) Document-driven DSSs** (also known as text-oriented DSSs) are used to manipulate unstructured documents available in various formats, such as written reports, memos,

emails and newspaper clips. Due to the manipulation of a large amount of unstructured data, these DSSs utilize a lot of computer storage and need efficient processing power; and

e) **Knowledge-driven DSSs (**also known as knowledge-based DSSs or knowledge-centred DSSs) are systems that provide specialized problem-solving expertise from stored facts, rules and procedures that can be stored in a knowledge-base. They mainly provide guidelines to their users about various suggestions and recommendations of actions through a combination of a set of rules or cases and a knowledge-base.

For developing a DSS to model CI interdependencies, it is important to consider the needs and preferences of the decision-makers. As the damage to the CI networks directly or indirectly affects the population, therefore, it is equally important to develop a DSS that can self-learn, identify associations between various types of CI network data, and perform heuristic operations, when needed. Therefore, a knowledge-driven or Knowledge-centred Decision Support System (KCDSS) for modelling CI interdependencies can be a very useful tool, as it can provide specialized problem-solving expertise stored in a structural form of data that would enhance the decision-making capabilities of its end-users (Ahmed et al., 2010; Shaofeng Liu & Zaraté, 2014). A properly designed KCDSS needs to involve well-structured knowledge elicitation and knowledge modelling techniques. Knowledge elicitation in the context of this study is a process to collect and analyse how the CI network providers make decisions in critical situations. This knowledge can be collected through various methods, some of which can be interviews, questionnaires, focus group workshops and naturalistic observations. Furthermore, other available documents, drafts and personal notes specific to past experiences can also be useful (Duah et al., 2014; Lovrencic & Klicek, 2004). After elicitation of useful knowledge, the KCDSS needs the knowledge to be modelled properly so that it can be used for improved decision-making. Two of the most popular approaches for knowledge modelling are Case-Based Reasoning (CBR) and Rule-Based Reasoning (RBR). To structure knowledge elicitation and knowledge modelling activities, a well-defined knowledge elicitation method needs to be developed throughout the design and development process of the KCDSS (Gavrilova & Andreeva, 2012).

2.8 Chapter Summary

This literature review presented an overview of various DSSs, modelling and simulation methods for CI, existing software and systems and modelling techniques for understanding CI interdependencies. A primary outcome of the literature review has been the identification of gaps in existing knowledge concerning the interdependency analysis of multiple CIs. The appropriateness and value of modelling and assessment methods were assessed against CI network providers' needs and some important research and development (R&D) limitations were identified. These limitations include the unavailability of relevant data and the difficulty accessing a large amount of data for the modelling approaches. Another limitation is the lack of an integrated approach to model CIs and to analyse the impacts of disruptions while considering the wide range of stakeholder objectives. These gaps, as identified in the literature, provided a direction for future research to develop more meaningful and practical DSS using modelling and simulation approaches to minimise the impacts of natural hazards on CI network failures.

3 RESEARCH METHODOLOGY

3.1 Introduction

The previous two chapters introduced the research problem, explained the need and the motivation of conducting the proposed research and identified the knowledge gaps after having conducted a comprehensive literature review. The knowledge of the research gaps led to research questions and objectives. The methodological elements of this study are explained through the use of the *research onion,* a research methodology introduced by Saunders et al. (2015) to conduct scientific research.

3.2 Research onion methodology

The research onion consists of several layers where each layer represents a key step for conducting a research project, as shown in Figure 3-1. A researcher peels off one layer of the research onion at a time to explain more detailed activities necessary to drive the research process.

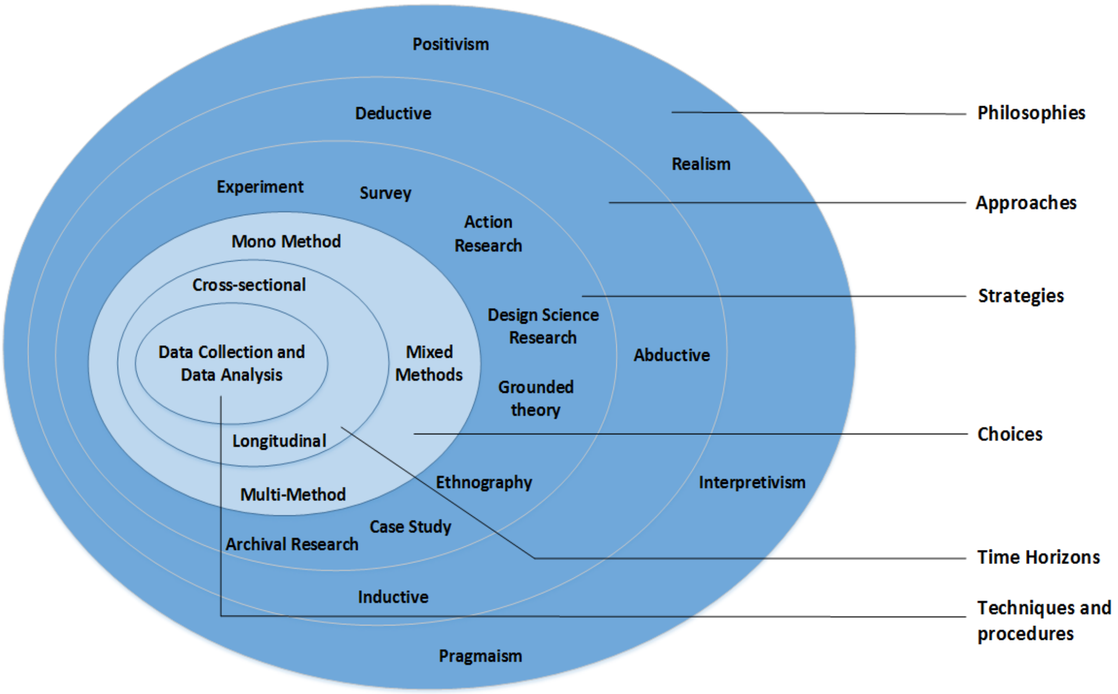

Figure 3-1. Research onion (Source: Saunders et al., 2015)

The research onion stipulates that research should begin with an understanding of research philosophy, which is the outermost layer. The second layer describes the research approach followed by the third layer that represents the research strategy, which defines how the research fits with the subsequent three innermost layers of the onion. Thus, drawing from the different layers of the research onion, the following sections argue for and elaborate on, the detailed research process used in this study.

3.2.1 Research philosophy

The research philosophy (that is the outermost layer in a research process), is concerned with knowledge creation and provides the ideological basis for a methodology (Sahu, 2013a). Typically, it consists of ontology and epistemology. Ontology refers to the nature of reality, while epistemology refers to the theory of knowledge (Masucci et al., 2009). When it comes to conducting IS-related research, there are two main philosophical views, namely: Positivism and Interpretivism (Creswell, 2014).

Positivism has its roots in natural sciences and is related to the discovery of generalizable laws (Ives et al., 1980). Positivists hold a deterministic philosophy in which it is believed that causes usually determine effects or outcomes. Therefore, researchers who adopt this philosophy tend to quantify measurements through experiments, simulations or surveys (Creswell, 2014). A researcher starts with a theory, collects data that ultimately supports or opposes the theory, and then makes necessary revisions to the theory, through additional tests and experiments. Interpretivism is subjective, as opposed to positivism that believes in the objective nature of reality (Sahu, 2013a). Instead of starting with a theory like positivists, interpretivists seek to understand the world in which they live and work. The researchers use this philosophy to interpret the situation through subjective meanings of their experiences with the involvement of human participants (Saunders et al., 2015). Both positivism and interpretivism have different and contradictory beliefs and views and most of the time researchers aligned their methodology with one or the other. Yet in some situations, researchers blend concepts from both philosophies, for instance, when complex research draws on objective and subjective research practices. In such situations, an alternative research philosophy such as pragmatism can be used (Creswell, 2014).

Pragmatism argues that science aims to facilitate human problem-solving, therefore the research problems and questions are the most important determinant of a research strategy (Yin, 2014). While each research philosophy has strengths and weaknesses, pragmatism recognises that researchers need to draw on a philosophy that is best suited to successfully reach the objectives of that particular research. In this way, as argued by Creswell (2014), pragmatism focuses on whatever works for finding solutions to problems. On many occasions, researchers have adopted a combination of research methods that include elements of more than one research philosophy for various parts of their project to improve the quality of research and to better fulfil the research objectives (Gonzalez & Dahanayake, 2007; Tolk et al., 2013).

As defined in Chapter 1, this study aims to develop a KCDSS that is driven by an impact assessment framework capable of modelling interdependencies between different CI networks. To achieve this aim and to answer the research questions, it can be argued that this study needed to adopt multiple philosophies and methods to interpret CIs, as no single perspective is sufficient for covering the scope of the research problem and for successfully reaching the objectives. The impact assessment framework aiming to understand CI interdependencies needed a positivist approach. But the later parts of this study required the exploration of the usefulness of simulation results in supporting the decision-making process of emergency management stakeholders, including CI network managers, asset managers, risk and assurance managers. This required gathering and understanding stakeholders' decision-making processes needed an interpretivist approach.

Having considered the nature of the research problem and identifying the research questions, aims and objectives, this study combines the strengths of both objective (positivist) and subjective (interpretivist) philosophical views. Hence, it is argued that pragmatism is the best-suited research philosophy for this study.

3.2.2 Research approach

After having decided the appropriate philosophy, the second layer of the research onion guides the researcher to decide the most appropriate overarching approach for the research. According to Saunders et al. (2015), there are two main approaches to research; deductive and inductive. A deductive approach starts with forming certain hypothesis and theories that are then tested using the selected research strategy (explained in Section 3.2.3), whereas, an inductive approach develops theories based on the result of the data analysis.

Most research studies choose either a deductive or inductive approach (Creswell, 2014). Studies that are well supported by literature and demonstrate theoretical approaches using hypotheses, draw on a deductive approach (Saunders et al., 2015). On the other hand, the inductive approach is more suitable to situations where the topic is relatively new and has less literature. With an inductive approach, researchers start by generating and analysing data to interpret theoretical themes that emerge from the available data (Peters, 2017). However, in some instances, instead of selecting either of these two, an abductive approach is used which combines features from both approaches (Creswell, 2014).

In this study, there is no intention to test theories, propositions, or hypotheses. The first two objectives of this study require a review of existing literature and analysis of relevant documents to understand the overall structure and functionality of CI. Apart from the literature review, the major outcomes of the first two objectives are achieved by collecting data through existing hazard modelling tools combined with expert elicitation with CI network providers to develop the desired impact assessment framework. The third objective aimed to utilize the developed framework with the recovery strategies in the form of a knowledge-base for the implementation of the KCDSS, whereas, the final objective evaluates the KCDSS from a functionality perspective and feedback from stakeholders. After careful consideration of the research objectives, a balanced abductive approach was adopted in this study to start with an observation that seeks to find the simplest and most likely explanation.

3.2.3 Research strategy

As defined by Saunders et al. (2015), the research strategy is the research onion's next layer. It is driven by the research questions, objectives, existing knowledge in the field, resources, approaches, and the researcher's philosophical underpinning. According to Saunders et al. (2015), there are seven research strategies, namely experiment, survey, grounded theory, ethnography, archival studies, case study and action research. Considering the objectives of this study, the researcher has evaluated the suitability of these existing strategies. However, while the research objectives of this study are positioned primarily in the domain of IS with a blend of software engineering, operation science, information sciences and social sciences, it can be argued that none of these available strategies fit the objectives of this study.

As an alternative, a research strategy used in the IS literature called Design Science Research (DSR) more appropriately supports interdisciplinary research that spans across technology and social domains (Hevner et al., 2004). DSR resembles Action Research (AR) as it identifies real-world problems along with actions that might improve them, while stakeholders can participate actively in the research process (Järvinen, 2007). However, DSR is different from AR because in AR the stakeholders often initiate the research and the researchers then facilitate the research process. However, with DSR, researchers primarily aim to solve complex problems by taking the initiative in the research process as both a researcher and observer working closely with the stakeholders (Arnott & Pervan, 2018; Iivari, 2007). Therefore, it can be argued that DSR is a more suitable alternative strategy to conduct this study.

DSR has origins in engineering, computer science and management science, and employs a variety of methods and techniques. DSR states and predicts observable phenomena within a field of research and studies the change in the state of the world that corresponds to the introduction of an artificial construct ('artefact'), which can be further described as an artificial object made by humans to solve practical problems (Peffers et al., 2007). Artefacts are physical entities, drawings, a set of guidelines or an Information and Communication Technology (ICT) solution. The production of artefacts is the foundation and key attribute of the DSR methodology. Peffers et al.

(2007, p. 6) defined an artefact as "any designed object with an embedded solution to an understood research problem”.

Artefact design in this study looks at how the CI components can be identified, how they behave or interact with each other, how their interaction affects their performance and how a customizable KCDSS can be useful for the recovery of these CI components due to person-generated or natural hazard-based disasters. These aspects are highly design-oriented, and consequently, the DSR paradigm has been utilized in this study. The design method described by Hevner et al. (2004), as well as the concepts discussed by Iivari (2007), provide comprehensive guidance for the artefact design process. Supported by the DSR, two artefacts are designed and developed in this study:

- The **first artefact** for this study is the conceptual framework for the integrated impact assessment of CI networks. This framework includes CI component representation, CI damage representation, CI network functionality assessment and CI interdependency assessment modules.
- The **second artefact** is the development of a KCDSS. The first artefact has been integrated with the knowledge-base of repair, recovery and related decision-making strategies to implement the KCDSS.

In a DSR based development of the DSS, the artefact design is essential. Recent literature has identified that artefact design can significantly improve the quality of the DSS development process and enhanced decision-making support through better engagement with the experts of relevant industries (see, for example, Ahmed & Sundaram, 2011; Knutas et al., 2017; John Venable et al., 2016). Hevner et al. (2004) argue that it is necessary for all IS research resulting in the production of artefacts to be both rigorous and relevant, which is illustrated using three overlapping research cycles in Figure 3-2.

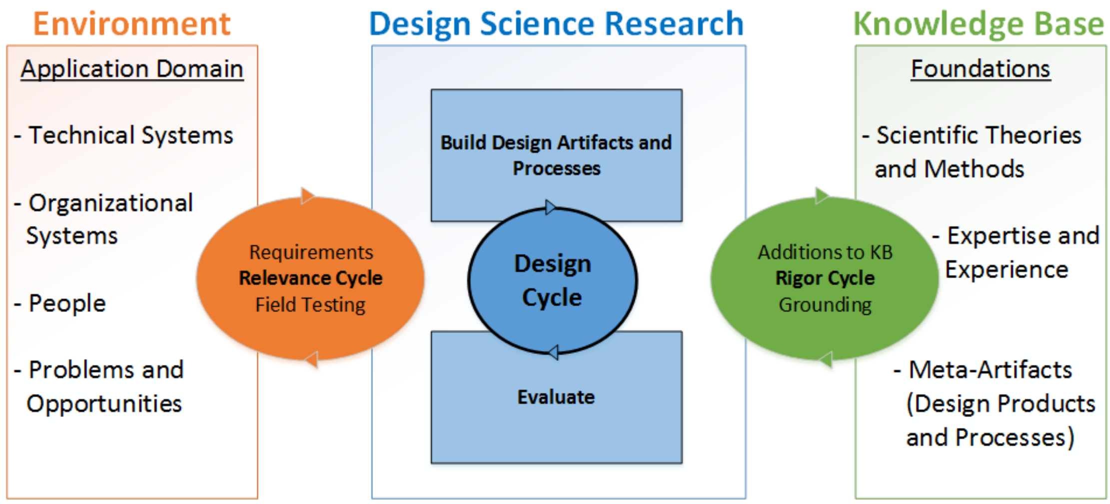

Figure 3-2. Design Science Research Cycles (Source: Hevner, 2007)

The Relevance Cycle connects the relative environment of a research project's application domain with DSR activities. The Rigor Cycle connects DSR activities with the knowledge-base in existing scientific foundations, researchers' experiences, and expertise within the same field as the research project. In the middle of a DSR, the Design Cycle builds artefacts, which are later evaluated through interaction with relevant organisational and technical systems. These three cycles must be present in any project following the DSR strategy, and its research problem and objectives should be mapped onto the three cycles (Hevner, 2007). This study, therefore, seeks to address the research objectives by the development of two novel and interrelated artefacts through a rigorous research process. The following subsections briefly explain the definition of each cycle.

a) The relevance cycle

DSR intends to improve the research environment within the relevance cycle by introducing the processes for creating new and innovative artefacts (Pries-Heje et al., 2008). An application domain of the relevance cycle consists of the people, organisational systems, problems and opportunities, and technical systems that interact with each other to achieve a goal (Hevner, 2007).

Thus, the relevance cycle initiates DSR by providing a context for the research project. This context is useful to identify the opportunities and related problems as input for the research. After successful execution of the projects, the relevance cycle also provides a mechanism to define various acceptance criteria for evaluation of the results. To be a part of the DSR process, the evaluated research outputs also need field testing, after which they become part of the environment for providing opportunities for future research (Hevner, 2007). The new artefact may have issues related to performance and usability that may limit its utilisation in practice. As such, it may need another iteration of the relevance cycle that starts with feedback from the environment as a result of field testing and may also require the reconsideration of research requirements (Arnott & Pervan, 2012).

Throughout any project, linkages between the designed artefacts and the organisations and especially with the people should delineate the needs and requirements of decision-makers (Prasanna & Huggins, 2016; Thompson et al., 2006). In the context of this study, emergency management is the application domain and the two artefacts needed to be designed and evaluated according to the field requirements as specified by the CI network providers. Information was gathered from various stakeholders through expert elicitation, which guided the researcher to understand the region-specific problems and opportunities.

b) The rigor cycle

To provide a foundation for a rigorous DSR, the DSS needs to have a comprehensive knowledge-base of existing scientific theories and computational strategies (Hevner, 2007). The knowledge-base in a DSR study includes two additional types of knowledge that are relevant to the environment or application domain of the research:

1. The experiences and expertise of different researchers; and
2. The existing artefacts and research processes.

To ensure methodological rigor in this study, foundational information about appropriate theories for CI component representation, CI damage representation, CI network functionality assessment and CI interdependency assessment modules was gathered from academic literature. The resultant conceptual framework is used to develop the KCDSS. The researcher has thoroughly studied the requirements for developing a knowledge-base to make sure that the produced designs will contribute to the application domain of this study instead of just routine designs based upon the application of already known processes. A detailed literature review has revealed several key research gaps and helped the researcher to identify the purpose and need of conducting this study.

c) The design cycle

The central design cycle is the heart of any DSR project (Hevner, 2007). This cycle iterates between research activities related to the artefact design, evaluation and subsequent feedback to refine the design further. Simon (1996) asserts that the entire process within design-based research deals with generating various alternatives with corresponding evaluation against predefined requirements to finalise a satisfactory design. As discussed in the previous two cycles, the relevance cycle is required to gather information requirements while the rigor cycle helps in defining the design and evaluation of theories. The design cycle is heavily dependent on the other two cycles for collecting relevant information and designing an artefact according to the needs of the environment. However, the design cycle still has a significant amount of independence during the actual execution of the research (Hevner, 2007).

This core cycle of DSR starts with awareness of the problem to inform the design of research artefacts. This study used various research instruments to engage with relevant regional emergency management organisations and stakeholders. This process was helpful to gain an in-depth understanding of the current state of the art of the CI interdependencies in the context of Aotearoa New Zealand that revealed actual problems and identification of research gaps in the field. The two artefacts of this study were then designed, developed, and evaluated by representatives from various fields of emergency management to fulfil the relevance and rigor requirements.

The first artefact has been evaluated throughout its design process so that it can accurately establish the connectivity between CI components and become ready to be integrated into the second artefact. The development of the KCDSS artefact has been evaluated using different interview sessions from a list of related stakeholders. The evaluation process utilized the FURPS model (FURPS stands for evaluating the functionality, usability, reliability, performance, and supportability attributes), which is discussed in detail in Chapter 6. After having specified the entire research process driven by the principles of DSR, a research framework is developed to accomplish the research objectives. Figure 3-3 illustrates a clear picture of the proposed research framework and how the objectives of the research are mapped onto the three DSR cycles.

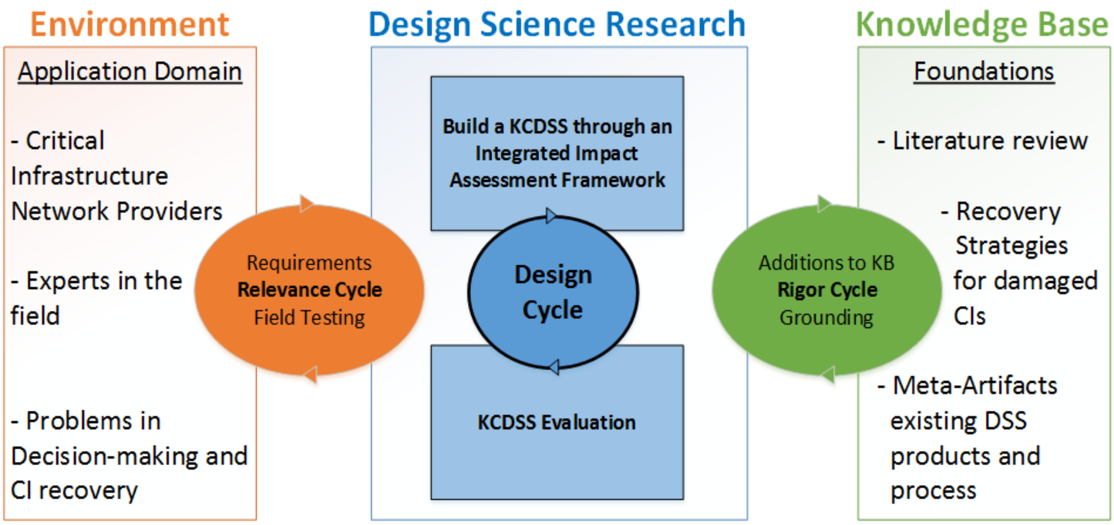

Figure 3-3. Graphical illustration of the proposed research framework driven by the DSR three cycle view

3.2.4 Choice of research

As mentioned by Saunders et al. (2015), the innermost three layers of the research onion are defined by the selected research strategy. In this way, the choice of research that is also the methodological design of this study describes the methods that support the principles and functionality of the DSR. According to Creswell (2014), researchers have a choice of three available methods. They can use a mono method data collection technique that is either qualitative, for example, with interviews, or quantitative, for example, with graphs or statistics. The analysis is then followed with a mono method qualitatively through narratives or quantitatively through statistical analysis. Alternatively, researchers can use a multiple methods approach. In qualitative multi-method designs, more than one qualitative data collection technique is associated with analysis procedures. Similarly, in quantitative multi-method designs, a researcher can use more than one quantitative data collection technique along with associated statistical analysis procedures.

In many cases, researchers can also use a choice of mixed methods (Creswell, 2014). A mixed-methods design combines both qualitative and quantitative data collection techniques and corresponding analysis procedures by using any of the two available options: a mixed-method simple design that starts with qualitative data collection and analysis and subsequently a quantitative data collection and analysis to gain more information; and a mixed-method complex design by choosing quantitative analysis techniques to analyse qualitative data or vice versa (Saunders et al., 2015).

In support of the selected pragmatic research philosophy, this study has used a combination of qualitative and quantitative research methods to obtain an in-depth insight into the topological configuration of the CI network components and the elicitation of recovery strategies for the damaged components. The benefit of using qualitative research methods is to obtain an in-depth understanding of the experts' behaviour and decision-making strategies (Jonker & Pennink, 2009). These approaches include participant observation, interviews, focus groups and case studies (Bogdan & Biklen, 2007; Elliott & Timulak, 2005). The research material needs to be systematically collected and interpreted. Proponents of a scientific approach argue against a qualitative method because of the concern that subjective qualitative material cannot be validated and that with smaller sample sizes, a realistic representation cannot be achieved (Bogdan & Biklen, 2007; Gentles et al., 2015). However, qualitative approaches do not claim the same measures of validity, nor do they assume to be able to represent larger populations like quantitative methods (Jonker & Pennink, 2009).

Quantitative research focuses on systematic measurement techniques by the collection of numerical data, which is then analysed through statistics and mathematical modelling techniques (Creswell, 2014; Nan & Sansavini, 2017). The advantage of doing quantitative research is that it handles large sample data that can be validated and verified to generate precise numerical results (Jonker & Pennink, 2009). The problem with adopting this mode of research is that the researchers cannot personally interpret the meaning and behaviour of certain phenomena. The rationale for choosing the mixed-method approach is based on the diversity of the data and information needed for this study, including:

a) Quantitative data collection needs for CI networks and their corresponding components from the CI network providers.

b) Qualitative data collection needs through interviews with representatives from the selected CI network providers for the elicitation of repair and recovery strategies.

c) Quantitative data collection needs for evaluation of the KCDSS from a list of experts and potential end-users.

3.2.5 Time horizon

Saunders et al. (2015) classify any research as cross-sectional or longitudinal based on its time dimensions. Cross-sectional research is conducted at a specific point in time while longitudinal research is carried out at an extended period to track changes in time. Although the simulation results predict the restoration of a region in various timestamps, the observed data for CI network components and their damage are collected from a single hazard event. Therefore, this study can be classified as a cross-sectional study.

3.2.6 Techniques and procedures

At this point, after peeling away all the external layers of the research onion, the innermost layer of the research onion is revealed. This layer is significant because it specifies the techniques to accomplish the goals being set through the outer layers. The research techniques involve data collection and analysis procedures.

3.2.6.1 Data collection

As discussed in the section 3.2.4, this study needed both qualitative and quantitative data collection techniques because of its specific needs, requirements and different research objectives. The research philosophy, research approach, research strategy, and objectives of research usually dictate the appropriate research method to use (Yin, 2014). One of the main advantages of using DSR as a research strategy is the opportunity to employ various data collection techniques. The data collection in this study is done in three phases:

1. **Data collection - Phase I:** This data collection phase was an essential prerequisite of this study as its objective was to provide characteristics of CI network components. However, the huge amount and variation in the formats of different types of CI components presented a considerable obstacle and involved complex data collection and management. The topological data for electricity and road networks was acquired in Geographical Information System (GIS) format through several channels that influenced the quality of the study sample and required various data pre-processing and management procedures. Damage data was collected using a risk analysis tool, namely *RiskScape*, which is used to model damage to the network components for a chosen hazard. Topological and damage data for potable water network was not properly organized and available for this study. As the component structure of the potable water network looks similar to the electricity network, therefore, the researcher designed and used placeholder data for the potable water. Once the real network data will be available, it can replace the placeholder values. Chapter 4 elaborates this process in detail through the design of an integrated impact assessment framework.
2. **Data collection - Phase II:** The second phase of data collection was needed to understand the decision-making approaches adopted by regional CI network providers for recovery of damaged CI network components. This data was used for the development of the knowledge-base component of the KCDSS. Data collection in this phase was qualitative as it helped the researcher to understand different recovery strategies adopted by the experts according to the variability of hazard scenarios and their corresponding damage to the CI networks. For this purpose, Critical Decision Method (CDM), was utilized, which is a Cognitive Task Analysis (CTA) method for requirement elicitation. A comprehensive discussion about this phase is provided in Chapter 5.
3. **Data collection - Phase III:** During the evaluation phase of this study, quantitative data was collected through questionnaires and interviews about functionality, usability,

reliability, performance, and supportability features of the KCDSS. The KCDSS prototype was demonstrated to a range of different experts from the relevant fields of emergency management to get their feedback for further improvements. A comprehensive discussion about this phase is provided in Chapter 6.

a) Source of data

Due to a variety of different data collection needs, each phase of this study needed a different data collection and analysis method. The detailed discussion about research methods and techniques for data collection and analysis are presented in Chapters 4, 5 and 6. However, a brief discussion about the methods utilized in this study is presented below:

1. Interview method

Interviewing is a data collection method that provides support for the identification of innovative concepts, or a better description of the existing knowledge that is otherwise not easy to understand. Interviewing process generally involves an *interviewer* who asks questions from the *respondent* in a face-to-face manner or through telephonic or internet-based audio/video communication (Hickey & Davis, 2003). Interviews enable the exploration of important parameters of research. Due to the interactive and collaborative nature of this study, all the interviews were done face-to-face (Saunders et al., 2015).

In this study, a semi-structured interview approach was adopted that contained open-ended questions for the interviewees to allow them to share their experiences without any interruption from the researcher. The semi-structured interview approach provided a balance between unstructured and structured interview approaches that allowed the researchers to collect rich, experiential data about the problem space (Hoffman et al., 1998; Saunders et al., 2015). This approach provided the researcher with a better understanding of the topological structure of the CI network components and the strategies to recover the damaged components of different CI networks. Furthermore, the face-to-face interviewing made it easier for the researcher to keep the process in line with the changing nature of this study. Data collection and analysis were time-consuming because the interviewed experts were in senior positions within their organizations, so it was not easy to find the time or collect the relevant information in a single sitting. Interviewing to understanding the CI network recovery methods was still considered the most appropriate data collection method for this study compared to other methods like surveys or questionnaires because the responses from experts prompted more questions to further clarify recovery processes and the researcher acquired more comprehensive results (see Chapter 5 for more details).

2. Questionnaire method

Although most qualitative studies prefer to use interviews for the collection of data, researchers can also use other data collection methods as primary sources or in partnership with other methods (Creswell, 2014). In terms of quantitative data, a comprehensive statistical analysis is usually needed on the numerical data to provide quantitative information. Quantitative research requires data consisting of numbers to be objectively evaluated, while bias is excluded as much as possible. Typically, the quantitative method makes use of a questionnaire. Questionnaires can be used to get data from a wider audience compared to interviews, but they are not able to be customized to individual experiences or generate misinterpretation.

During the evaluation phase of this study (see Chapter 6), the researcher used questionnaires with the interviews to ensure in-depth knowledge was gained about the experts' perceptions for the final prototype of the KCDSS. The combination of interviews and questionnaires enabled the researcher to guide the evaluators if they were uncertain about any questions. Moreover, the results were gathered at the same time as the interviews which saved time and effort with posting the responses.

b) Sampling strategy

The choice of qualitative or quantitative approaches of data collection and analysis also guides the appropriate sampling strategy to be used in the study (Coyne, 1997). For example, sampling techniques such as random sampling are hardly utilized for collecting data in qualitative research, because the purpose of those studies is not to calculate probabilities from a sample of the population (Gentles et al., 2015). Thus, the major goal of the qualitative data for this study was to provide a clearer understanding from the perspective of experts, instead of generalizing them across a population (Bogdan & Biklen, 2007; Marshall & Rossman, 2015).

In this study, the researcher utilized a combination of purposeful sampling strategies. Purposeful sampling produces idiographic knowledge (that is the knowledge about specific situations) (Patton, 2014). As the knowledge elicitation part of the study was specifically related to the types of decisions made by experts when initiating a region-specific recovery process for damaged CI network components, it is logical to draw on purposeful sampling. There is a range of sampling sub-types within the purposeful sampling class, as identified by Patton (2014). However, after a careful evaluation of these, the following two sampling strategies were chosen that are most suitable for this study:

1. ***Criterion sampling***

Criterion sampling requires that before the data collection process starts, researchers need to set criteria as the basis for choosing their participants in a study (Sahu, 2013b). Therefore, in this study, the participants were carefully selected based on their ranks, positions and relevance to the study to make sure that their expertise was verified and not based on assumptions. All the selected participants had prior experiences in managing and making critical decisions on recovery of damaged CI network components and had experience in risk and assurance or asset management tasks.

2. ***Snowball or chain sampling***

Snowball sampling is a non-probabilistic sampling technique that researchers utilize to identify potential participants (Bogdan & Biklen, 2007). This technique is more suitable for studies that have difficulty in identifying participants with the characteristics of interest. By using a snowballing strategy, researchers can identify potential participants from someone who knows someone, and the chain goes on until data saturation has been reached (Gentles et al., 2015). This sampling technique was effective for identifying participants, especially for the evaluation of KCDSS, when it was difficult for the researcher to identify and create a representative sample of the relevant participants to this study.

c) Sample size

For a study involving qualitative data collection techniques, it is a challenge to decide on suitable sample size (Sahu, 2013b). The second phase of qualitative data collection in this study was done through face-to-face semi-structured interviews with representatives from CI network providers for the elicitation of repair and recovery strategies. Due to the nature of the qualitative study, the researchers did not pre-define a sample size. The experts' data, therefore, continued until the required level of expertise was elicited and the researcher considered that data saturation had been reached. Klein et al. (1989) believe that three to four experts are enough for the research utilizing purposeful sampling techniques to target only the relevant participants who have been involved in decision-making roles. The sample size for the qualitative data collection part of this study was set to target at least two experts at the managerial level from each of the CI network providers to understand their decision-making process for recovery of damaged CI network components. For the evaluation phase, the study aimed at fifteen to twenty evaluators to gather broad feedback from a variety of experts about the KCDSS prototype. The knowledge-base development through elicitation of recovery strategies from the selected CI network providers is discussed in Chapter 5 and the feedback of different experts after evaluation of the KCDSS prototype is discussed in Chapter 6.

d) Ethical considerations

Important considerations while producing ethical research are to avoid any potential harm to both participants and researcher. Massey University Online Human Ethics Application has been completed, and this study has been deemed to be of low risk (see Appendix A). This study involved semi-structured interviews with emergency management stakeholders to understand their recovery process for damaged CI networks. In this situation, there is no significant chance of causing any discomfort to the participants, hence only low-risk ethics approval was needed.

3.2.6.2 Data analysis

Data analysis procedures are used to categorise, examine, tabulate, test or sometimes recombine both quantitative and qualitative collections of data to address the initial propositions of a study (Yin, 2014). Before the analysis, data collected from sources that have non-written evidence like interviews and questionnaires need to be transcribed into written accounts. As explained in the research strategy, this study progressed from the collection of topological data for the CI network components including their characteristics, locations, and connectivity. Based on the characteristics of topological data, this study used semi-structured interviews through critical decision method by Klein et al. (1989) to understand the recovery strategies of CI network providers for the damaged CI network components. These strategies were then analysed and transferred into the knowledge-base component of the KCDSS. The topological data of CI networks and knowledge-base of the recovery strategies are the core part of the KCDSS to model CI interdependencies and to generate the desired results. The third and final stage of data analysis was completed during the evaluation phase of this study. The feedback from the experts was analysed using the FURPS model to garner useful information about the limitations and prospects of the KCDSS. These processes of data analysis are described in Chapters 4, 5 and 6 along with their corresponding data analysis techniques.

3.3 Chapter Summary

This chapter outlined the development of the research design and presented the methods used to conduct this study. The chapter first presented the direction of research as identified by the literature review and formulation of the research questions by following the research onion methodology of Saunders et al. (2015). Within this process, a few potential research methods to answer the research questions were discussed to outline how the researcher found the most suitable research strategy for this study. As a result, a DSR paradigm was deemed most appropriate. The next chapter explains the design of the conceptual artefact of this study through the development of an integrated impact assessment framework to model CI interdependencies.

4 ARTEFACT - I: FRAMEWORK FOR INTEGRATED IMPACT ASSESSMENT OF CRITICAL INFRASTRUCTURE NETWORKS

4.1 Introduction

The primary aim of this study is to provide methods to allow CI network providers and relevant emergency management personals managers to assess the impacts of disasters on CI networks and the propagation of damage caused by these disasters from one CI network to the other networks in a region of interest. Recently, several software packages have been developed to address various aspects of individual models (see, for example, Bebbington et al., 2008; Bell et al., 2007; Boulos et al., 2014; Buxton et al., n.d.; Nan & Sansavini, 2016; Zorn & Shamseldin, 2016). However, it is essential to link these models to increase their uptake in hazard-impact assessments. At present, there is no such structured framework to link different models together and there is a need to understand the information needed in the flow from one model to the next, to facilitate integrated impact assessment of infrastructure networks (Paltrinieri et al., 2013). In this chapter, an integrated impact assessment framework is developed consisting of the topological and damage data for CI network components, which is collected as the first phase of quantitative data collection.

Impact assessment studies are generally carried out independently for each CI network that relies on several models representing the (a) hazard, (b) performance of individual CI network components, (c) collective performance of each CI network and (d) interdependencies between multiple CI networks (Chen et al., 2016). These studies start with selecting a hazard scenario. The vulnerabilities of exposed components are usually modelled based on evidence-based damage data from past events to predict the likelihood of damage in future events (Schmidt et al., 2011). On the other hand, when there is not enough evidence-based damage data, specific vulnerability functions are developed through analytical methods or based on expert opinion (Zhang et al., 2016). Finally, damage and recovery models are used to determine the impact of damage to the CI network components in terms of the LOS of the CI networks and their time to recover (He & Cha, 2018). There are several examples of individual hazard models (Schmidt et al., 2011; Wilson et al., 2014), vulnerability models (Menoni et al., 2002; Ouyang et al., 2009; Pant et al., 2017; Zhang et al., 2014) and damage models (Anil et al., 2016; Bočkarjova et al., 2004; Johansen & Tien, 2017). Although these studies address independent models of hazard, vulnerability and damage, for the CI components individually or the CI networks as a whole, there is a need to integrate these models within a generic framework that can facilitate various linking strategies: (i) linking the performance of different components considering intra-dependencies within a network to assess its functionality; and (ii) linking across different networks considering their interdependencies (Peerenboom & Fisher, 2007; Puuska et al., 2018). This approach enables the generation of functionality and disruption of services from CI networks across a region. Developing such a framework in an integrated way by linking these models can form the basis of a KCDSS to improve the existing decision-making process both qualitatively and quantitatively (see Chapter 5).

4.2 Conceptualization of the framework

The proposed framework for integrated impact assessment of CI networks in this study allows the different CI network models to maintain their strengths and the consistency of their inputs and outputs in a transparent manner. The framework is tested using real electricity and road network data in the Wellington region. Additionally, placeholder values for potable water network have been used to test additional complexities due to the involvement of three CI networks. The most important feature of this framework is that it is valid for both the component and network-level linkages. The component level linkage is modelled through dependency identification between the components of an individual CI network to generate network-level performance. Similarly, the linkages between multiple CI networks are modelled through interdependency interactions between components of these CI networks. To model both types of linkages, the impact assessment framework, as depicted in different blocks of Figure 4-1, integrates the following four modules that are designed for this study:

a) **CI Component representation module –** to represent topological information of the CI network components;
b) **CI damage representation module –** to represent damage to CI network components based on different types of hazards, their intensities and vulnerability levels;
c) **CI network functionality assessment module –** to assess the functionality of an individual CI network based on the components' connectivity and likely damage; and
d) **CI interdependency assessment module –** to assess the functionality of multiple CI networks based on their interdependencies.

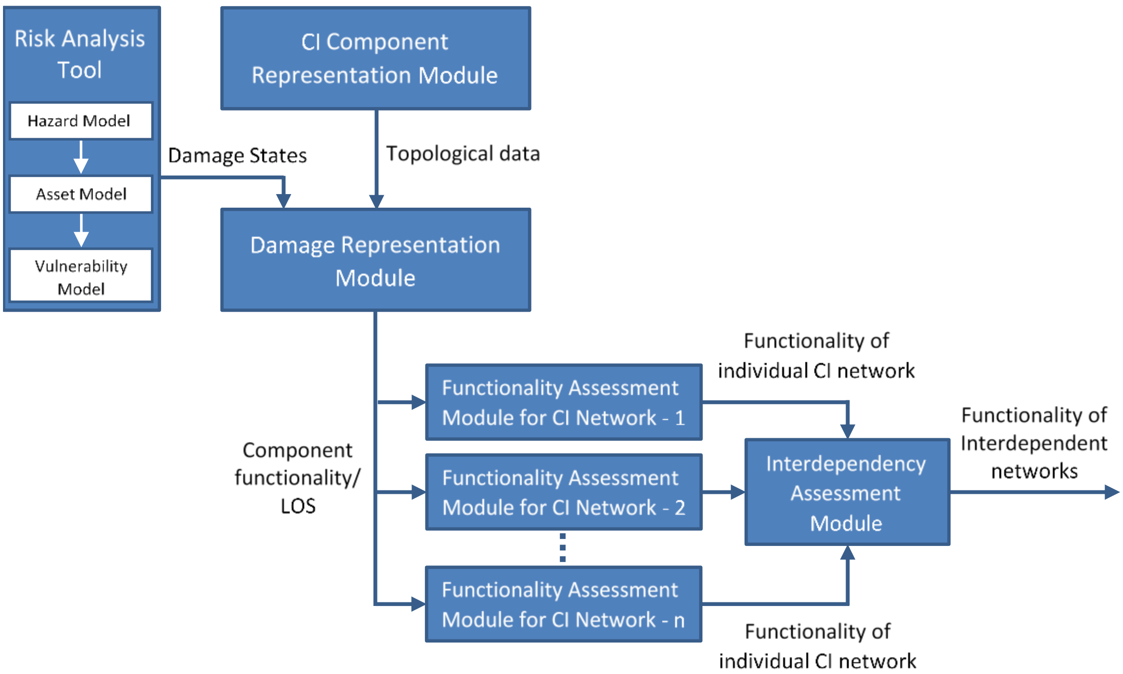

Figure 4-1. A schematic infrastructure impact assessment workflow that demonstrates the linkages between each module. Here 'n' number of CI networks are depicted as this workflow is applicable for a wider set of networks

The impact assessment workflow starts with collecting topological information for the individual CI network components and representing it in a suitable format through the CI component representation module. Different risk analysis tools are available to represent damage to CI components. These tools can use hazard models (to simulate the hazard intensities, for example, earthquake shaking, landslides, floodwater flow characteristics, tsunami overland flow depths, volcanic ash dispersion and settlement) with asset models (CI network components) and vulnerability models (how much damage is caused by the hazards) to generate damage and loss information in the form of ‘damage states’ at the component level, as illustrated in Figure 4-1 (Bell et al., 2007). This information is then aggregated for functionality assessment of individual CI networks. If there is more than one CI network involved in the impact assessment process, then an interdependency assessment module can be utilized. The detailed workflow of each of the four modules is discussed in the following sections.

4.2.1 CI component representation module

The impact assessment of a CI network is largely influenced by the connectivity between the components and their functional hierarchy. Therefore, it is necessary to appropriately characterize the interdependencies within a CI network and the interdependencies between components of multiple CI networks under consideration (Huang et al., 2014; Nan & Sansavini, 2017). The topology network-based approach is increasingly becoming preferred for situations in which the stakeholders from the local and regional government and CI network providers need to identify the vulnerable parts of the CI network and the consequent level of disruption to the services, to choose suitable mitigation approaches (Hasan & Foliente, 2015; Pant et al., 2017). The application of this approach can prove its value if topological data and connectivity links for CI network components are available. In this study, there were opportunities to employ detailed data related to CI networks from regional CI network providers, therefore, a *topology network-based approach* is applied to model the performance of individual CI networks and to account for their interdependencies. The data acquisition process adopted in this study for electricity, potable water and road networks is discussed in the following sections.

4.2.1.1 Acquisition of the CI components’ topological data

Comprehensive datasets and access to relevant information for CI networks are fundamental for implementing the topology network-based approach, as it provides useful information for analysing CI network performance and to understand the socio-economic impacts of disruptions. Datasets include information around spatially distributed locations of CI network components, their connectivity concerning the nature of interdependencies and vulnerability characteristics. Collecting such a wide range of information from the CI network provider is usually challenging because of their privacy, security and proprietary concerns (Rinaldi et al., 2001). Additionally, most of these CI networks are owned by private organizations and therefore some of them have restricted policies for collecting and sharing data. The first phase of data collection for this study involved the collection of quantitative data related to the components of electricity and road networks. As mentioned earlier, the scope of this study is the Wellington region as it is considered a region of very high seismicity with a history of earthquakes in the past (Get Ready, n.d.). In 1848, Wellington was affected by the Marlborough earthquake and then seven years later by a magnitude 8.2 earthquake which is the most powerful earthquake in Aotearoa New Zealand history. The epicentre of this earthquake was almost 140 kilometres along the Wairarapa Fault near Palliser Bay. Two earthquakes of magnitude 7.2 and 7.0 respectively hit Wellington and Wairarapa regions in 1942 causing substantial damage to some of the buildings. The most recent and powerful earthquake was the 2016 Kaikoura earthquake that had significant impacts on some of the multi-storeyed buildings in Wellington’s CBD (New Zealand Parliament, 2016).

Therefore, the regional structure of the Wellington region’s electricity, potable water and road networks were studied through available literature, documental resources and personal communications with the regional CI network providers. The primary source of data for the topological structure of electricity and road networks was acquired in GIS shapefiles. The researcher designed GIS shapefiles with placeholder data for the locations, connectivity and other related parameters of the potable water network. ESRI (2017) defines a shapefile as “a vector data storage format for storing the location, shape, and attributes of geographic features. A shapefile is stored in a set of related files and contains one feature class”. These shapefiles usually contain detailed information for an individual component which can also represent its supply zones using meshblocks. Statistics New Zealand (2020) defines a meshblock as:

> A meshblock is a defined geographic area, varying in size from part of a city block to large areas of rural land. Meshblocks are contiguous: each meshblock borders on another to form a network covering all New Zealand, including coasts and inlets.

The shapefiles needed some cleansing and then converted into Comma-separated Values (CSVs) for a better understanding and representation of connectivity between various CI network components. The result of this data collection phase formulated the basis for the selection of CI network components for this study and is discussed in the following subsections.

a. Components of the electricity network

Wellington region's metropolitan power supply is delivered through an electricity network consisting of 220kV, 110kV, 33kV, 11kV and 400V network components. Transpower New Zealand network consists of a series of Grid Exit Points (GXPs) that provide the electricity supply to Wellington Electricity (WE), which delivers it to commercial and domestic users (Transpower New Zealand, n.d.; Wellington Electricity, n.d.). The GXPs are connected through high power 110kV cables passing through transmission structures, and the supply from GXPs to substations is connected through 33kV overhead or buried sub-transmission cables (Mowll, 2012). Each substation supplies a zone or area consisting of businesses and households. Wellington's electricity supply zones are represented using meshblocks, their supplying substations and GXPS are represented as nodes or points and the connecting cables and transmission structures are represented as links or lines, in Figure 4-2.

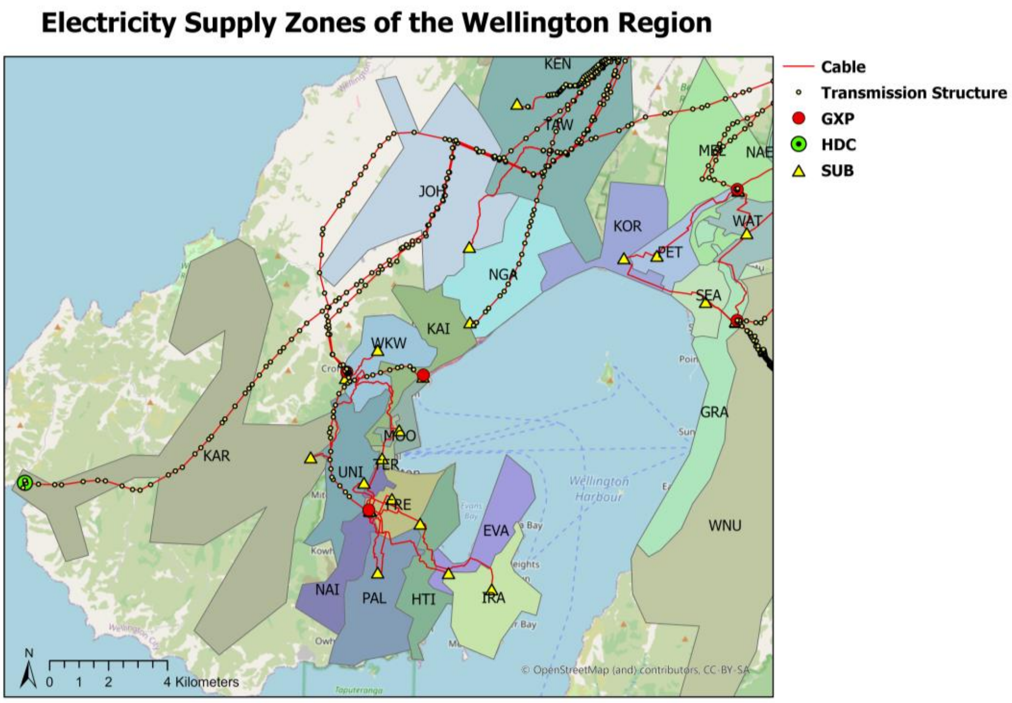

Figure 4-2. Wellington region's electricity supply zones and significant components modelled for this study

b. Components of the road network

A road network consists of many significant components including a road carriageway, supporting structures, retaining walls and tunnels. Road impacts can be modelled in several ways with varying resolutions. In this study, the role of the road network is considered as its ability to provide access to the damaged sites of electricity and water networks and how quickly it can provide access in response and recovery phases. Therefore, a simplified network of 'road zones' has been utilized in this study as opposed to full network analysis. An expert judgement workshop was held in the past between Waka Kotahi NZ Transport Agency, regional city councils and Opus International Consultants Limited, Wellington in which the Wellington region was divided into 24 different road zones as shown in Figure 4-3. This data related to the road zones was provided by Waka Kotahi NZ Transport Agency in GIS shapefile format for this study.

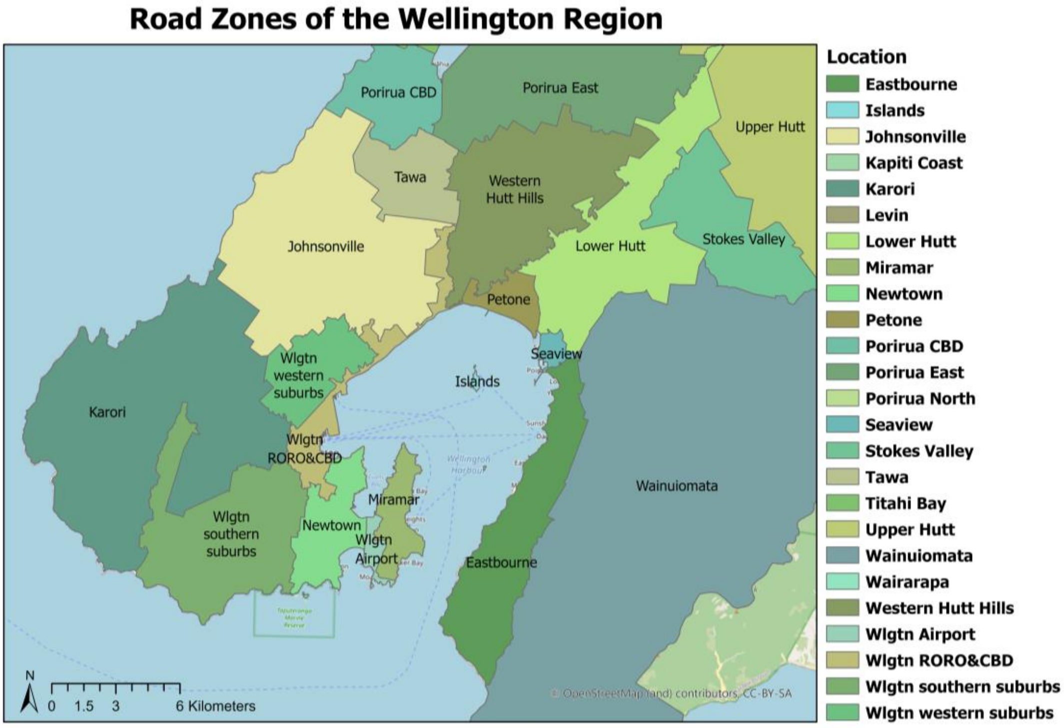

Figure 4-3. Wellington region's road zones

The shapefile was then converted into a CSV file to represent a 'time to recover' matrix between the 24 road zones as shown in Table 4-1. The matrix can show an estimated number of days needed to provide access between 24 different road zones. These estimates were calculated based on dependencies of the road network on other CI networks and the probable damage to different elements of the road network such as bridges, tunnels, connecting roads etc. The exercise of creating these road zones and the road access matrix is not part of this study and the 'time to recover' matrix is utilized in this framework to estimate the additional time needed to access the damaged components of electricity and potable water networks.

Table 4-1. Estimated outage times (in days) for road access between road zones

Zone	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
A																								
B	7																							
C	7	5																						
D	7	3	5																					
E	7	3	5	2																				
F	7	3	5	2	2																			
G	7	3	5	2	1	2																		
H	7	7	7	7	7	7	7																	
I	7	7	7	7	7	7	7	3																
J	13	13	13	13	13	13	13	13	13															
K	7	7	7	7	7	7	7	5	5	13														
L	14	14	14	14	14	14	14	14	14	14	14													
M	10	10	10	10	10	10	10	10	10	13	14	14												
N	14	14	14	14	14	14	14	14	14	14	14	7	14											
O	14	14	14	14	14	14	14	14	14	14	14	14	14	14										
P	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15									
Q	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	7								
R	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40							
S	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	7	3	40						
T	7	3	5	3	3	3	3	7	7	13	7	14	14	14	14	15	15	40	15					
U	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	7	7	40	7	15				
V	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	7	7	40	7	15	7			
W	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	40	30	30	30	30		
X	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	40	21	21	21	21	30	

c. Components of the potable water network

Wellington's potable water network consists of two parts: (i) the bulk water supply network and (ii) the reticulation network. The bulk water network components including reservoirs, treatment plants, pump stations and their respective connecting pipelines have been modelled in this study. The topological information related to the locations of potable water network components, connecting pipelines from treatment plants to pump stations and from pump stations to reservoirs is designed by the researcher using placeholder values. The reason for using placeholder values at this stage is the unavailability of the real data during this study. The pipelines that are part of the reticulation network down the reservoir are beyond the scope of this study. Figure 4-4 shows some part of the potable water network that is designed for the study area in which bulk water treated in the treatment plants is supplied to reservoirs through pumps stations and finally carried to the household and businesses within the potable water supply zones, represented as meshblocks.

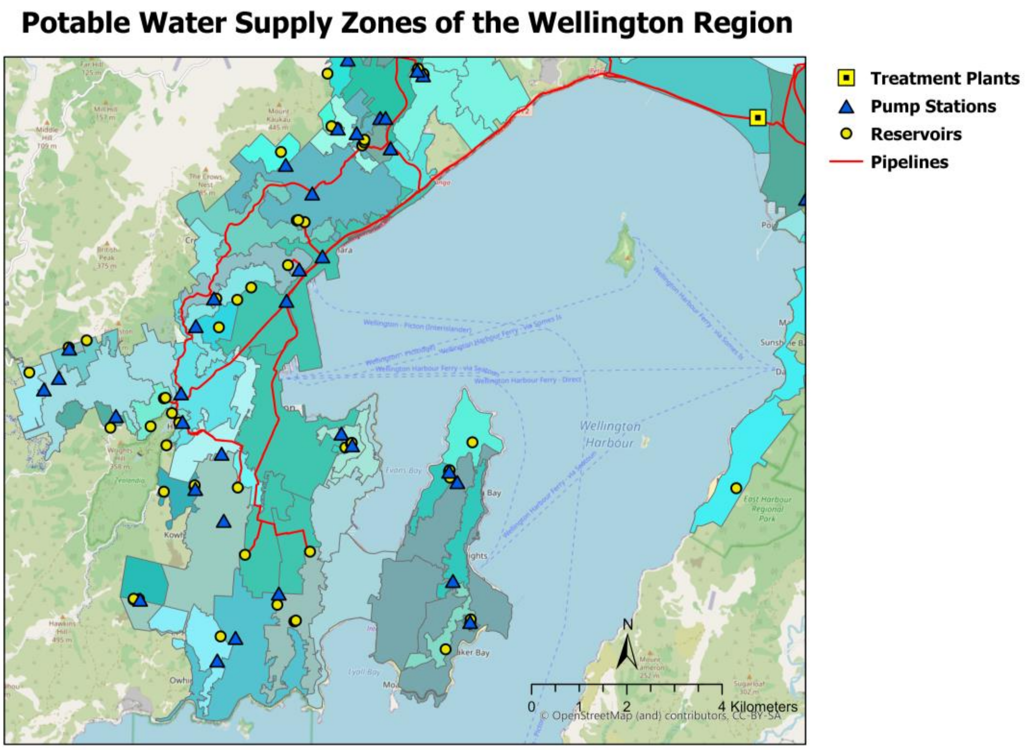

Figure 4-4. Wellington region's potable water supply zones and significant components modelled for this study

4.2.1.2 Analysis of the CI components' topological data

Based on the understanding of the regional structure of the electricity, potable water and road networks in the Wellington region, the collected data is then analysed and processed to make it suitable for the modelling of CI networks' recovery. In the topology-based network approach, the point components (e.g. a pump station in a potable water network or a substation in an electricity network) are modelled as '*nodes*' and linear components, e.g. electricity cables and water pipes are modelled as '*link*' or '*edge*'. The nodes are connected using the links and it is important to identify the direction of the flow of services between various nodes. For a graphical representation of the dependency relationships between different CI components, this study used dependency matrices (Setola & Theocharidou, 2016). A dependency matrix is a matrix having rows and columns labelled with either 1 (if there is a flow of service from node *i* to node *j* that means *j* is dependent on *i*) or 0 (if there isn't any flow of service from node *i* to node *j* that means j is not dependent on *i*). An example of a dependency matrix between nodes *i, j and k* is shown in Table 4-2.

Table 4-2. An example of a dependency matrix between nodal components of a CI network

		To		
	Nodes	***i***	***j***	***k***
From	***i***	0	0	0
	j	1	0	0
	k	0	1	0

After understanding the dependency relations between different components of a CI network, a further analysis is needed for their input characteristics. The input parameters for nodal components include an identifier, component type, and the road zone in which it is located. The input parameters for link components include an identifier, source type (GXP/substation/treatment plant etc.), destination type (substation/pump station/reservoir), structural characteristics (material type) and the road zones through which they are passing to connect a source node to the destination node. By considering road zone information at the node level, the input data makes it convenient to compute the access time to the node's location from any other road zone using the 'road zone matrix'. It is worth noting that in a real network, there can be multiple links in different paths connecting a source node and a destination node to ensure redundancy in the network. These links representing cables of the electricity network or pipes of the potable water network have different material types and they pass through different road zones. Hence, there are multiple entries in the input data file for each of these links following different paths (1 & 2) as shown in Table 4-3 and further explained using Figure 4-5.

Table 4-3. An example representation of nodes and edges as input file

id	Links	Source	Destination	Cable/pipe material	Road zone
1	NodeX-NodeY-1	X	Y	A	RoadZone-A
2	NodeX-NodeY-1	X	Y	A	RoadZone-B
3	NodeX-NodeY-1	X	Y	B	RoadZone-C
4	NodeX-NodeY-2	X	Y	A	RoadZone-A
5	NodeX-NodeY-2	X	Y	B	RoadZone-B
6	NodeX-NodeY-2	X	Y	C	RoadZone-C

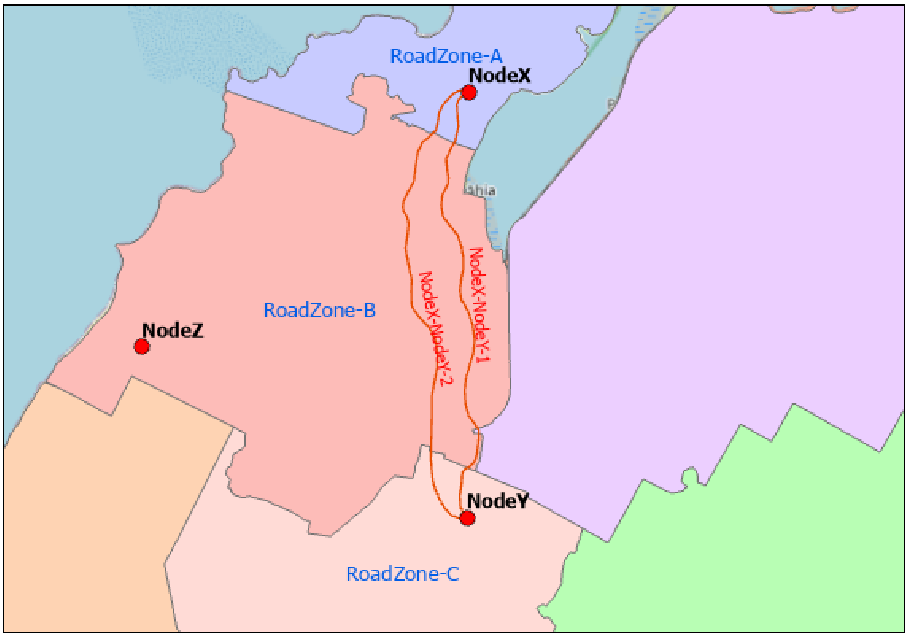

Figure 4-5. An example depiction of the connectivity between two nodes through multiple links (material A or B may be included)

In an independent network model, two nodes can either be connected directly by a single link or multiple links as explained earlier or indirectly accommodating intermediate nodes and additional links as required. In such cases, there is a need to identify and design all the possible *routes* by adding the *links* together. An example of such a scenario is shown in Figure 4-6. There is no direct path from NodeX (source node) and NodeZ (destination node) of the same CI network, but there are five *links* that can be used to make six possible *routes* from NodeX to NodeZ, passing through NodeY.

1. Route-A includes Link 1 (NodeX-NodeY-1) and Link 4 (NodeY-NodeZ-1)
2. Route-B includes Link 1 (NodeX-NodeY-1) and Link 5 (NodeY-NodeZ-2)
3. Route-C includes Link 2 (NodeX-NodeY-2) and Link 4 (NodeY-NodeZ-1)
4. Route-D includes Link 2 (NodeX-NodeY-2) and Link 5 (NodeY-NodeZ-2)
5. Route-E includes Link 3 (NodeX-NodeY-3) and Link 4 (NodeY-NodeZ-1)
6. Route-F includes Link 3 (NodeX-NodeY-3) and Link 5 (NodeY-NodeZ-2)

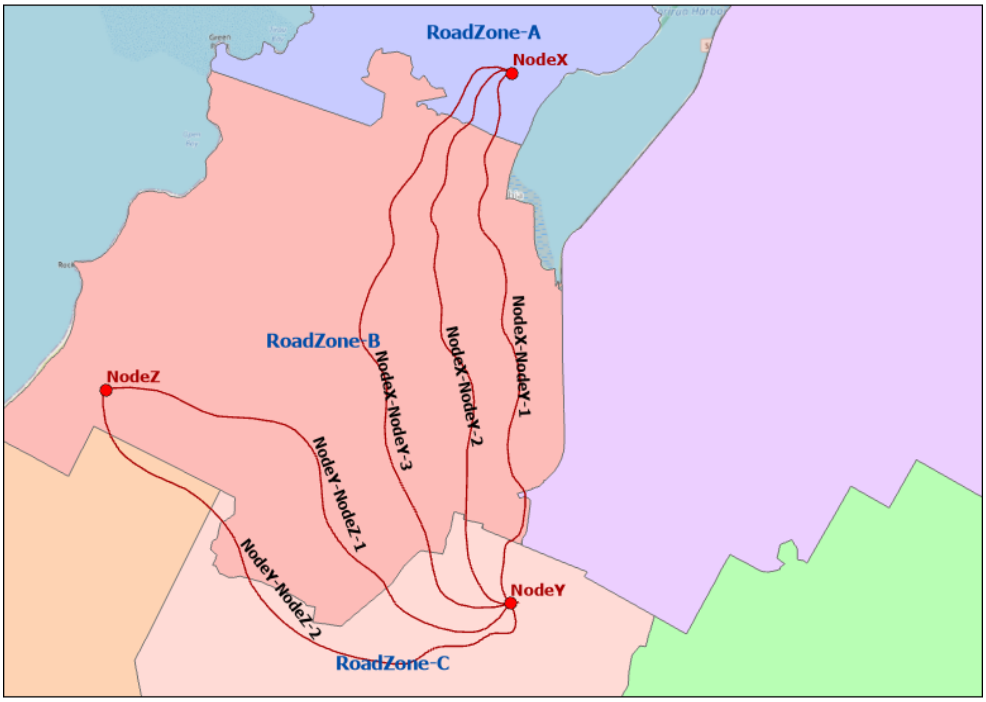

Figure 4-6. Multiple links and routes between source and destination nodes

The *links* and *routes* are created to choose the best possible path from all the available paths to compute the optimum recovery time for a node from its source node. The reason for adding multiple *links* was to provide redundancy in the network so that if one link fails then another link is available to continue the flow of the network.

4.2.2 CI damage representation module

After the topological representation of CI network components, the damage representation module refers to the simulation of physical damage to CI components, which is then presented to the CI network functionality assessment module to estimate the impact of damage on a CI network service. A recovery model is then used to describe the restoration process of a damaged CI network with and without dependencies on the other CI networks. Similar to the acquisition of topological data for the CI network components, another data acquisition process was needed for the estimation of damage to various types of CI network components, which is discussed in the next section.

4.2.2.1 Acquisition of the CI components' damage data

Information related to the damage of CI network components needed to be acquired from a separate hazard and risk modelling tool (or software) as depicted earlier in Figure 4-1. Therefore, a risk analysis tool, namely *Riskscape* is used to model damage to the network components for a chosen hazard. RiskScape is a multi-hazard risk assessment software tool that predicts the severity of damage (represented as 'damage states' (DS)) and direct losses for CI components exposed to natural hazards (Bell et al., 2007; Schmidt et al., 2011). RiskScape generates the damage states of different components within the identified CI networks. Based on different damage states appropriate repair/recovery strategies were adopted in this study to estimate outage of services. The final outputs are timestamped outage maps that determine a CI network service outage area due to a hazard. The process of damage assessment from RiskScape starts from modelling a hazard scenario on the identified CI network components. It then combines spatial information on hazards, components, and their vulnerability to predict damage states for the CIs (Bell et al., 2007).

Hazard models help us to mathematically describe the variation of hazard intensity across a region of interest considering the frequency and source of the hazard (Chen et al., 2016). In this study, a deterministic Wellington Fault Mw7.5 earthquake hazard scenario including related secondary hazards such as liquefaction and ground subsidence is modelled by RiskScape to generate the damage. The hazard model includes the earthquake source (geometry and magnitude), the site model representing soil properties, and ground motion prediction models that estimate shaking from the source to site of interest i.e. CI network component's location. The fragility functions of RiskScape used Modified Mercalli intensity (MMI) and Peak Ground Acceleration (PGA) as the ground shaking intensity measure. A set of fragility functions is available in RiskScape that is suitable for various types of CI network components to predict their likely damage states (DS1 to DS5, representing 'light' to 'extreme' damage) for a given level of hazard intensity. By modelling uncertainties in hazard and using probabilistic fragility functions, RiskScape can generate multiple damage scenarios for a network under consideration (Schmidt et al., 2011). Uncertainty modelling is beyond the scope of this study, therefore only a single deterministic scenario is used.

4.2.2.2 Analysis of the CI components' damage data

Although the damage data for this study has been acquired from RiskScape, due to the standardized structure of the impact assessment framework, this data can be acquired from other similar models as well. The collected data provides details on the damage sustained by each component in terms of damage states and the number of components in each damage state. Table 4-4 shows some parts of an example damage file for representing the damage states of different links between the nodes.

Table 4-4. An example of input file for linear components with their damage information

Id	Links	Source	Destination	Mat	Road zone	DS1	DS2	DS3	DS4	DS5
1	NodeX-NodeY-1	X	Y	A	RoadZone-A	0	5	15	0	0
2	NodeX-NodeY-1	X	Y	A	RoadZone-B	0	17	11	10	0
3	NodeX-NodeY-1	X	Y	B	RoadZone-C	0	4	1	0	0
4	NodeX-NodeY-2	X	Y	A	RoadZone-A	0	3	2	12	0
5	NodeX-NodeY-2	X	Y	B	RoadZone-B	0	11	18	10	0
6	NodeX-NodeY-2	X	Y	C	RoadZone-C	0	21	36	31	0

Each link between a source and the destination contains several segments and the last 5 columns of Table 4-4 show the number of segments in each damage state. For example, the first row shows that for the link *NodeX-NodeY-1* with source *X* and destination *Y*, having mat (material type) *A*, passing through *RoadZone-A* has *0 segments* in *DS1*, *5* in *DS2*, *15* in *DS3* and *0* in *DS4* and *DS5*. Information around the time needed to repair the damaged components and the recovery strategies for various types of components under different damage states is discussed in detail in Chapter 5.

4.2.3 CI network functionality assessment module

The analysis of CI network functionality needs to aggregate all the information from the significant components in one place, which means that a component level functionality assessment is needed first. The component functionality models address the level of functionality of the components of a CI network distributed over a region, based on the damage information about each component and its connectivity (Lee et al., 2018; Unen et al., 2011). The recovery times for individual components of a CI network are calculated using the damage state and applying the respective recovery strategy for each component (nodes and links). For point components (i.e. nodes), recovery time is directly mapped for each damage state, whereas, for link components, recovery time computation is a complex process and needs an implementation of the shortest path algorithm.

In this study, Dijkstra’s algorithm has been applied to calculate the minimum recovery time from a source node to the destination node (Dijkstra, 1959). Dijkstra's algorithm is a useful algorithm for topology network-based modelling techniques to find the single shortest path. It does not need to know the target node beforehand and finds the shortest path from a node to every other node in the network. Therefore, Dijkstra’s algorithm finds the shortest path from a source node (for example, a GXP of an electricity network) to all the destination nodes (for example, the substations of an electricity network) in a given graph. We start the algorithm by generating an SPT (shortest path tree) with a given source as root by maintaining two sets. One set contains the nodes included in SPT and the other set includes the nodes that are not yet included in the SPT. At every step of the algorithm, a node is chosen which is not yet included in the set and has a minimum recovery time from the source. The path finally generated by Dijkstra’s algorithm shows the optimal route among all the other available routes from a source to a destination node. Thus, this algorithm can handle the redundancy in the CI networks by finding the best available path automatically through the following steps:

Dijkstra's Shortest Path Tree Algorithm

1 **Input:** Create a set for calculating the recovery times and name it *calcRT (Calculate Recovery).* This set is initially empty, and it keeps track of all the included nodes.

2 Assign a recovery time value to all the nodes of the input graph. For the source node, the recovery time value is 0 so that it is picked first and the recovery times for all the other nodes are set as INFINITE.

3 While *calcRT* does not include all nodes:

4 Pick a node *x*, which is not already in *calcRT* set and has the lowest recovery time.

5 Include this node *x* to the *calcRT* set

6 Iterate through all the adjacent nodes of *x* and then update their recovery times. For every adjacent node *y*, if the sum of recovery time value of *x* (from source) and weight of edge *x*-*y*, is less than the recovery time value of *y*, then update the recovery time value of *y*.

7 **Output:** A set of recovery times from a source node to the destination node with minimum recovery time

An example scenario is presented in Figure 4-7 to calculate the optimum recovery time from node *'A'* to node *'G'*. Initially, the set *calcRT* is empty, and recovery times assigned to the vertices are *{0, INF, INF, INF, INF, INF, INF}* where *INF* means infinite.

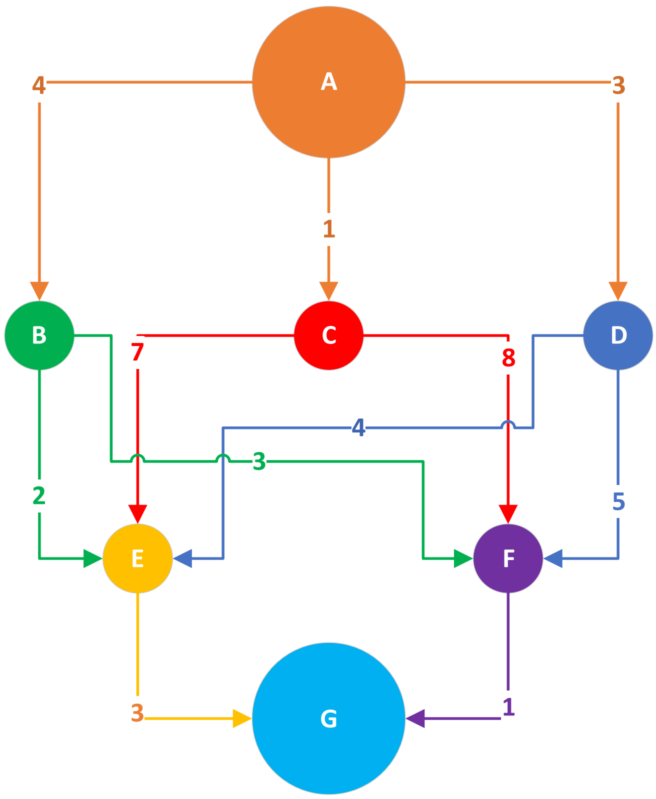

Figure 4-7. An example scenario of connectivity between different nodal components

We start the algorithm by first picking the source node and then pick the adjacent node with minimum recovery time value from the previously selected node and it should be not already included in the *calcRT* set. We then update the recovery time values of its adjacent nodes and repeat the process until the algorithm has visited all the nodes in the graph and find the minimal recovery time from the source node to all the other nodes. For the above example, the following steps are needed:

a) Pick the source node, which will be '*A*' and *calcRT* becomes {A}. Adjacent nodes of *'A'* are *B, C* and *D* and their recovery times are updated as 4, 1 and 3, respectively.

b) The next node with minimum recovery time and not already included in the set is node *'C'* and *calcRT* becomes {A, C}. The recovery times of adjacent node *'E'* becomes 8 and the recovery time of node *'F'* becomes 9.

c) The next node with minimum recovery time and not already included in the set is node *'D'* and *calcRT* now becomes {A, C, D}. The recovery times of node *'E'* and *'F'* change to 7 and 8, respectively.

d) The next node with minimum recovery time and not already included in the set is node *'B'* and *calcRT* becomes {A, C, D, B}. The recovery times of node *'E'* and *'F'* change to 6 and 7, respectively.

e) The next node with minimum recovery time and not already included in the set is node *'E'* and *calcRT* becomes {A, C, D, B, E}. The recovery time of the node *'G'* becomes 9.

f) The next node with minimum recovery time and not already included in the set is node *'F'* and *calcRT* becomes {A, C, D, B, E, F}. The recovery time of node *'G'* changes to 8.

At this stage, the algorithm has visited all nodes in the graph and has been able to find the minimal recovery time from the source node to all the other nodes. In the above example, an optimal path from node *'A'* to node *'G'* is resulted as highlighted in Figure 4-8, with recovery time 8 and this optimal path allows us to handle the redundancy in the network.

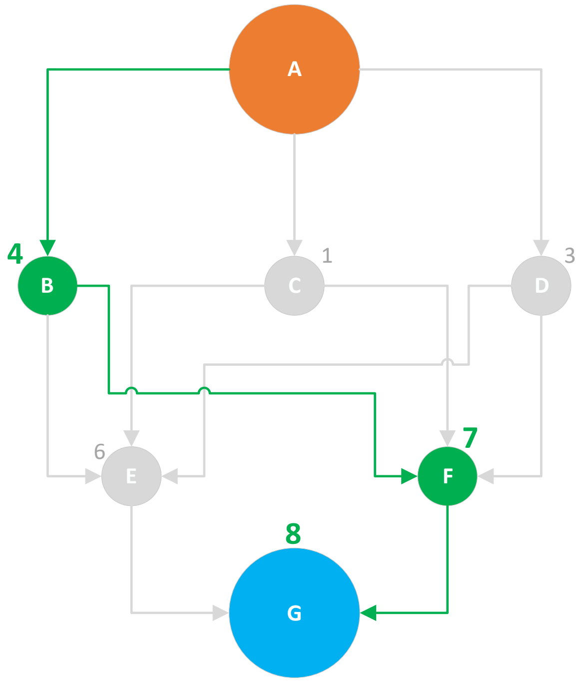

Figure 4-8. Optimal recovery path from a source node to a destination node after applying Dijkstra's algorithm

4.2.4 CI interdependency assessment module

CI networks are vulnerable not only through the disruption of components within a single CI network but also because of dependencies between components of different CI networks. When the impact assessment is done for multiple CI networks, interdependencies need to be modelled to arrive at the integrated functionality or LOS that can be utilized for the analysis of social and economic impacts. Simple examples of these dependencies are between pump stations of a potable water network and the substations of an electricity network. The combined effects of these dependency relationships can rapidly increase the scope and extent of CI network disruption beyond that of the original failure. These escalating failures are often referred to as cascading failures (Dueñas-Osorio & Vemuru, 2009; König & Schauer, 2019).

The modelling of interdependencies between CI networks can be challenging because it requires the collection of a large amount of detailed information from different organizations (Pant et al., 2017). There is no accepted best approach for modelling these interdependencies and many approaches have been proposed over the last few years with new approaches often being trialled on either a small region with numerous types of CI or larger regions but considering limited numbers of CI types (Cheng, 2017; De Nicola et al., 2016; Digioia et al., 2012; Panzieri et al., 2005; Pinnaka et al., 2015; Rahman et al., 2011; Wilson et al., 2014). Not many studies have considered large geographical areas and multiple CI networks because of the difficulty in collecting the information needed to populate the models to a level of completeness that allows informative modelling.

Recently, the international community studying CI interdependencies has favoured the use of a *system of systems (SOS)* approach (Eusgeld et al., 2011). The system of systems approach takes separate models for each of the networks or CI types and knits them together to create a more complex model that considers the interdependency relations between different components. A system of systems approach supports the use of a hierarchical architecture where the top tier is the 'whole' system of systems, consequent tiers are the interaction among various CI networks and the individual components within each CI network, as illustrated using a horizontal hierarchy in Figure 4-9.

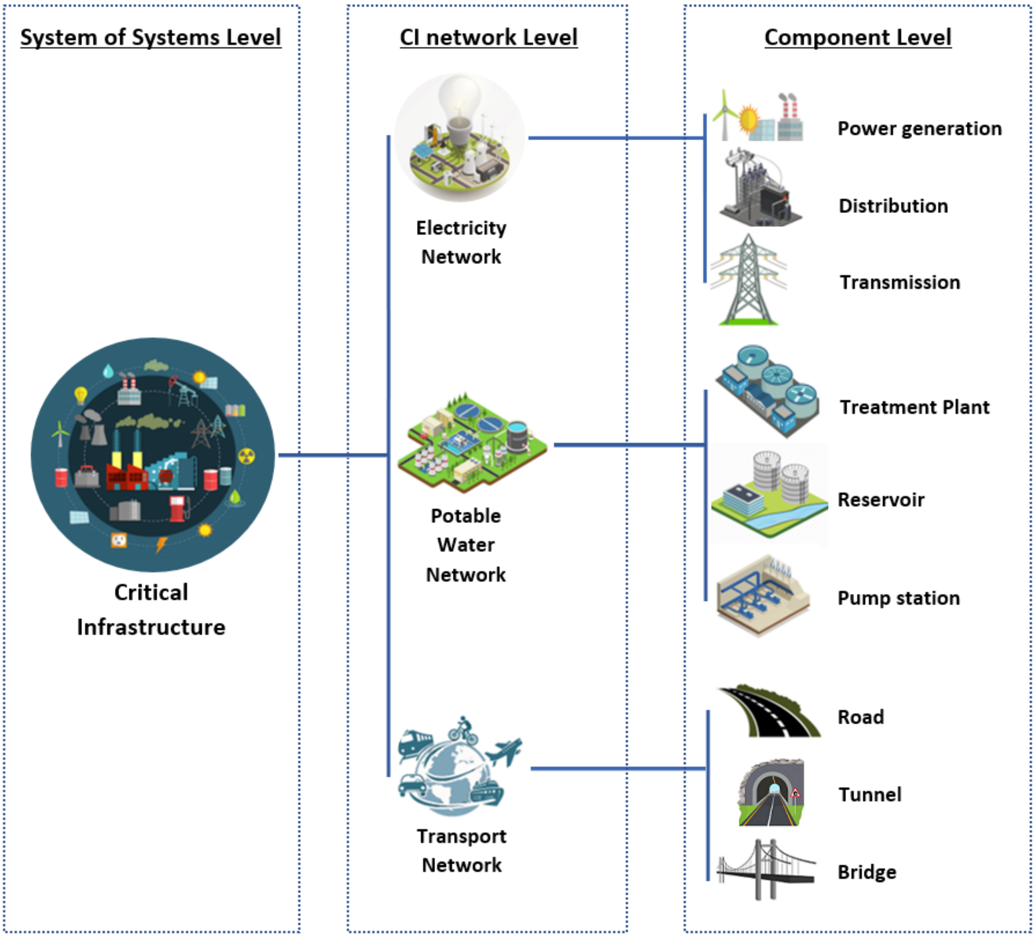

Figure 4-9. System of systems hierarchical structure

The system of systems approach needs to elicit and carefully define the nature of the connections between different components at the systems level and the connections between different infrastructure networks at the CI network level. Among CI networks of electricity, road and potable water supply, there are some obvious dependency links. The relative importance of the links can change, however, depending on whether it is a normal operating situation or a post-event period where the emphasis is on recovery and reinstatement. In normal situations, out of the three CI network types, electricity is the main driving type because the other two networks are strongly dependent on the electricity network. In a recovery situation, roads take a greater level of importance because road access controls the ease with which repair and reinstatement operations can take place. Similar to the dependency matrices for components of an individual CI network, the dependency matrices for multiple CI networks are created to understand the dependency relationships between them. An example is shown in Table 4-5, in which nodes EA, EB, EC and ED represent the components of the electricity network, whereas nodes WA, WB, WC, WD and WE represent the components of the potable water network.

Table 4-5. An example of a dependency matrix between components of different CI networks

		To				
	Nodes	**WA**	**WB**	**WC**	**WD**	**WE**
From	**EA**	0	0	0	0	0
	EB	0	1	0	0	0
	EC	0	0	0	0	0
	ED	0	0	0	1	0

At this stage, the integrated impact assessment framework has gathered the required topological and damage data for the components of the modelled CI networks. In Figure 4-10, the integrated linkage process between electricity, potable water and road network models is depicted.

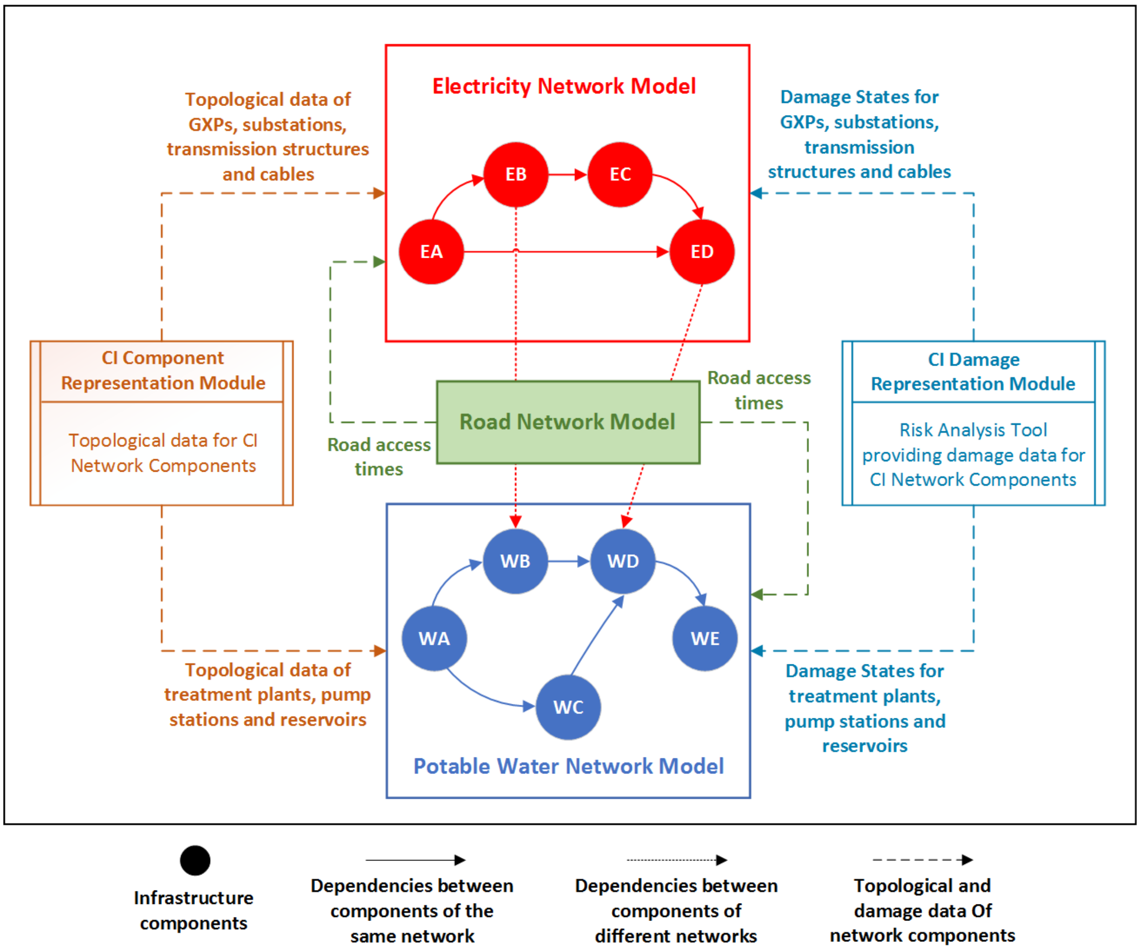

Figure 4-10. An integrated methodology for linking electricity, potable water and road networks

Further explanation about this integrated methodology is presented through a step-by-step process:

- Step 1: During the CI network representation phase, the component data for electricity, potable water and road networks is collected. The data for the electricity and potable water network components is processed and represented in the form of nodes and edges using a topology network-based approach. The whole study region is then divided into different road zones to provide further information about road access to these components.
- Step 2: During the damage representation phase, damage data (generated by RiskScape) for the three modelled CI networks represents different damage states for the components of these networks.
- Step 3: The network data (topological and damage) is then integrated using the connectivity

data between the components of the modelled CI networks to understand the flow of services and cascading failures of the components due to the failure to the components to which they are dependent.

The conceptual integrated impact assessment framework at this stage is ready to be implemented to generate the desired results. Different modules within the framework have been designed to keep them independent from the variation of CI networks' topological data and damage models. This framework has been designed using a system of systems approach to be flexible to include more CI networks in future easily by including their topological and damage data. Similarly, damage representation models other than RiskScape can also be utilized for the representation of damage to the existing CI network components. The software implementation of this framework is presented in the next chapter with the inclusion of the recovery strategies, as it is also important to understand how the damaged CI network components can be accessed and repaired. Through the detailed analysis of the generated results, all vulnerabilities in the network can be identified and subsequent decisions can be made to improve the recovery times of CI network components.

4.3 Chapter Summary

The emphasis of this chapter was to design an integrated impact assessment framework for CI network models as the first artefact of this study. To ensure methodological rigor in this study, foundational information is gathered from the academic literature of appropriate theories for CI component representation, CI damage representation, CI network functionality assessment and CI interdependency assessment modules. This framework is robust and built on transparent methods to translate results between different computational modules, resulting in a more advanced and integrated or linked system of systems. The motivation for this part of the study is to work towards a better understanding of how the modules can interact, while preserving their respective strengths, and to give an improved representation of both the flows of information and the impacts of the modelled components. The in-depth analysis of CI network functionality with the dependencies between components of different CI networks has provided some key points to be considered as below:

1. When different CI network component models are linked to model a single CI network, the damage or functionality impacts of one component model must be reflected in other models so that combined effects of intra-dependencies can be analysed.
2. An understanding of interdependencies between the components of two different CI network models is crucial to interlink multiple CI networks. The effort required in this process can be quite demanding, and expert elicitation can be an effective approach to enable this.
3. For those CI network models where the direct linkage is not possible, sophisticated interface models should be used to integrate across the different models.

The first artefact of this study has been designed through an integrated impact assessment framework that can further be implemented and tested using software platforms to generate the desired results. The next chapter discusses how the structured data from this conceptual framework is utilized to develop a KCDSS that will ease the decision-making requirements of the relevant stakeholders.

5 ARTEFACT - II: DEVELOPMENT OF KNOWLEDGE-CENTRED DECISION SUPPORT SYSTEM (KCDSS)

5.1 Introduction

Following the design of the integrated impact assessment framework as the first research artefact, a KCDSS is developed as the second research artefact of this study to validate the architecture of the framework. DSSs can be used as a tool by the researchers and relevant stakeholders to investigate how well the system supports the work and find areas of strength and weakness in the design of their frameworks (Zakaria et al., 2015). The development of KCDSS is driven by the Design Science Research (DSR) methodology. The DSR methodology not only guides the development and implementation of the KCDSS but also facilitates its demonstration and evaluation (Arnott & Pervan, 2018). The KCDSS implementation addresses the fourth objective of the research and serves as a working product of the proposed artefact of Chapter 5. The core of any KCDSS consists of different types of knowledge that makes it different from a traditional DSS. This knowledge is captured and stored within the DSR's rigor cycle (that is the knowledge-base), for the benefit of the DSR's relevance cycle (that is target environment) in which a DSS will be deployed and for the end-users who will interact with the DSS. A comprehensive review of the literature indicates different types of DSSs have different design and implementation challenges, and a DSS that supports the understanding of CI network interdependencies may require specialized modelling techniques, software implementation and database components (Giovinazzi et al., 2017; Neville et al., 2016).

The key criteria for the successful use of any software-based applications supporting emergency management is considered as the ability of the software to facilitate its end-users by providing the right information at the right time (Prasanna & Huggins, 2016; Rosato et al., 2016; Yang et al., 2014). The end-users as decision-makers usually face a few to more than hundreds of choices of decisions and they must narrow down the possible choices to a reasonable number. Decision support using a well-defined knowledge-base can be useful for decision-makers to choose the best option from a variety of available choices of decisions (Osatuyi & Andoh-Baidoo, 2014). Computers can use the support of some prebuilt algorithms to evaluate the scenarios and then assist the decision-making capabilities of the decision-makers by presenting a variety of alternative options in the form of knowledge (Anzaldi et al., 2014). The sophisticated analysis provided by a knowledge-base can become an important factor in making more accurate and valuable decisions (Shaofeng Liu & Zaraté, 2014; Müller et al., 2019). Therefore, a well-defined and properly structured implementation of the conceptual framework by using a KCDSS can assist the researchers and relevant decision-makers to get new ideas and find areas of strengths and weaknesses in their built systems. This can lead to exploring new system requirements and making further refinements and improvements to their frameworks. Therefore, the second artefact of this study is accomplished by developing a KCDSS as a completely customizable support tool for decision-making. With the support of this decision support tool, the end-users of this KCDSS will be able to test and verify various recovery strategies for interdependent CI networks.

5.2 Architecture of KCDSS

It is a complex and computationally intensive process to analyse and understand the performance of CI network while handling a myriad of information and data including (i) structure of the CI network and the dependencies existing between their components; (ii) different severity levels of damage sustained by the CI network components; (iii) their respective service recovery times; (iv) road access times to the damaged site from the locations of resource availability; (v) order and priority of recovery of service over the distributed region; and (vi) ability to test various 'what-if' scenarios with adding/removing network components in a simulation-based approach.

To address and accommodate all the above-mentioned needs, this study developed and demonstrated a computer-based KCDSS through a three-tier client-server software architecture pattern (Schuldt, 2009). In a traditional one-tier architecture, all the required components of a software application including user interface, central core logic or middleware and back-end data are on a single server or platform (Schuldt, 2009; Taylor, 1998). Two-tier architecture decouples the back-end data from middleware and user interface but the latter two are still bound together within the same platform. Both one-tier and two-tier architectures do not perform well for software applications that require the complex processing of a huge amount of data. With the growing needs of technology, sometimes there is a need to convert the desktop applications into web-based or mobile-based applications that needs modified design of the user interface. These changes in one-tier and two-tier architectures need a lot of modifications in the middleware as well (Du Bois, 2013). Three-tier architecture resolves these problems as each tier is developed and maintained as an independent module, which includes: (i) the presentation tier (user interface layer) in which input and output data of the CI networks is operated; (ii) business logic tier (application processing layer) which accommodates functions for analysing network performance and computing the outputs; and (iii) data tier (database and knowledge layers) in which CI network component's properties, their damage states and knowledge-base of recovery strategies are stored to support the other two tiers. The benefit of using a three-tier architecture to develop the KCDSS is that any of these tiers can be modified or replaced independently due to the changes of circumstances and user needs without affecting the other tiers (Shamsaie et al., 2007). A short description of each tier is listed below:

a) **The presentation tier** mainly deals with user interfaces and translates tasks and results to something meaningful for the end-users. This tier displays information related to services like network design and updating, map building, scenario creation and visualization of the results. In simple terms, it is the layer which the end-users can access directly (such as a web page, or an operating system's graphical user interface (GUI)) (Ramirez, 2000).

b) **The business logic tier** moves and processes data between the two surrounding tiers through the processing of different commands and calculations, coordination with the application tasks that will allow it to make logical decisions and evaluate the results. The business logic tier can also function independently from the presentation tier and can still control the software application and perform the detailed processing tasks (Schuldt, 2009).

c) **The data tier** enables the end-users to store and retrieve key information related to the important components of the application from the database and related knowledge from the knowledge-base. The information is then passed back to the business logic tier for processing, and the results can be linked to the presentation tier for visualisation (Wijegunaratne & Fernandez, 1998).

The next section provides details of the implementation of the KCDSS. It first specifies the software tools used for the implementation, and then it presents the overall implementation process based on the three-tier architecture platform, which provided a modularization to simplify the implementation process. In this regard, this section suggests the appropriate technologies and the software development techniques required for the KCDSS implementation following the characteristics and requirements of each layer of the three-tier architecture.

5.3 Implementation of KCDSS

For the development of web applications and even desktop applications, front-end and back-end technologies go side by side. Nowadays, software development is evolving rapidly that needs a combination of different technologies to build just a single software application (Du Bois, 2013). Therefore, the software developers intending to develop dynamic web-based applications have tedious work to integrate Hypertext Markup Language (HTML) codes with server-side programming languages (Pop & Altar, 2014). The same process is needed for developing other complex applications that need a whole team of skilled developers (Zlatev et al., 2013). Each developer in the team chooses a domain of speciality, such as JavaScript for client-side interaction; HTML and CSS for developing visualisation tools of the presentation tier; C#, Java, Python, PHP, ASP, etc., for developing server-side logic and Microsoft SQL Server, Oracle Database or MySQL for storing and management of databases and knowledge-bases. While working in a team, these software developers need to work efficiently so that their codes fit the overall design of the software application.

Typically, the user interface can be accessed on a desktop computer or a web-based GUI. Business logic uses an application server or a web server to execute its various modules that can store and retrieve information from a relational database management system (RDBMS) through a database server. Therefore, from the software implementation point of view, the KCDSS developed in this study runs on an environment consisting of a web server, application server and database server. A summary of the functionalities of these three servers is listed below:

1. A **client computer** or **web browser** has the front-end user interface through which the decision-makers can have access to the KCDSS.
2. A front-end **web server** receives Hypertext Transfer Protocol (HTTP) requests from the presentation tier and renders the static or dynamically generated HTML results back to the user interface.
3. An **application server** containing software codes and visualization styles to do dynamic content processing.
4. A back-end **database server or data store** built on datasets and the Database Management System (DBMS) software to store and retrieve the required information from the database and knowledge-base.

The business logic tier is the middle tier between the presentation tier and the data tier operating through a web server and an application server. The KCDSS is implemented as a web-based application in which the users make their requests through a *web (client) browser* and the business logic tier uses its *web server* to transfer user requests to the *application server*. The application server then invokes the queries for the data tier, which runs on a *database server* and consists of a DBMS to access all the datasets stored in the database. The database server retrieves the information that was requested from the database and returns the result to the application server. This flow of information between the different components is illustrated in Figure 5-1.

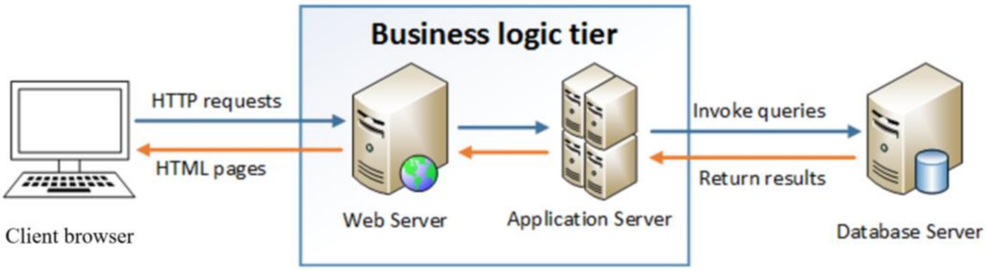

Figure 5-1. Flow of information in the KCDSS architecture (Source: Shamsaie et al., 2007)

There are some application design paradigms and patterns that support the three-tier architecture design by providing the supporting tools to separate various components of the software being developed. Some of the most popular design patterns are Model-View-Controller (MVC), Model-View-Presenter (MVP) and Presentation-Abstraction-Control (PAC) patterns (Voorhees, 2020). These three application design paradigms support the three-tier architecture design by providing the support for separating different components of the software being developed. Software developers can choose any of these according to the relevance with the software development features and needs and goals of their study (Pop & Altar, 2014).

In this study, the researcher had to develop all components of the KCDSS by himself through: a) a proper storage mechanism for database and knowledgebase; b) interactive visualisation tools for the presentation tier; and c) control of all the application processes through the implementation of the designed algorithms in the business logic tier. This process needed careful management of different types of software codes by separating the presentation tier from the business logic and data storage of the KCDSS. Therefore, based on these objectives and software development needs, the researcher has chosen the MVC pattern for the software development of the KCDSS. MVC was originally formulated by Trygve Reenskaug (1979) into the Smalltalk-76 programming system. An MVC pattern is a software design architecture in which the business logic can be isolated from the presentation and data tiers (Krasner & Pope, 1988). As this study involved a large amount of CI network data and the knowledge-base of recovery strategies for the damaged components of the CI networks to model the CI network interdependencies, this isolation between the three tiers significantly improved the efficiency of the KCDSS and made its maintenance easier. The MVC pattern can also be integrated with the three-tier architecture model according to the specific software design. The three-tier architecture for this study is depicted in Figure 5-2, and a brief discussion of three modules of the MVC pattern is presented afterwards.

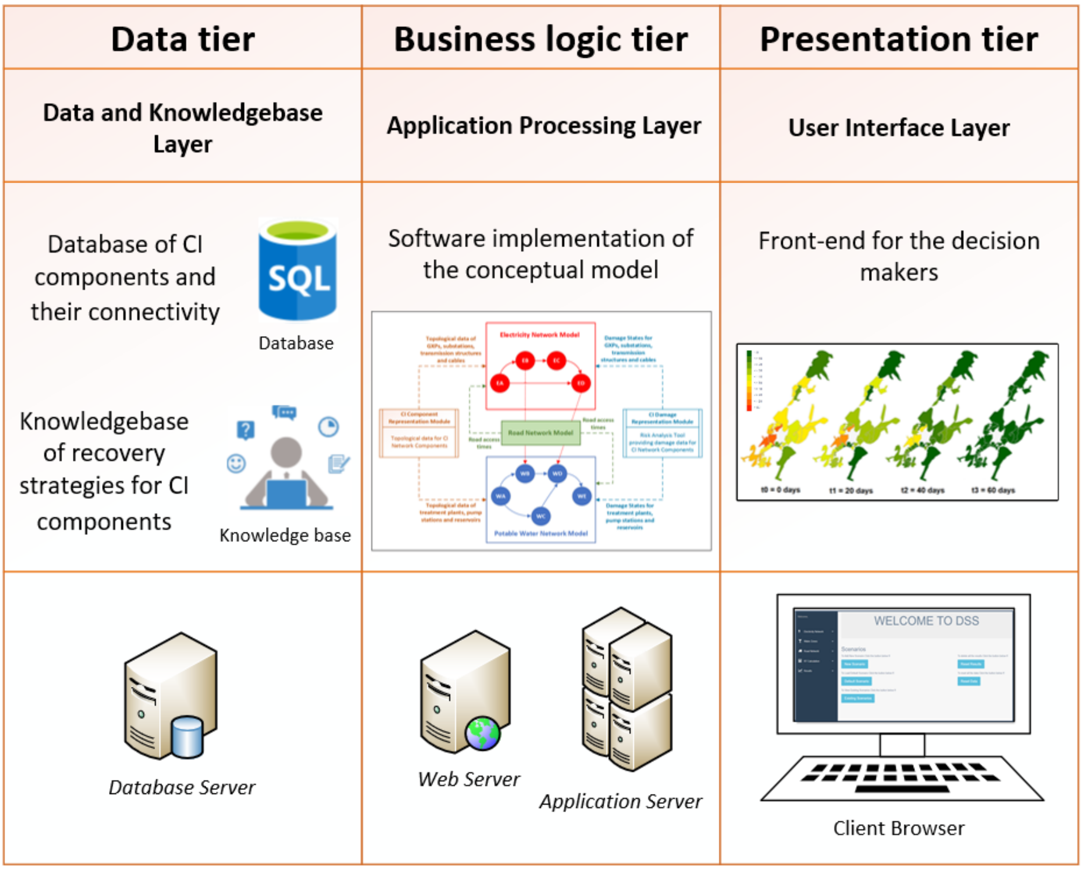

Figure 5-2. Three-tier architecture design with MVC modules

a) **The Model** is responsible for the data and knowledge management routines that are used to execute the operations to create, read, update, and delete the data within the database (Kantartzis & Malesios, 2018). A model contains all the application's business logic, validation logic, and database access logic that cannot be managed through a view or a controller. A Model is responsible for managing the data objects and real-world entities along with their characteristics, states of operation and their mapping with application states (Maria, 1997).

b) **The View** represents the presentation layer and is responsible to provide a visualization mechanism through graphical interfaces. It is responsible to retrieve the required data from the model into a form suitable for user interaction, and normally contains HTML content that is transferred to the web browser for display. A view is like a single displayed page, which contains HTML contents and scripts being written in some other scripting programming languages, for example, C# or Visual Basic.NET. The view also takes notes of any changes to the presented data entities and posts the data back to the controller, which updates the data objects behind the scenes. The view represents the entire web application to the user and is a critical part of the software application where collaborative development is needed (Krasner & Pope, 1988).

c) **The Controller** holds the business logic of the application and works between the model and view of the MVC pattern (Farshidi et al., 2018). It is responsible for controlling the way a user interacts with a software application. It receives user inputs from the view, passes them to the model, receives results from the model and sends them back to the view. The controller is therefore the entry point into a software application and interacts directly with the user actions. It also manages the model updates by updating the data objects via the database (Pop & Altar, 2014).

The KCDSS has eventually been developed using a three-layer architecture with layering in ASP.NET MVC 5 with Entity Framework and SQL Server. The ASP.NET MVC framework is a lightweight, open-source, object-oriented and highly testable presentation framework that is optimized to be used with ASP.NET. It provides a pattern-based way to build dynamic applications that enables a clean separation of concerns (Pop & Altar, 2014). The server-side coding and web application development are carried out in Microsoft Visual Studio IDE. The first step to creating a web application involves the implementation of a three-tier architecture in ASP.NET MVC with Entity Framework involving Language-Integrated Queries (LINQ) to access the Relational Database Management System (RDBMS) through stored procedures. Stored procedures enhance the flexibility of system design, support data layer simplification and improve the efficiency in the implementation of the application (Shushu Liu, 2010). The results of database and knowledge-base queries are displayed using Microsoft ASP.NET AJAX tools. The user interface design of the application is implemented using a responsive bootstrap template. The following sections detail the implementation of each of the three tiers.

5.3.1 Data tier

The Entity Framework (EF) code-first approach is utilized in this study to design the data tier. Software coding is done in C#.NET and then EF approach is used to further create the database from the code. In the code-first approach, classes are first created for the domain entity and with the help of code-based migration, the database schema is created or updated in the SQL server. Data is stored in two different components: the database and the knowledge-base. The database contains the topology and damage data of the CI network components, whereas, the knowledge-base contains various recovery strategies acquired from the relevant experts for disrupted CI networks. These components are individually discussed in the next sections.

5.3.1.1 Database component

The database component is an essential part of the data tier as it provides the basic structure to organize all the topological and damage data of the CI components to make it useful for CI network functionality assessment. Therefore, a properly built database component stabilizes and organizes the input data and can be extended in future to include more data from additional CI networks. It allows the development of a flexible and customizable KCDSS by providing support for new features. The database component in this study includes the topological data that includes the configuration and connectivity of the CI network components. It also includes the damage data that stores the damage states of different components of the CI networks. The relationships between the entities in the KCDSS are illustrated through Entity-Relationship (ER) modelling (Bagui & Earp, 2003). ER modelling has been a popular database modelling technique that describes data as *entities*, *attributes*, and *relationships* between them.

An *entity* can be defined as an object that has a physical existence, such as a substation, an electricity cable, a pump station. It can also be an object with a conceptual existence, such as a CI network's outage results. Each entity has certain properties that are known as *attributes*. For example, a substation in this study has been described by its name, location, capacity, type, etc. A database usually contains groups of entities that are similar. For example, an electricity network database would contain its components of substations, GXPs, cables and transmission structures as different entities. Within a substation entity, there can be many individual substations that share the same attribute types but have their values within those attributes. A *relationship* is used to define the dependencies between two or more entities. Relationships in ER modelling are represented through cardinalities, which are numerical attributes of the relationship between two entities or entity sets (Chen, 2002). These cardinalities represent:

- **a) one-to-one relationship,** in which one entity from entity set *X* can be associated with exactly one entity of entity set *Y*, and vice versa;
- **b) one-to-many relationship,** in which an entity from entity set *X* can be associated with multiple entities of an entity set *Y*, but an entity from entity set *Y* can only be associated with one entity of entity set *X;* or
- **c) many-to-many relationship,** in which one entity from entity set *X* can be associated with more than one entity from entity set *Y* and vice versa (Bagui & Earp, 2003).

There have been several ER diagrams generated between different database tables for this study. An example ER diagram with entities, attributes and relationships between the modelled CI networks is shown in Figure 5-3. The entities are written as the title of the different tables, for example, Stations, Reservoirs, Roadzones, etc. Attributes are the parameters or properties of each of the tables and are listed inside the blocks, for example, Id, Name, Detail, RoadZoneId, etc. All these tables are connected through lines representing their relationships. In this study, only one-to-many relationships are used. An example of such a relationship can be seen between reservoirs and road zones. A road zone can have many reservoirs, but every single reservoir is only associated with one road zone. The key sign represents how the attributes are linked between two tables. In this case, the *Id* attribute of the *Roadzones* table is linked to the *Reservoirs* table as *RoadZoneId*. These ER diagrams are developed based on the interdependency relationships between the three CI networks (discussed in Chapter 4) and form a basis for the implementation of the core functionality of the KCDSS.

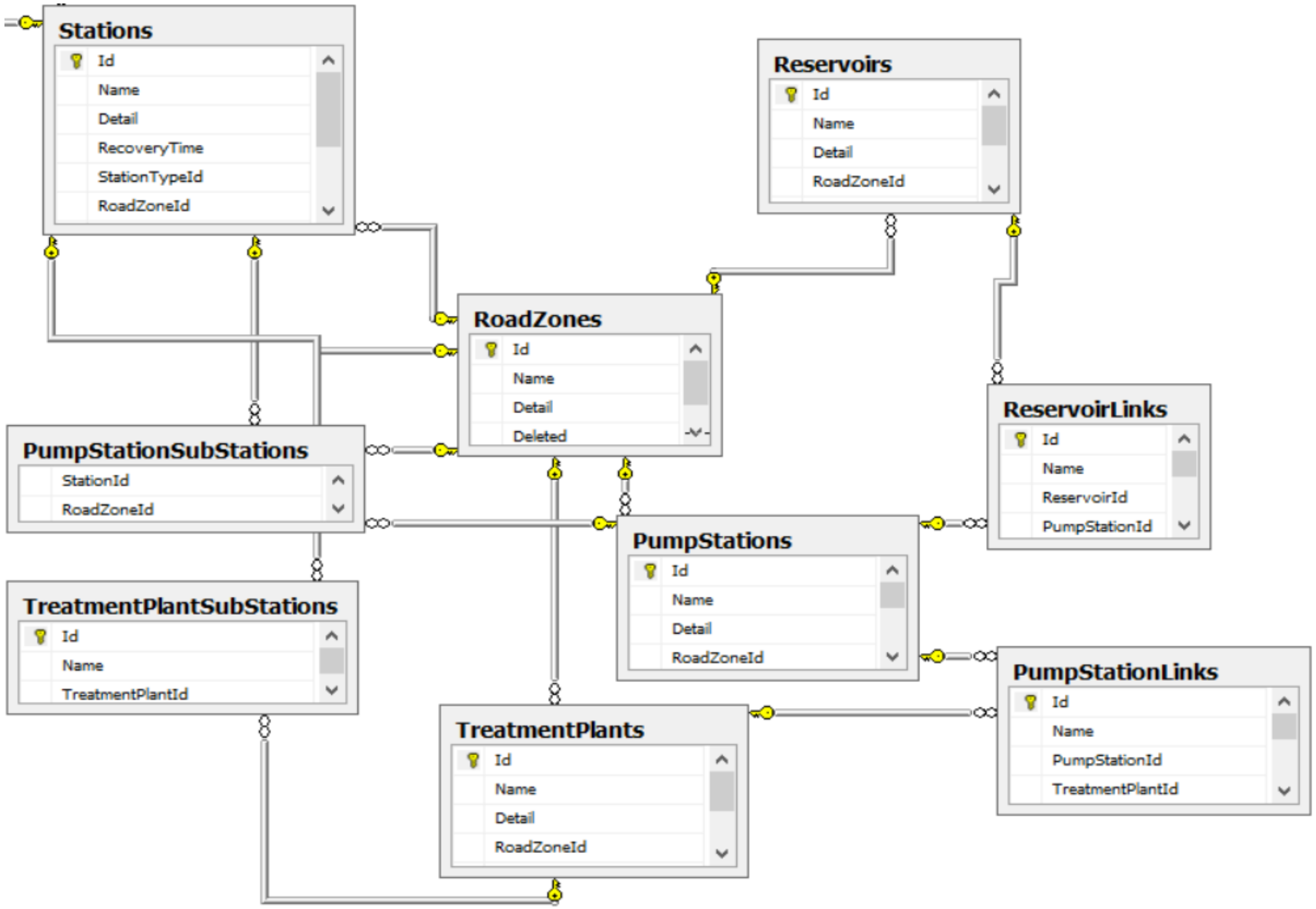

Figure 5-3. ER Diagram: electricity, potable water and road network database

5.3.1.2 Knowledge-base component

As mentioned earlier, the primary aim for developing a KCDSS was to utilize a knowledge-base platform through elicitation and sharing of experts' knowledge. The knowledge-base in this context is populated with effective recovery procedures of damaged CI network components. Therefore, the development of the knowledge-base component is the fundamental part of the KCDSS to carry out the recovery process of damaged CI components. It is important to understand that the knowledge-base does not replace the decision-makers by making decisions by itself, but rather provides appropriate strategic information in a timely, efficient, well-organized and easy-to-access format that allows the decision-makers to make informed decisions (Shaofeng Liu & Zaraté, 2014). The knowledge-base within the KCDSS is designed through a knowledge management process to assist the decision-makers in recognizing the recovery procedures for CI network components, which allows proper management of the available resources. The main components of the knowledge management process are shown in Figure 5-4.

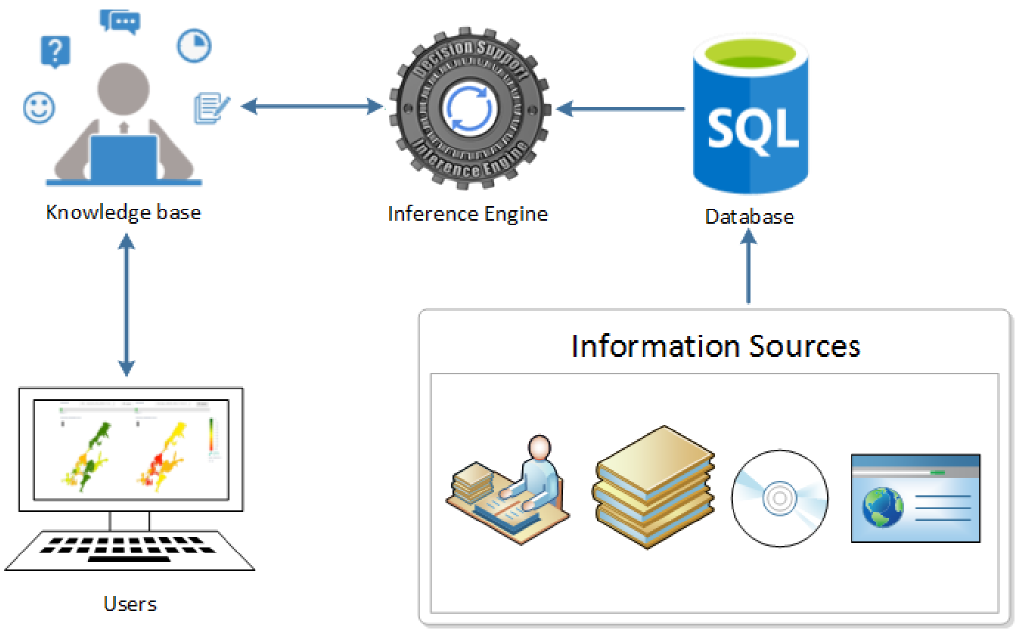

Figure 5-4. Main components of the knowledge management process

As discussed in the previous section, the topological data of CI network components is stored in the database component that needs to be integrated with the knowledge-base of repair strategies from the knowledge-base component to provide useful information for enhancing decision-making. This knowledge-base is then retrieved by an inference engine that performs a reasoning process on the stored knowledge to draw conclusions about the available recovery options. The important aspect of the inference engine is that it strengthens the KCDSS through an ability to infer new recovery strategies depending on the different varieties of damage data. This process is discussed in detail in Section 5.3.1.3. The knowledge-base has been developed through the elicitation of recovery strategies from road and electricity network providers in the Wellington region. Some other information sources included past and recent studies, existing literature and ongoing work by different model developers within New Zealand and around the world. Using a knowledge-base, the KCDSS provides customizable options for the repair of CI network components, prioritization of the recovery tasks for critical components and an ability to test various 'what-if' scenarios with adding/removing network components. A brief description of the knowledge elicitation process is explained in the next section.

a) Data collection of recovery strategies from CI network providers

Although the topological and damage data collected for CI network components and discussed in the previous chapter gives an understanding of the basic characteristics, connectivity and a process to model damage to the selected CI network. But there is also a need to properly utilize this data by understanding the process of repairing the damaged CI network components and estimating the time needed for recovery of CI network services. This process involves another phase of data collection to understand various recovery strategies of the relevant stakeholders, which in this case were electricity and road network providers. A similar process can be adopted in future for potable water network, by replacing the placeholder topological and damage data with real data. Experts from regional potable water network can also be involved to understand region-specific recovery strategies for the damaged components.

The main purpose of having a successful stakeholder involvement is to create an opportunity for all the participants to discuss solution possibilities. There were several challenges during the engagement with experts from electricity and road networks in the Wellington region, as the network providers used their storage mechanisms, data formats and have varying attribute properties for their CI network data. Each type of the modelled CI network required a different modelling mechanism due to the varying nature of its constituent components and the involved complexities of restoration procedures. The elicitation of recovery strategies from the selected participants was useful for the researcher to understand available resources and personnel within the selected CI network providers, access to the repair equipment, specific regional needs to prioritize repairs of certain critical facilities and any alternate plans for a faster recovery process. The selected participants belonged to Wellington Electricity (WE), Waka Kotahi NZ Transport Agency, Transpower NZ and Wellington lifeline utility group (WeLG) and they were selected based on their ranks/positions and through peer nomination. An agenda was sent before the interviews to the participants with a list of questions and a brief introduction about the knowledge elicitation process (see Appendix B). A summary of the selected participants is presented in Table 5-1:

Table 5-1. Summary of selected participants

Characteristics	Description
Total participants	Two from WE and Waka Kotahi NZ Transport Agency and one each from Transpower NZ and WeLG
Interview duration	Each interview lasted around 60 to 90 minutes
Years of experience	All the experts had more than 15 years of experience in their respective fields.
Industries represented	Emergency response and recovery, lifeline group, lifeline utility providers and emergency management research.
Professions of experts	Asset engineer, senior asset manager, senior engineer, manager risk and assurance and lifeline utility controller

The knowledge elicitation process gave insights about the CI network recovery strategies in a structured format, which was then transferred into the KCDSS to provide training and decision aiding facilities to the decision-makers. In this study, the researcher has used the Critical Decision Method (CDM) which is a type of Cognitive Task Analysis (CTA) technique for the knowledge elicitation (Klein et al., 1989). CDM is a modified version of the Critical Incident Technique (CIT), a work by Flanagan (1954) through a case-based knowledge elicitation strategy. Many researchers have adapted Flanagan’s early work, but the most popular and successful conceptual adaption was done by Klein et al. (1989), who defined the CDM as “a retrospective interview strategy that applies a set of cognitive probes to actual non-routine incidents that required expert judgment or decision making” (Klein et al., 1989, p. 264).

The knowledge elicitation process with usual interviews generally has a voluminous amount of data which is then transcribed with additional efforts. Researchers working in non-routine decision-making environments prefer to use CDM, as it provides a useful mechanism for elicitation of human knowledge and decision-making tasks (Wong, 2004). CDM provides a structured knowledge elicitation strategy, which starts with a narration of the past event by the participant. The interviewer then asks more questions to identify decision points and sketch a timeline of different events narrated by the participant. The benefit of using the CDM technique is to have a detailed investigation of the incident during the interview and the researcher usually do not need to transcribe a large amount of data afterwards. For example, in the case of identification of recovery strategies for damaged CI network components, after the initial description of a past event, the researcher further investigated why a certain decision was made for the narrated situation and the objectives achieved by applying a recovery strategy. Therefore, the CDM provides a better representation of a past event with details about the causes, effects and solution mechanisms adopted by the relevant decision-makers (Hoffman et al., 1998). Participants were first asked to narrate a challenging CI network recovery incident. A hypothetical earthquake hazard scenario for electricity and road networks in the Wellington region was presented to the participants to identify their possible actions, procedures, and relevant decisions. The scenario was:

> Briefly explain what you would do if you are informed about an electricity outage in multiple locations after an earthquake in the region. You have to make decisions about the management of your available resources and the initial steps needed for the recovery process.

Participants narrated a past challenging event from start to finish with a detailed description of the sequential tasks and courses of actions. The researcher sketched a timeline to graphically design the different events and the decision action points. The participants gave continuous feedback at the points where any changes were needed in the sketching of the timeline. Therefore, the important information, relevant decisions and appropriate actions for the narrated event were all elicited during the interview and because of the paper-based timeline, the participants also responded interactively. The procedure of analysing the elicited knowledge of recovery strategies is discussed in the following section.

b) Data analysis

Wong (2004) proposed two methods to analyse the collected data through CDM and suggested that researchers can apply the analysis method according to the research objectives of a study. The studies that have clear concepts about the research problem and the datasets are not based on just the observations or personal experiences but rather involve a theoretical deduction, are analysed through a *structured approach*. On the other hand, the studies where the classification of data and the concepts are unclear, an exploratory *emergent themes approach* is more suitable (Harenčárová, 2015). Both the approaches provide a different perspective of the data and as this study had a priori theoretical concept of CI network component recovery modelling, therefore, the structured approach was more suitable for this study. Wong (2004) proposed a step-by-step guideline for the researchers who use the structured approach.

The first step of this guideline is to create a decision chart to illustrate the decision process adopted by the participants on a timeline. Timelines are usually sketched on a paper during the knowledge elicitation process to make it easier for the participants to remember and indicate their key decisions along the timeline. The second step is to create a narrative-based incident summary to elaborate the timeline design in a more meaningful way. The third step is to make decision analysis tables through the identification of goals and strategies from the first two steps. Based on the type of research, if the data is collected from multiple types of incidents then additional steps are needed to organize and compare the items of interest for each incident. For this study, only the first three steps were needed as the data collection was done for elicitation of recovery strategies for a single hazard scenario of the Wellington region. Figure 5-5 provides an overview of this structured analysis process, followed by a brief description of the three steps.

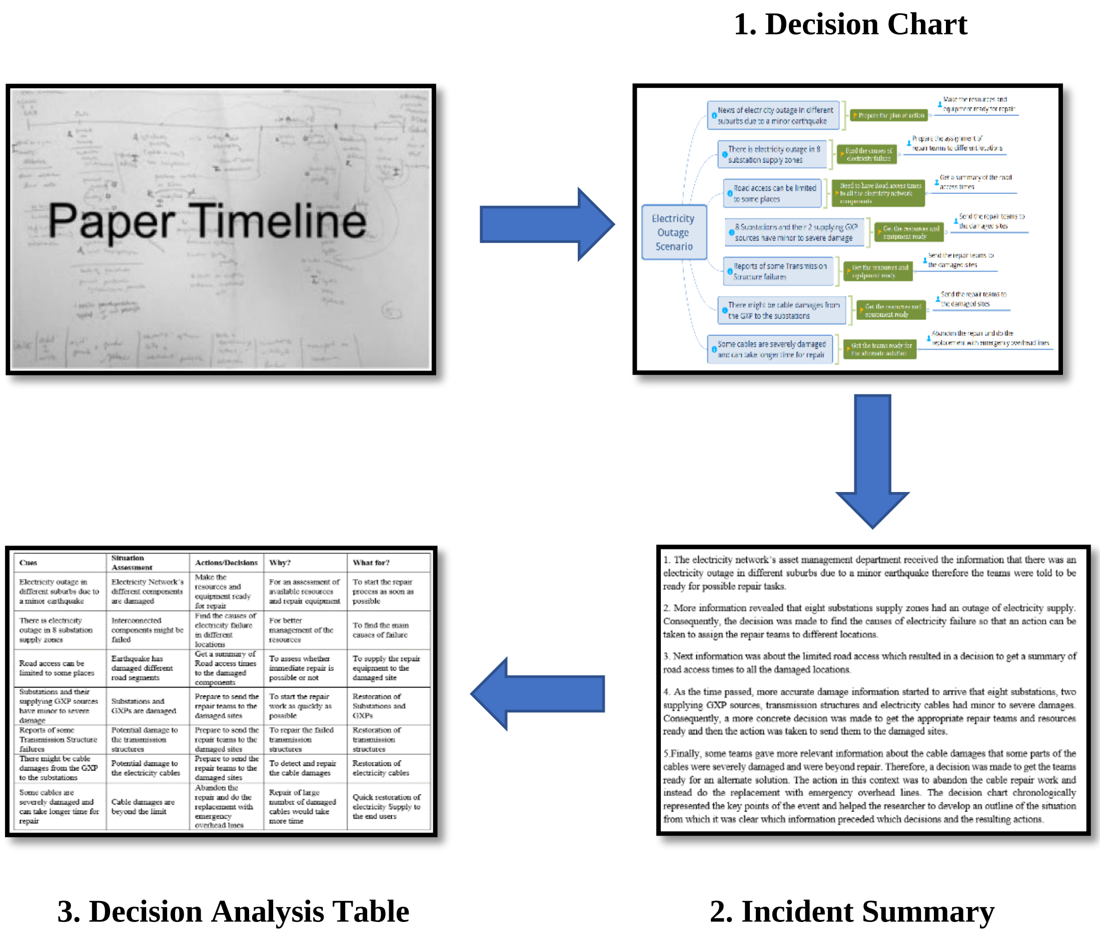

Figure 5-5. Steps of the structured analysis of CDM data.

Step 1: Decision chart

To save time and effort, researchers using CDM draw the timeline on a paper during the interviews and take further feedback from the participants to verify that they have correctly identified all the decision points. This process saves their time for transcribing a huge amount of elicited knowledge after the interviews. Instead, they transform the paper timeline into a decision chart that organizes all the events chronologically to give a visual representation of the details gathered through the interviews. Therefore the first step in this study was to create a decision chart from the timeline using a mind mapping software named XMind (XMind, n.d.). Figure 5-6 shows the decision chart with the chronological structure of the events and summarizes the three types of points of interest, i.e. information, decision, and action.

The first information received by the CI network providers was the electricity outage in different suburbs due to an earthquake event. The next point was the decision to prepare the plan of action. This decision was followed by the action to make the resources and equipment ready for repair. The next information was more specific where: eight substations supply zones had an outage of electricity supply. Consequently, the decision was made to find the causes of electricity failure so that action can be taken to assign the repair teams to different locations. The next information was about the limited road access, which resulted in a decision to get a summary of road access times to all the damaged locations. As time passed, more accurate damage information started to arrive that eight substations, two supplying GXP sources, transmission structures and electricity cables had minor to severe damage. Consequently, a more concrete decision was made to get the appropriate repair teams and resources ready and then the action was taken to send them to the damaged sites. Finally, some teams gave more relevant information about the cable damage that some parts of the cables were severely damaged and were beyond repair. Therefore, a decision was made to get the teams ready for an alternative solution. The action in this context was to abandon the cable repair work and instead do the replacement with emergency overhead circuits.

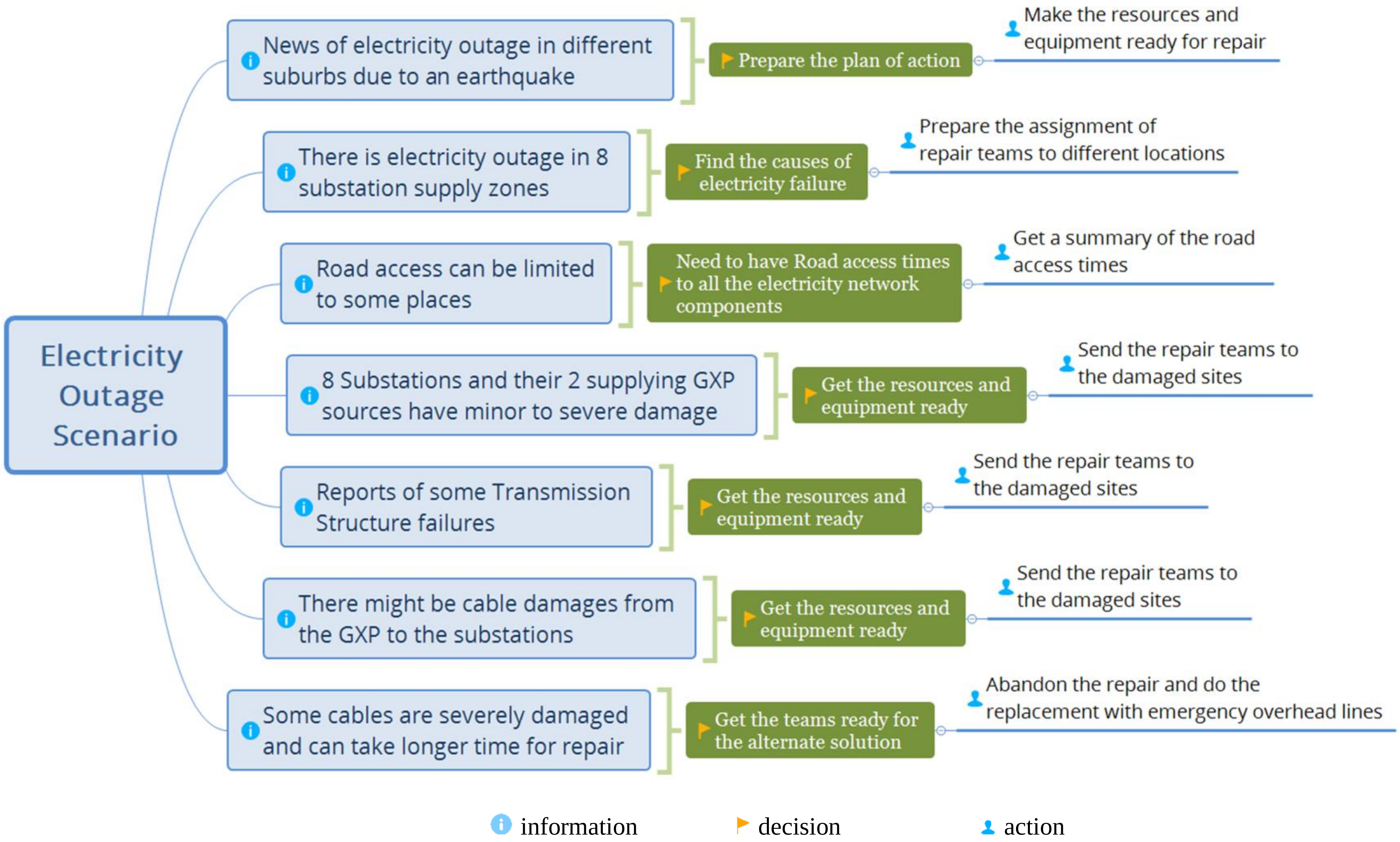

Figure 5-6. Decision chart with the chronological structure of the events summarized as information, decision, and action.

Step 2: Incident summary

The decision chart chronologically represented the key points of the event and was therefore helpful to create an understanding of the situation and the researcher was able to create an outline to show the relevant information followed by the undertaken decisions and the resulting actions. The incident summary provides a better narration of the decision points and includes any related assumptions. Some of these assumptions include practical limitations on the execution of restoration activities, including:

- **Scope of network components being modelled:** For the electricity network modelling, the modelling scope was limited to transmission network from generation units to the substation level and the network performance in terms of recovery time was computed and represented as 'outage time' for supply zones of substations (33kV). For the recovery of components in the distribution network (below 33kV), a predefined restoration time was assumed in consultation with clients.
- **Locations of resource availability:** The majority of necessary skilled resources and associated repair equipment/ material was assumed to be locally available, and there would be enough repair staff as required to undertake restoration work in multiple locations at a time. After the initial response phase, more repair staff will be available to reduce the remaining recovery time according to the amount of newly available resources.
- **Estimated repair time of components:** The repair times and preferred strategies for various types of electrical cables were obtained in consultation with experts and other sources. For example, the repair of Paper Insulated Aluminium Sheathed (PIAS) and cross-linked polyethylene (XLPE) may be different, because some of these cables were solid fluid-filled and were harder to repair (Giovinazzi et al., 2017). Further details on practical constraints for repairing these cables as modelled include:
  - Solid insulated cables (for example, XLPE and PILCA) take three days per fault to repair with two repairs possible to be done on a circuit simultaneously. These cable circuits are abandoned if there are nine or more faults on the circuit;

    - Fluid-filled cables (for example, PIAS) are complex and need more time to repair. The first repair on a cable will take 15 days. The cable repair needs to be abandoned if there is more than one cable fault on the circuit;
    - For the circuits whose repair works are abandoned, there was an alternate plan to replace the cable circuits with emergency overhead circuits. Their construction from source GXP to target substation needs 20 days and four circuits can be built in parallel. According to Wellington Electricity, more help in terms of hardware and line staff is likely to arrive in the region very soon, so it is assumed that after the first four emergency overhead circuits, all the remaining circuits can be built in the next 20 days;
- **Priority and order of recovery for electricity supply zones:** The supply zones identified with a higher order of priority by the experts are recovered first by using emergency overhead circuits. These priorities were based on the significance of the facilities located in different electricity supply zones. For example, some of the critical facilities such as hospitals, fire brigade offices, police stations and other emergency management organisations have the highest priority for the restoration of CI network services.
- **Road access time:** The road outage times are represented in a matrix with the assumed number of days between one zone to the others during the response and recovery stages after an event. As discussed in Chapter 4, every component of the electricity network is mapped with an associated road zone. This is required to account for the access time to reach the location of the damaged component.

Both the decision chart and incident summary properly organized the information, decision and actions during the recovery procedures and were therefore helpful to give a brief and clear description of the situation. These two steps form the basis of developing the decision analysis table to organize the collected data for knowledge modelling.

Step 3: Decision analysis table

The previous two steps give a useful guide to the recovery situation narrated by the experts. They provided a structured approach to filter important information, action, and decisions that lead to the recovery of damaged CI network components. This structured data, therefore, formed the basis for designing the decision analysis table. The first column of the decision chart contains cues, which are the information part of the decision chart. The second column contains a situation assessment that gives relevant situational characteristics of the cues. The third column lists the actions and decisions that were identified in the decision chart. The fourth and fifth columns of the decision analysis table provide additional information about the reasons (Why?) and the goals (What for?) of all the actions and decisions made due to particular information in the different recovery management situations. In this way, the decision analysis table, demonstrated in Table 5-2, links the information with the undertaken decisions and the resulting actions along with their reasons and goals. There were four important cues in the decision analysis table that are summarized based on the information listed in the decision chart. These cues are:

1. Electricity outage in eight substation supply zones due to an earthquake event. The situational assessment revealed that there would be some damage to the electricity network's components. Based on this information, the Actions/Decisions column contains the decisions of making the repair teams and resources ready and to find the causes of electricity failure as a plan of action. The rationale for this decision was better management of the resources based on their availability, as shown in Why? Column of Table 5-2. The goals behind this decision and action were to find the main causes of failure and to start the repair work as soon as possible. These goals are shown in the last column of What for?

2. The second cue was the information about limited road access to some of the damaged sites. The situation assessment revealed that similar to the electricity network, there would be damage in the road network as well. An action was taken to get a summary of updated road access times to the damaged sites. The reason for this action, as shown in Why? column, was to assess whether the immediate repair was possible or not so that the repair equipment and staff can be allocated to the sites where the road access was available.

Table 5-2. The decision analysis table with structured data of elicited recovery strategies using CDM

Cues	Situation assessment	Actions/Decisions	Why?	What for?
Electricity outage in different suburbs due to an earthquake event	Electricity Network's different components are damaged	Make the resources and equipment ready for repair	For an assessment of available resources and repair equipment	To start the repair process as soon as possible
There is electricity outage in eight substation supply zones	Interconnected components might be failed	Find the causes of electricity outages in different locations	For better management of the resources	To find the main causes of failure
Road access can be limited to some places	An earthquake has damaged different road segments	Get a summary of Road access times to the damaged components	To assess whether immediate repair is possible or not	To supply the repair equipment to the damaged site
Substations and their supplying GXP sources have minor to severe damage	Substations and GXPs are damaged	Prepare to send the repair teams to the damaged sites	To start the repair work as quickly as possible	Restoration of Substations and GXPs
Reports of some Transmission Structure failures	Potential damage to the transmission structures	Prepare to send the repair teams to the damaged sites	To repair the failed transmission structures	Restoration of transmission structures
There might be cable damage from the GXP to the substations	Potential damage to the electricity cables	Prepare to send the repair teams to the damaged sites	To detect and repair the cable damage	Restoration of electricity cables
Some cables are severely damaged and can take a longer time to repair	Cable damage is beyond the limit	Abandon the repair and do the replacement with emergency overhead circuits	Repair of a large number of damaged cables would take more time	Quick restoration of electricity supply to the end-users

3. Later, some more accurate information revealed the exact amount of damage to the substations, GXPs, transmission structures and electricity cables. This information was helpful to make informed decisions for assigning the appropriate number of people and amount of repair resources to the damaged sites. These decisions and actions were critical for starting the repair work as soon as possible for the restoration of electricity services.
4. The final cue revealed that some of the electricity cables had too much damage and the situational assessment showed that this cable damage was beyond the limit of maximum damage that can be repaired. Therefore, the appropriate decision and plan of action were to abandon the repair work and do the cable replacement with emergency overhead circuits. This action was taken to restore the electricity services as quickly as possible.

The structured approach to analyse the CDM data proved to be useful to effectively organize a large amount of data. It will also be useful when real data of potable water network will be available as similar steps will be needed to do the knowledge elicitation from the relevant decision-makers. The three steps of this structured approach guided the researcher to properly gather the required recovery strategies from the experts in such a way that the timeline of the situation was constructed along with the interviews. This process was also helpful for the experts to give feedback for improvements on the identification of all the decision points. The digitized version of the timeline in the form of XMind based decision chart was even more structured and easily understandable by the experts. Based on their further feedback for the information, decisions and actions of the decision chart, the researcher was able to create the decision analysis table to understand experts' logic behind different actions and the decisions and to link the cues, goals, and reasons to these decisions/actions in a structured way to do the knowledge modelling.

5.3.1.3 Knowledge modelling

The structured approach of analysis for CDM based expert knowledge provided useful support to organize the elicited knowledge in the decision chart and decision analysis table. This structured knowledge must be represented in a proper format so that it can become part of the KCDSS. Knowledge engineers use various reasoning techniques to represent the knowledge and this process is called knowledge modelling (Becu et al., 2003). The benefit of using KCDSSs as compared to conventional model-driven DSSs is their capability to present and model the knowledge. A model-driven DSS uses a predefined set of commands and instructions for providing decision support, whereas, a KCDSS uses its inference engine to retrieve useful knowledge from the knowledge-base in the form of rules or cases to simulate human reasoning. Therefore, a KCDSS supports the decision-makers more intelligently and interactively for solving their problems (Osatuyi & Andoh-Baidoo, 2014).

The reasoning techniques are integrated with the three-tier architecture of the KCDSS in such a way that the business logic tier manages, configures and combines different parts of the inference engine to provide useful decision-making support. Two of the most popular approaches for knowledge modelling are Case-Based Reasoning (CBR) and Rule-Based Reasoning (RBR). CBR uses machine-learning algorithms to find solutions for a problem in the database of past similar experiences. The alternate solutions for a given problem are defined as "cases" that consist of several variables in the database. CBR works on the reuse of existing knowledge and keeps improving it over time to provide a better problem-solving environment (Lu et al., 2016). On the other hand, RBR is one of the most popular knowledge modelling techniques in the field of artificial intelligence. RBR efficiently models human experts' reasoning and problem-solving knowledge through a set of rules that give a solution to the problem (Williams & Wood, 2015).

In this study, RBR is chosen for modelling the CDM knowledge because of the varying nature of recovery techniques of the damaged CI networks. The advantage of using RBR for this study is that the different rules for CI network recovery techniques are not dependent on historical data but rather based on observation, experiments and theory of the involved experts. Furthermore, modification and maintenance of the knowledge-base were also relatively easier to manage and these rules can be generalized for CI network data in other cities as well. RBR also provides a useful structure of IF-THEN statements to encode the human expert's reasoning. In this type of knowledge modelling, the experts' knowledge is represented through IF-THEN pairs.

In the context of this study, the IF condition of the rule carries the CI component (for example, an electricity cable) and related damage (for example, cable break), whereas, THEN part represents the consequence, decision or action (for example, an electricity outage or repair is needed) (Wang, 2013). The conclusion from this rule is that in case of an electricity cable failure, there is an electricity failure and consequently there is a need to find the cable fault to start the repair work. There are also some possibilities of having more than one IF condition, which is then listed using an AND part. Similarly, there can be multiple THEN sides that represent multiple decisions or actions taken for a specific situation. Whereas, in some situations, one IF condition does not work and an ELSE condition is used to differentiate the two conditions. An example of such a case is shown below:

IF the Substation is out of electricity,

AND the source GXP is working properly,

THEN identify the damage in electricity cables from GXP to the Substation,

AND identify the damage in transmission structures from GXP to the Substation,

ELSE find damage to GXPs other than the main source GXP.

The conclusion from this rule is if there is an electricity outage in a substation zone, and the supplying GXPs are working properly, then identify the connecting cables and transmission structures for any possible damage.

The IF-THEN rules designed for this study are based on the expert knowledge elicited and represented in the decision analysis table. From the elicited knowledge, different knowledge modules have been created that model the recovery process of the damaged CI network components. As the recovery strategies were elicited primarily from Wellington region's electricity network (WE and Transpower NZ) and road network (NZTA) providers, these knowledge modules represent the modelled knowledge for electricity network with its dependency on the road network. For the potable water network, similar knowledge of recovery strategies can be modelled in future.

Module 1: Knowledge-base module for the repair of damaged substations and GXPs

Based on the elicited knowledge from WE and Transpower NZ, the recovery of substations and GXPs depend on the estimated amount of their damage. As discussed in Chapter 4, the damage to these components is represented in different damage states. According to the elicited repair strategy from the participated experts, the damage states between 1 to 3 are considered as *minor damage* and, therefore, those components do not need any repair. Whereas, the damage states of 4 and 5 are considered as *severe damage* and therefore, the components in these damage states need immediate repair. Based on the detailed discussion, the formulated rules for the substation and GXP repair are:

IF component type is Substation,

AND Damage state is 4,

THEN Substation needs 3 days for repair,

AND add additional time for road access.

ELSE IF Damage state is 5,

THEN Substation needs 30 days for repair,

AND add additional time for road access,

ELSE Substation does not need repair.

IF component type is GXP,

AND Damage state is more than 3,

THEN GXP needs 4 days for repair,

AND add additional time for road access,

ELSE GXP does not need repair.

The repair work of these components is also dependent on the availability of road access. Therefore, the logical rules have also added road access times in the overall recovery time calculation of the substations and GXPs. The rule logics for the above-mentioned strategies are presented in the form of a flow chart in Figure 5-7

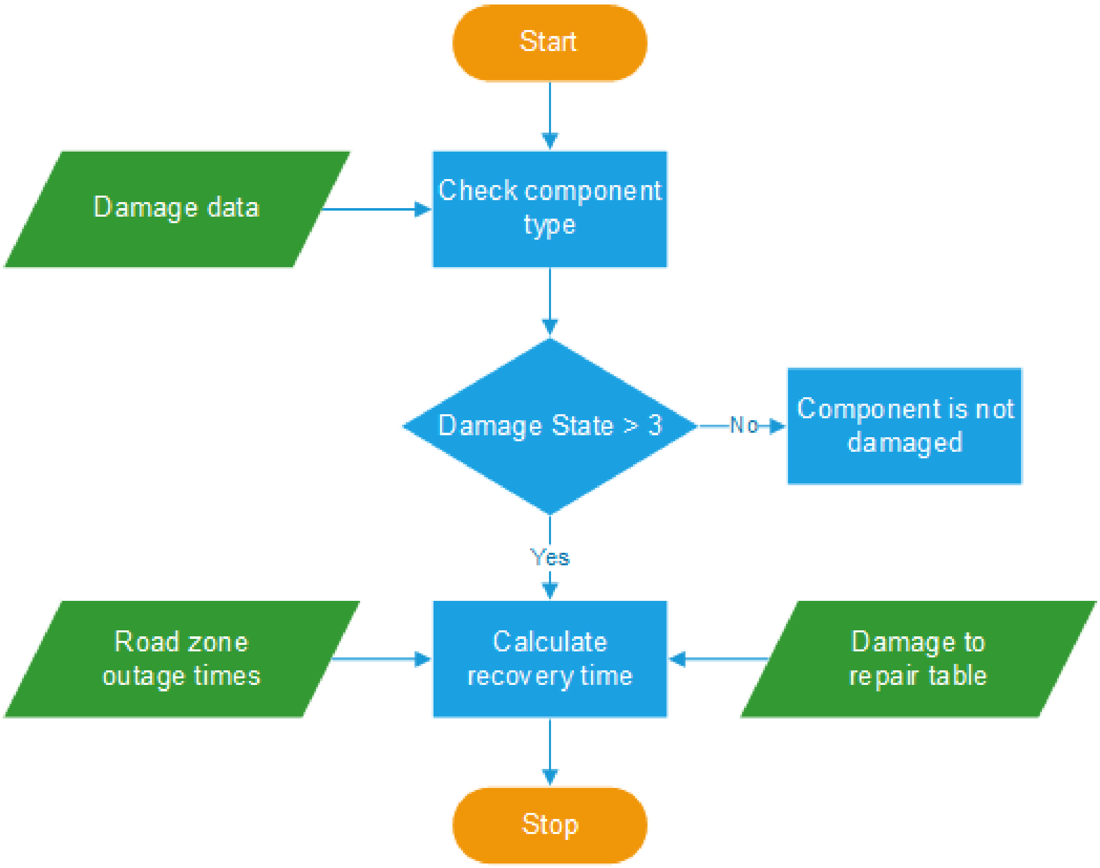

Figure 5-7. Flow chart for the recovery modelling of electricity substations and GXPs

Module 2: Knowledge-base module for the repair of damaged electricity cables

This section discusses the knowledge modelling of electricity cables that are the most critical and complex part of the whole modelling process. The algorithm for the creation of *cable links* and *cable routes* is discussed in Chapter 4 where it was identified that each link between a source GXP and the destination substation contains several cable segments. Furthermore, a detailed discussion was done on the handling of multiple cable links from a GXP to a substation. Based on the responses from the participated experts, the electricity cables with different material types have their respective repair methods and times. Therefore, the following rules have been designed for the repair of damaged cables:

IF component type is Cable,

AND Damage state of a cable segment is less than or equal to 3,

THEN Cable segment is not damaged,

ELSE Count damaged cable segments.

IF material type is XLPE,

AND the number of damaged cable segments is more than 8,

THEN damage is not repairable,

ELSE Check the damage to repair table to do the repair work,

AND add additional time for road access.

ELSE IF Material type is PIAS,

AND the number of damaged cable segments is more than 1,

THEN damage is not repairable,

ELSE Check the damage to repair table to do the repair work,

AND add additional time for road access.

These cables with different material types are also dependent on the availability of the repair personnel and the repair equipment. As the identification and repair of damage in a cable segment take some time, therefore, the cables with only a certain amount of damage can be repaired simultaneously. If the damage exceeds that limit, an alternate strategy is needed that has also been included in the decision analysis table. The alternate strategy is to replace the damaged cable segments with emergency overhead circuits. As this cable replacement work also needs a lot of resources and repair staff, therefore, according to the experts' estimation, only four such circuits can be replaced at a time. The first four circuits are installed in the places where the top prioritized critical facilities are located. Therefore, all the substation zones were given a priority number for this circuit replacement. The rule logic for this strategy is presented below:

IF component type is Cable,

AND damage is not repairable,

AND source substation has a critical facility,

THEN replacement with emergency overhead circuits need 20 days,

AND add additional time for road access,

ELSE replacement with emergency overhead circuits will start after the first 20 days,

AND add additional time for road access.

The rule logic for all the above strategies is presented in the form of a flow chart in Figure 5-8.

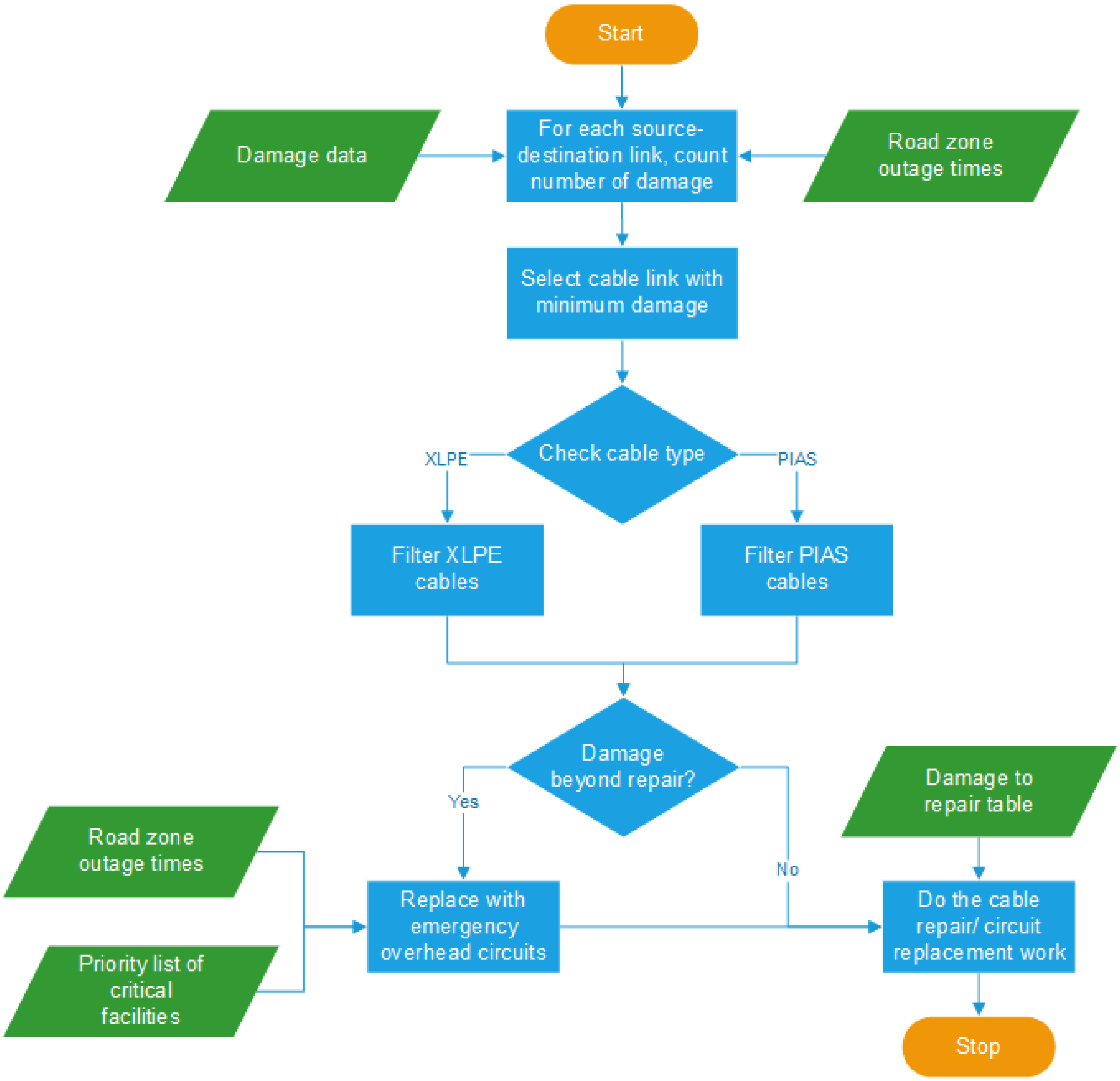

Figure 5-8. Flow chart for the recovery modelling of electricity cables

Module 3: Knowledge-base module for the repair of damaged transmission structures

Transpower NZ (n.d.) manages the transmission structures in the Wellington region and their asset management experts specified the strategies to repair different types of transmission structures. Like substations and cables, the repair work was done to only those transmission structures that had a damage state of either 4 or 5. Based on the elicited repair strategies, the following rules have been designed:

IF component type is Transmission Structure,

AND Damage state is less than or equal to 3,

THEN Transmission Structure is not damaged.

ELSE If Damage state is 4,

AND material type is STRN,

THEN repair work needs 2 days,

AND add additional time for road access.

ELSE IF material type is TRNS,

THEN repair work needs 3 days,

AND add additional time for road access.

ELSE IF Damage state is 5,

AND material type is STRN,

THEN repair work needs 3 days,

AND add additional time for road access.

ELSE IF material type is TRNS,

THEN repair work needs 4 days,

AND add additional time for road access.

These logical rules are also illustrated in the flowchart of Figure 5-9.

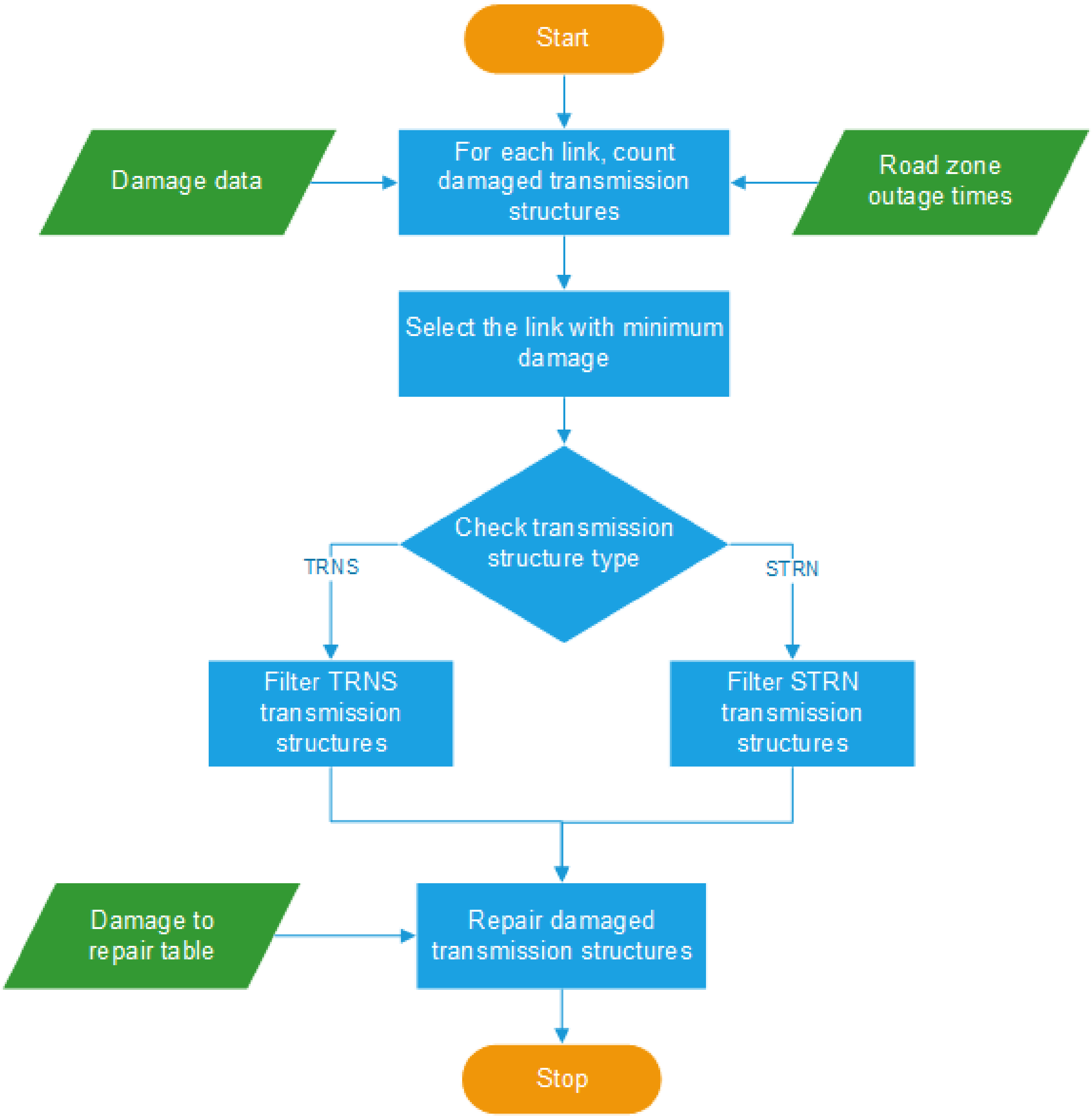

Figure 5-9. Flow chart for the recovery modelling of transmission structures

The topological and damage data for the electricity and potable water networks in this study is not dependent on each other and therefore this data can be uploaded in the KCDSS separately. But, for repairing the damaged components of these two networks, the road access times must be integrated into their topological and damage data. This integration is needed because the recovery time of these CI networks is based on the aggregated recovery times of each of their components. Therefore, the road access times are integrated at the component level, as discussed in Chapter 4. Based on the integration of different knowledge modules, a comprehensive description of the modelling process is depicted in Figure 5-10, as a flow chart diagram.

Figure 5-10. Flow chart for the recovery modelling of electricity and road networks

All the knowledge modules are integrated and linked to the database through the knowledge-base component of the KCDSS. This integration of different modules allows the interaction of expert knowledge and component data of electricity and road networks to assist the relevant users with CI recovery-related decision-making. CDM's structured approach can also be applied to the potable water network in future, for the elicitation of recovery strategies from the experts.

Through the inclusion of knowledge-base, the KCDSS can present a user-friendly environment to the CI decision-makers, so that they can prepare their scenarios by testing plans for inclusion of new components within their CI networks, test them with damage data of a variety of hazards using appropriate recovery plans to generate the corresponding outage results. The presentation tier or user interface layer can assist the decision-makers to interact with the KCDSS at every level of the knowledge management process. They can utilize the knowledge-base of recovery strategies throughout the process of creating and testing a specific CI network modelling scenario. Using the three-tier architecture, expert knowledge, topological and damage data for new CIs such as gas or potable water network can easily be integrated into the existing KCDSS. The results from KCDSS can be analysed in detail and compared with each other to identify the best possible recovery plan for the modelled scenario.

5.3.2 Business logic tier

The business logic tier is the central tier of the three-tier architecture. It controls both the user interface of the presentation tier and the underlying database and knowledge-base of the data tier, by hiding technical details from the end-users. Before storing the data in the database or after reading the data from the database, some logical operations are performed on the data in this layer using the C# .NET programming language. The business logic tier is composed of all the *controllers* of the MVC pattern that access the *model* to show the desired *views* to the decision-makers. This tier uses the characteristics of the CI network components along with the knowledge-base of strategic recovery plans to generate the desired outage results and timestamped maps. The core functionality for the business logic tier in this study is to interpret the CI network's topological and damage data from the data tier and generate the outage results based on the recovery strategies in the knowledge tier. Apart from this core functionality, some additional functional requirements are also implemented in this study to develop a what-if scenario based KCDSS.

Functional requirements are useful to capture the intended behaviour of a system and determine the necessary task, action, or activity that must be carried out by the system (Bagui & Earp, 2003). They refer to the application features that must be implemented by the developers to enable the users to accomplish their tasks (Le Blanc & Tawfik Jelassi, 1989). As mentioned above, the KCDSS has been developed not only to accomplish its core objective of calculating the recovery times for each CI network under consideration but also to provide enhanced features in terms of flexibility to (i) create and modify the database information; (ii) run several scenarios; (iii) view the output results; and (iv), extract critical information useful for decision-making processes. The knowledge elicitation and modelling in the previous sections were useful to create different knowledge modules. To implement these knowledge modules, the researcher has identified some functional requirements of the KCDSS that were discussed with the experts for the implementation of the business logic tier. The functional requirements are listed in Table 5-3 and then demonstrated using the interface screens of the presentation tier in Section 5.3.3.

Table 5-3. Functional requirements of the KCDSS

Functions	Description
Login functionality	An essential function in the KCDSS is that it allows only registered users to access, modify and visualise the available data.
Scenario creation functionality	One of the outstanding functions of the KCDSS is to allow its users to create various 'what-if' modelling scenarios through a step-by-step process in which the users upload the CI network's topological data. All the uploaded scenarios are available to the users to compare the results generated by each of them.
Outage map creation functionality	The users of KCDSS can upload damage realizations for a CI network modelling scenario to see a corresponding outage map.
Outage results review functionality	This function allows the users to get a detailed analysis of the modelled scenario. Users can see/ review recovery times of the modelled components to identify critical components that affect the supply of services.
CI component modification functionality	With this function, the users can modify, add, or delete the component data that they uploaded during the scenario creation. Therefore, there is no need to create a separate scenario if minor changes are needed in the existing scenarios.
Knowledge-base modification functionality	Just like CI component modification, all the repair strategies in the knowledge-base can be accessed and modified to allow the users to compare the results based on their modified strategies.

These functional requirements support the core functionality of the business logic layer, i.e. carrying out network performance analysis to estimate recovery time for both the individual and interdependent CI networks. The following section demonstrates these functional requirements through an easy to use graphical interface having a variety of customization options within the

KCDSS so that the end-users feel full authority and comfort in modifying any component and recovery data at any stage of the modelling process. Results generated with different options can be compared on a split-screen view encouraging a better user experience.

5.3.3 Presentation tier

The presentation tier or user interface layer provides a visualization tool for its end-users. This tier provides an access to all the functionalities of the KCDSS through user-friendly interfaces. These interfaces provide access to the data and knowledge related to CI network components through control elements, such as text boxes, buttons, labels, etc. After successful authentication, a *welcome screen* is displayed to the users, as shown in Figure 5-11. The central pane of the welcome screen is used for scenario management. The specific functions of each button are:

a) **New scenario:** The users can create a new scenario to model their desired CI networks. In the next steps, they can upload the component's topological data in CSV file format from the local storage, which is then stored in the database.

b) **Default scenario:** This is a shortcut to restore a pre-tested working scenario without any need to upload all the input files again. The results of this scenario became a contribution to the WeLG's Programme Business Case project (Wellington Lifelines Group, 2019).

c) **Existing scenarios:** This option takes the users to the list of all the existing scenarios from where they can restore or delete any scenario.

d) **Reset results:** This option deletes all the outage results. To prevent unintentional deletion, a confirmation dialog box is also presented to the users.

e) **Reset data:** This option deletes all the topological data of the selected scenario. It is useful if a user has done some unnecessary modifications such as adding any incorrect connectivity links between components or assigning new sources for a component. By using the 'Existing Scenarios' option, the users can restore the original topological data.

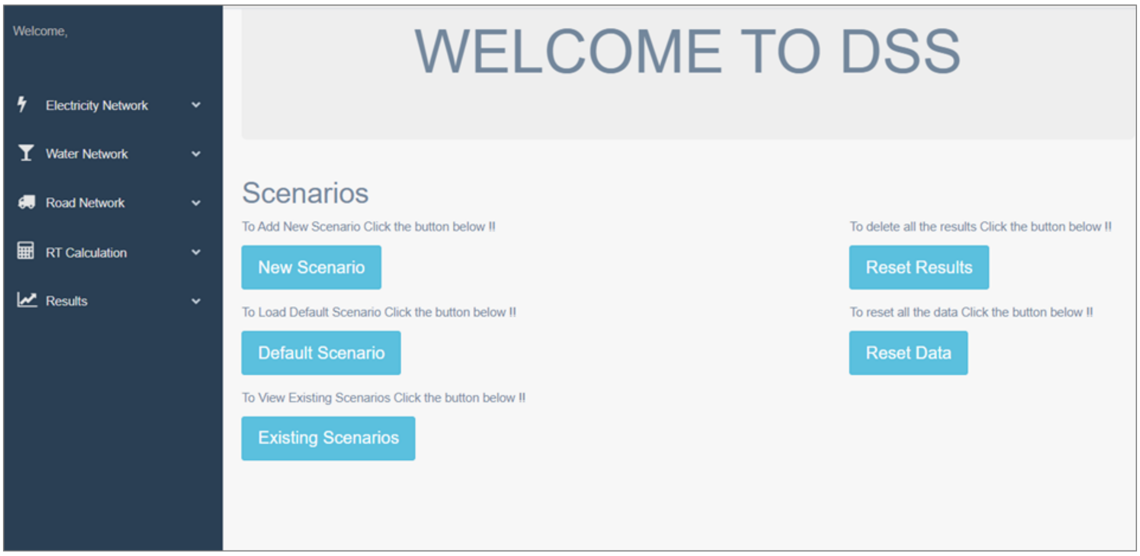

Figure 5-11. Welcome screen of the KCDSS.

The menu on the left side of the welcome screen contains all the topological data for the modelled CI networks through which the users can view, modify, delete or add any records. The topological data within each menu item is listed below:

- **Electricity network:** The components of GXPs, substations, cables and transmission structures are listed under this menu item.
- **Water network:** The components of treatment plants, pump stations and reservoirs are listed here.
- **Road network:** Road zone information can be accessed through this menu item.
- **RT (recovery time) calculation:** This menu item is used to upload the damage files for each modelled CI network.
- **Results:** This menu item shows the final outage results in tabular and graphical map formats. The map option also shows a split-screen to compare the results of more than one outage map.

The presentation tier is essential for the demonstration of the developed software and is also useful in evaluating the functional requirements to support the decision-making capabilities identified before the start of software development. Therefore, the tools developed and demonstrated in the following sections of the presentation tier are mainly used in visualising the

CI component data, their interdependencies and damage to recovery computation processes. The demonstration of all functional features and their capabilities to enhance the decision support of the KCDSS are discussed below.

5.3.3.1 Login functionality

Firstly, and importantly, the KCDSS requires login functionality. This step is critical because it contains the main security features of any software solution and prevents any loss of useful information. Login function also determines the functional properties that are presented to different types of users to provide access to only the features based on the user's job roles. With the login, a session is maintained for each user to keep track of all activities while using the KCDSS. Session management is useful to resolve any loss of data or functions and can therefore be needed in case of a system restore. A sequence diagram of the login activities is shown in Figure 5-12.

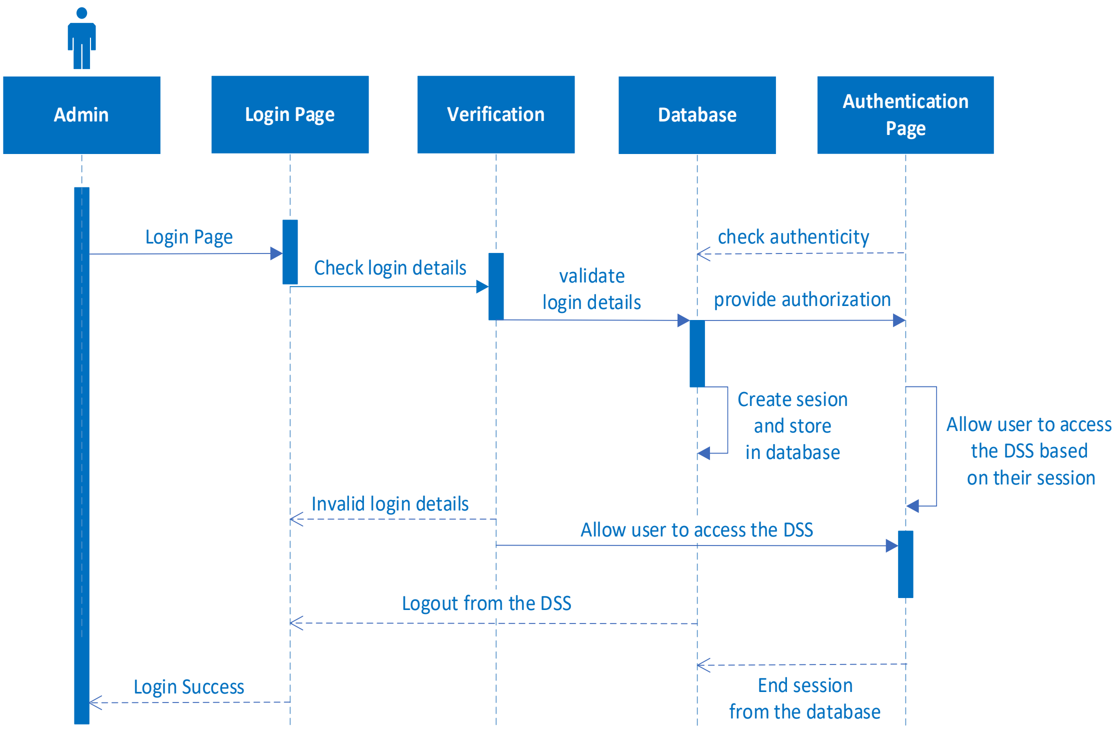

Figure 5-12. Sequence diagram of the login activities of the KCDSS.

5.3.3.2 Scenario creation functionality

The purpose of scenario creation is to configure the KCDSS by providing the required topological data of the selected CI networks. It works as a step-by-step procedure that first uploads the CI component's topological data into the KCDSS and then includes a knowledge-base of repair strategies. Every scenario is independent of each other, and multiple scenarios can be created in the KCDSS. The users can choose a scenario from the list of available scenarios, read the damage data and then generate the outage results.

Decision support capabilities

The scenario-creation functionality provides an opportunity for the end-users to create and load multiple independent scenarios. The step-by-step procedure for creating a scenario provides an error-free upload of the CI components and their repair calculations. The scenario creation functionality supports the decision-making capability of the KCDSS users to:

- Upload multiple scenarios with a selection of desired CI networks. Each scenario can represent a single CI network or multiple networks to provide interdependency-based results.
- Upload multiple scenarios for the same region, in which each scenario can contain the different topological structure of the CI components and the repair strategies to check the feasibility of up-gradation within a network.
- Upload multiple scenarios for different regions, with the region-specific CI components and their corresponding repair strategies.

Furthermore, the repair strategies can be modified at any time and the decision-makers can compare the results of different scenarios to choose the best option for their desired plans. The step-by-step procedure of scenario creation functionality starts with a selection of the CI networks, as shown in Figure 5-13.

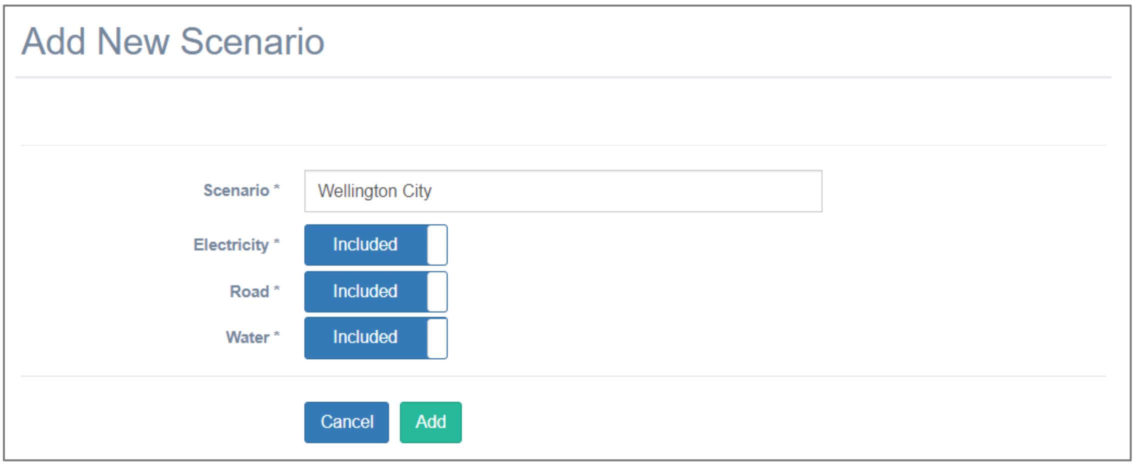

Figure 5-13. Selection of the CI networks for Scenario Creation.

Step 1: Upload compulsory data

After choosing the CI networks, the following steps require the users to upload some compulsory network-specific data, as depicted in Figure 5-14. In this example scenario, the component data for electricity, water and road networks is uploaded. In the first step, users need to upload the CSV files for *RoadZones*, *Substations*, *Priority Sites* and *Dependency Matrix*.

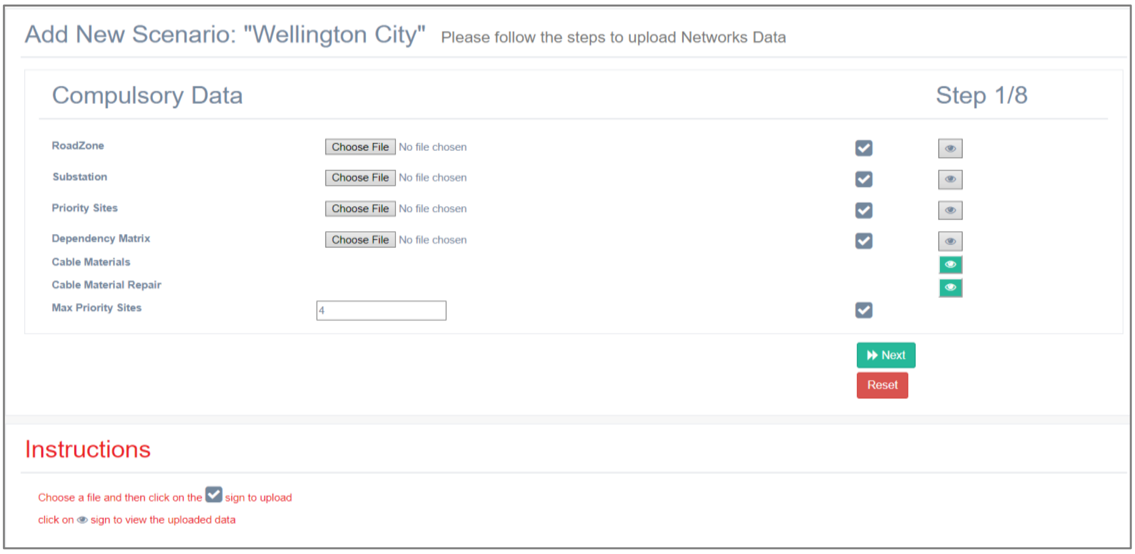

Figure 5-14. Scenario creation step 1: Upload required component data (example shown for electricity network).

The users are also able to modify the cable recovery settings in the knowledge-base. By choosing the green button in front of the *Cable Materials* option, they can view and edit the available list of all material types and the maximum number of repairable cable damage or faults. The *Cable Material Repairs* option shows the screen to view and edit repair times needed for the different number of cable faults. A screenshot for Cable Materials is shown in Figure 5-15, whereas, the screenshot for Cable Material Repairs is shown in Figure 5-16.

Material	Detail	Fault to Abandon	Actions
PIAS		2	
PILCA	PILCA, XLPE, Other	9	

Figure 5-15. List of all the cable material types and maximum faults to repair.

Cable Material	Fault From	Fault To	Days Required	Actions
PIAS	1	1	15	
PILCA	1	2	3	
PILCA	3	4	6	
PILCA	5	6	9	
PILCA	7	8	12	

Figure 5-16. Details of cable faults and the days needed to repair them for different types of cables.

Step 2: Upload electricity network component Data

In the second step (see Figure 5-17), the users can upload the electricity network's *Cable Links* (all unique cable links from a source to destination), *Cable Link Details* (cable links group by their materials and road zones), *Transmission Structure Links* (all unique links containing transmission structures from a source to destination) and *Transmission Structure Link Details* (transmission structure links group by their materials and road zones).

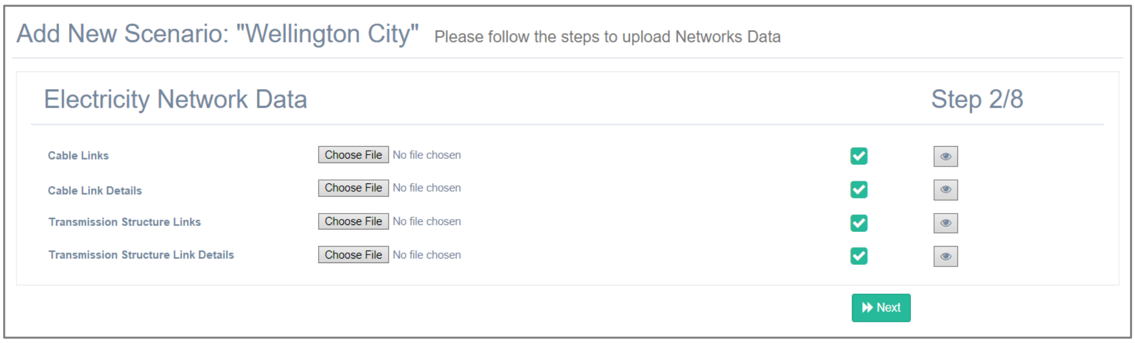

Figure 5-17. Scenario creation step 2: Upload electricity network's component data.

Step 3: Upload road zone recovery data

The third step (see Figure 5-18) of the scenario creation procedure is to upload the *RoadZone RT* (recovery times). These recovery times are in the form of a matrix, which contains the access time from one road zone to every other. The *RoadZone RT* is essential to calculate a realistic time for repairing the damaged CI network components.

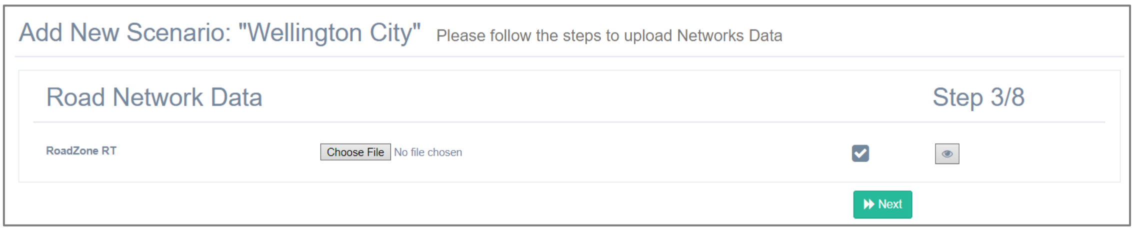

Figure 5-18. Scenario creation step 3: Upload road zone recovery times (time to recover matrix).

Step 4: Configure damage to recovery settings of electricity network components

The fourth step (see Figure 5-19) of the scenario creation process is to configure the repair times for the damaged electricity network components. For each damage state, the users can view or modify the repair times that are saved in the knowledge-base for recovery modelling. These customisable recovery calculation settings can be changed at a later stage as well to modify the default settings as per the user's choice.

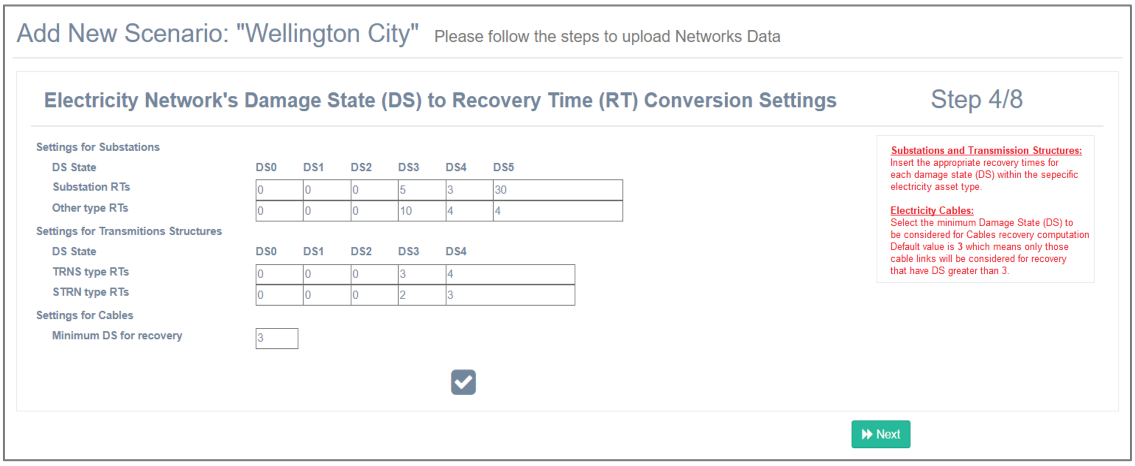

Figure 5-19. Scenario creation step 4: Configure damage to recovery settings of electricity network components.

Step 5: Upload potable water network's nodal component data

In this step (see Figure 5-20) of the scenario creation process, the user uploads the potable water network's topological data that includes *Water Supply Zones* information and the data for nodal components, such as *Reservoirs*, *Pump Stations* and *Treatment Plants*. The potable water data for Step 5 to Step 8 is designed by the researcher using placeholder values for testing purposes. When the real topological and damage data for the potable water network will be available, it will be uploaded similarly.

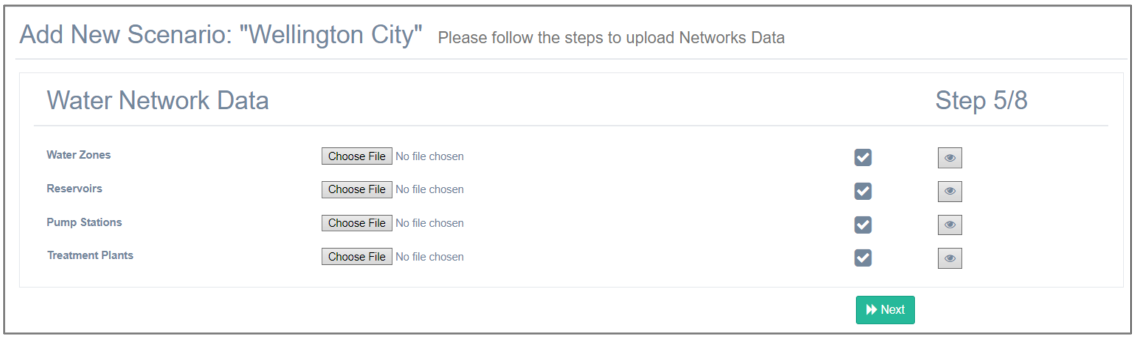

Figure 5-20. Scenario creation step 5: Upload potable water network's nodal component data.

Step 6: Upload potable water network's pipes data

The sixth step (see Figure 5-21) of the scenario creation process is to upload the pipes data and the dependency matrices for the potable water network. Pipes data links *Treatment Plants* with *Pump Stations* and *Pump Stations* with *Reservoirs*. This step also needs three dependency matrices to provide a source to destination connectivity between the nodal components of the potable water network. These matrices are between *Treatment Plants* to *Pump Stations*, *Pump Stations* to *Reservoirs* and *Reservoirs* to *Water Supply Zones*. Two more matrices are also needed to provide a source to destination connectivity between the nodal components of the electricity network with the potable water network. These matrices are between *Substations* to *Pump Stations* and *Substations* to *Treatment Plants*.

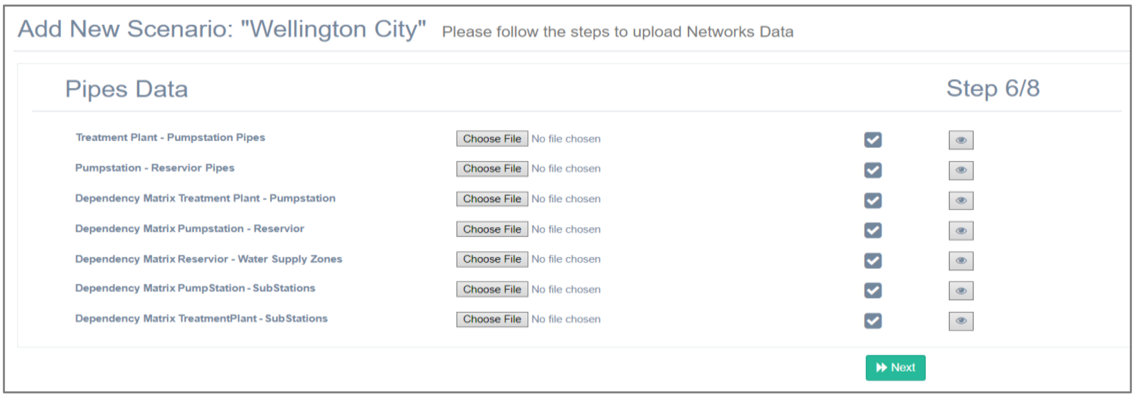

Figure 5-21. Scenario creation step 6: Upload potable water network's pipes data.

Step 7: Configure potable water network's pipe repair data

After uploading the topological data in the previous step, the KCDSS shows the next screen (see Figure 5-22) to view or edit the repair settings for the pipe breaks. The users can set the maximum number of repairable pipe breaks and the repair times needed for each pipe break.

Figure 5-22. Scenario creation step 7: Configuration of potable water network's pipe repair data.

Step 8: Configure damage to recovery settings of potable water network components

The eighth step of the scenario creation process provides configuration options for the damage to repair times of the components of the potable water network (see Figure 5-23). The users can view or modify the repair times corresponding to damage states of the nodal and pipe components of the water network. This configuration is then updated in the knowledge-base for recovery of the water network.

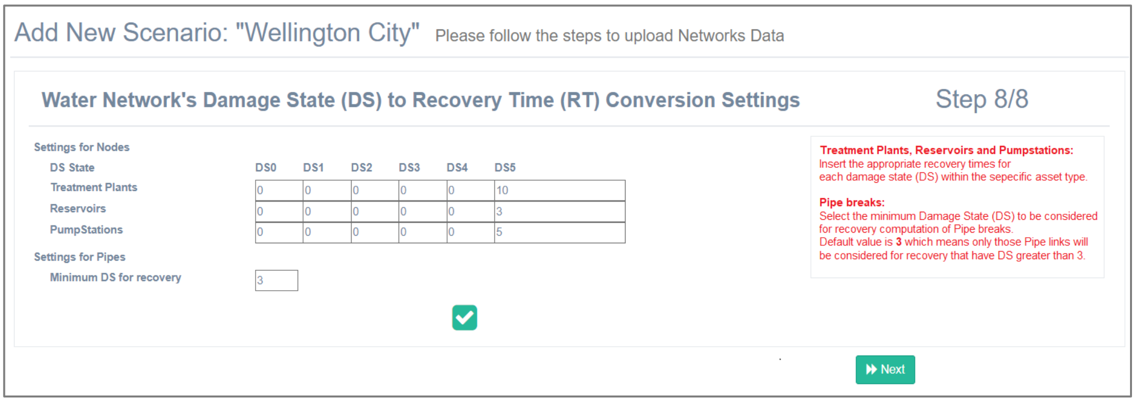

Figure 5-23. Scenario creation step 8: Configuration of damage to recovery settings of potable water network components.

Finally, after uploading the component data of the included CI networks, along with their knowledge-base configurations, the scenario is successfully created (see Figure 5-24). This scenario now has all the topological information for *electricity*, *potable water* and *road networks.*

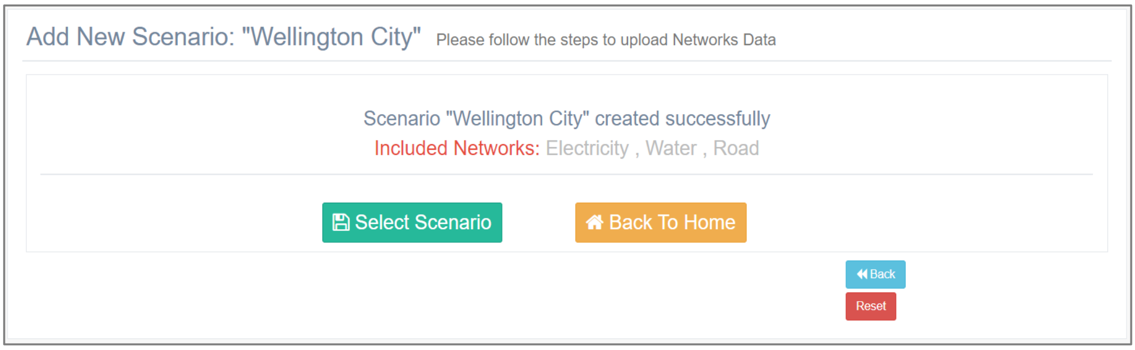

Figure 5-24. Scenario creation confirmation screen.

The scenario at this stage is saved in the database and the users can now select this scenario for testing the damage results. They can select any scenario from the available pre-loaded scenarios and can do the modifications as per their choice.

5.3.3.3 Outage map creation functionality

Outage map creation is one of the core functionalities of the KCDSS and a major objective of this study. After the creation of the scenarios, users can upload the damage files for the CI components. Once the damage files are uploaded, the business logic tier processes the damage data and computes the network recovery times based on the dependency links within a CI network or between different CI networks.

Decision support capabilities

The outage map creation functionality provides detailed results to the decision-makers for further analysis. An example of the resultant outage times for the electricity network's substation zones, with a dependency on the road network, is shown in Figure 5-25. The details in this figure include *Scenario Name*, *Substation Supply Zone*, *Recovery Time*, *Link* (default link from source to destination), *Link Detail* (the optimum route chosen from all the available links), *Calculation Type* (with or without road dependency) and the *Date/Time* when the results were generated. These results can also be copied or exported in CSV file format.

Final Outage

Copy CSV Search:

Scenario	Substation	Recovery Time	Link	Link Detail	calculation Type	Date Time
Default Scenario_WithRZ_0000_13-Feb-2020_09-47-07	WKN	47	VLR-WKN	VLR-WKN	WithRZ	13 Feb 2020 09:47:08
Default Scenario_WithRZ_0000_13-Feb-2020_09-47-07	RMT	47	VLR-RMT	VLR-RMT	WithRZ	13 Feb 2020 09:47:08
Default Scenario_WithRZ_0000_13-Feb-2020_09-47-07	PRW	47	VLR-PRW	VLR-PRW	WithRZ	13 Feb 2020 09:47:08
Default Scenario_WithRZ_0000_13-Feb-2020_09-47-07	PRB	13	VLR-PRA	VLR-PRB	WithRZ	13 Feb 2020 09:47:08
Default Scenario_WithRZ_0000_13-Feb-2020_09-47-07	PAK	47	VLR-PAK	VLR-PAK	WithRZ	13 Feb 2020 09:47:08
Default Scenario_WithRZ_0000_13-Feb-2020_09-47-07	OTK	3	VLR-OTK	VLR-OTK	WithRZ	13 Feb 2020 09:47:08
Default Scenario_WithRZ_0000_13-Feb-2020_09-47-07	KAR	54	WIL-KAR	WIS-KAR	WithRZ	13 Feb 2020 09:47:08
Default Scenario_WithRZ_0000_13-Feb-2020_09-47-07	BRO	47	UHT-BRO	UPH-BRO	WithRZ	13 Feb 2020 09:47:08
Default Scenario_WithRZ_0000_13-Feb-2020_09-47-07	MAI	47	UHT-MAI	UPH-MAI	WithRZ	13 Feb 2020 09:47:08
Default Scenario_WithRZ_0000_13-Feb-2020_09-47-07	TRE	47	HAY-TRE	HAS-TRE	WithRZ	13 Feb 2020 09:47:08

Showing 1 to 10 of 39 entries Previous 1 2 3 4 Next

Figure 5-25. Electricity network's outage times with dependency on the road network (sample outputs only).

The KCDSS can also display the results as time-stamped outage maps. The users can compare recovery times for different scenarios of the same CI network, or a comparison of recovery times for CI networks with and without dependencies on other networks, on a split-screen. Users can also move the timeline bar to see the improvement of the recovery process in different periods. A detailed analysis of these results can be useful for the identification of vulnerabilities within the modelled CI networks. The graphical display, as shown in Figure 5-26, is only for the visualisation of outage results and do not represent real data.

Figure 5-26. A split-screen of time-stamped outage maps for different scenarios (sample outputs only).

5.3.3.4 Outage results review functionality

The purpose of this functionality of the KCDSS is to show a detailed view of the amount of damage and recovery times for each of the modelled CI networks. The *Route Details* in Figure 5-27 show a summary for all the node and link components involved in the selected route, which, in this example, is *EVA-CPS*. The *station* here can be either a GXP or substation, *Source* is the immediate source of supply for the station, *Route Type* can be *Normal* (direct route) or *Joined* (a combination of multiple routes), *Station RT* shows the recovery times for the GXPs or substations, *Route* can be *Sub Route* (if the destination is a substation) or *GXP Route* (if the destination is a GXP) and *Cable RT* and *Transmission RT* show the recovery times for these components. By using the *Actions* option in the last column, the users can see the number of damaged components.

Route Details "EVA - CPS" Route

Create | Route Type

Copy | CSV

Search:

Station	Source	Route Type	Station RT	Route	Cable RT	Transmission RT	Actions
EVA	CPK	Normal	3	SUB Route	55	0	
CPK	WIL	Normal	4	GXP Route	0	17	
WIL	TKR	Normal	4	GXP Route	0	17	
TKR	HAY	Normal	4	GXP Route	0	17	
HAY	OTB	Normal	4	GXP Route	0	42	

Showing 1 to 7 of 7 entries

Previous 1 Next

Figure 5-27. Screen for a detailed analysis of the damage and recovery times for different component types.

Decision support capabilities

The outage results review functionality is particularly useful for the decision-makers to identify all vulnerabilities in the modelled CI network. The normal outage map just shows the recovery times of the supply zones, but this detailed analysis includes all node and link components involved in the selected route.

The utilisation of the outage results review functionality for enhancing decision support is further explained through an example scenario of Central Park (CPK) GXP, with its eight substations in the Wellington region. An illustration of all the computations is shown in Figure 5-28, in which eight substations connected to CPK GXP are *University*, *The Terrace*, *Evans Bay*, *8 Ira Street*, *Hataitai*, *Palm Grove*, *Nairn Street* and *Frederick Street.*

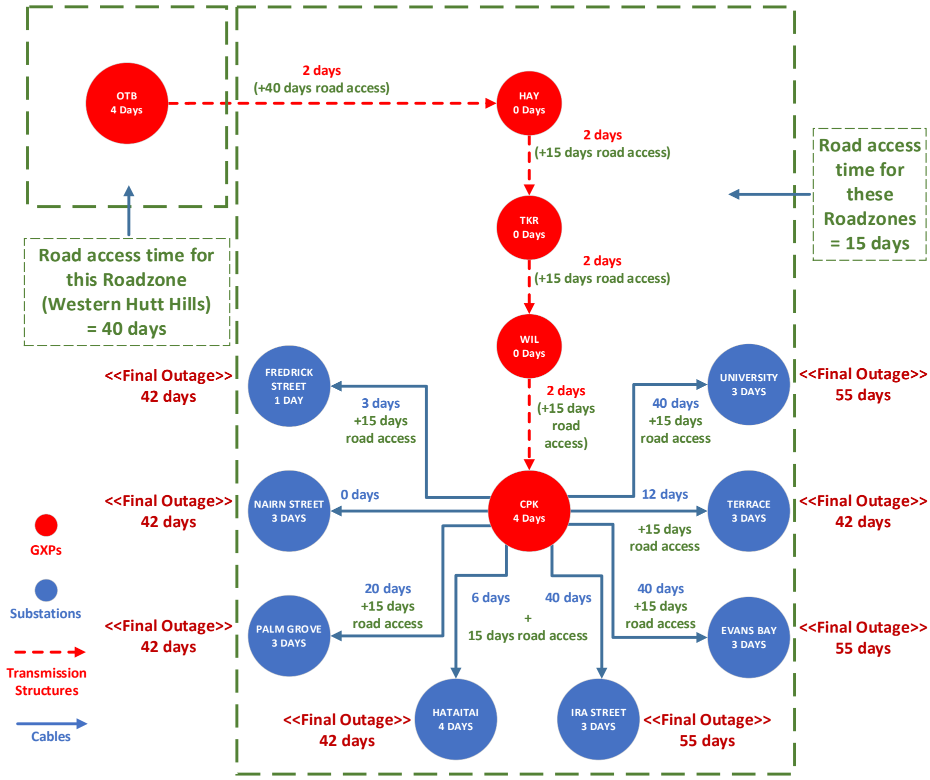

Figure 5-28. Recovery time computation of different substations through outage results review functionality

The recovery times for all substations and GXPs are mentioned within the nodes (without their road access time). All eight substations are connected to CPK through underground cables (shown with solid blue lines as links between the nodes). Besides the cable links, their recovery time is written in light blue colour, with road access times in green colour.

The main source of electricity in this scenario is OTB, which supplies electricity to HAY, which then supplies electricity further to TKR, WIL and then to CPK. The electricity supplied from OTB down to CPK is through transmission structures as shown in dashed red lines (with their recovery times and road access times). The CPK then supplies the electricity to all its substations through cables. All GXPs and substations of CPK and the cables between CPK and all substations have 15 days of road access time. From OTB to HAY, the road access time is 40 days, as the damaged transmission structures are in another road zone, named 'Western Hutt Hills'. After the calculation of recovery times for individual components connected to each substation, it is assumed through the knowledge-base that all repair work is done in parallel. A summary of the calculation is shown in Table 5-4. As mentioned earlier, modelling of the distribution network of the electricity network is beyond the scope of this study; therefore, the experts indicated during the knowledge elicitation process to add 10 days offset time for recovery of the distributed network part.

In this way, the outage results review function gives a detailed description of the damage and repair times for all the modelled components. Using these detailed results, all vulnerabilities in the network are easy to identify and provide better decision-making options. The decision-makers can also add new components, using the component modification functionality (see next section) to test and compare the feasibility of adding new components in the network before taking any decision.

Table 5-4. Summary of outage results for substations through the recovery times (in days) of their connected components.

Substation Recovery Times			**GXP Recovery Times**					**Cable Recovery Times**	**Transmission Structure Recovery Times**				**Substation Supply Zone Recovery Times**	
Sub	Name	RT	OTB	HAY	TKR	WIL	CPK	From CPK to Sub	OTB-HAY	HAY-TKR	TKR-WIL	WIL-CPK	Final Outage	Final Outage with offset
UNI	University	18	44	0	0	0	19	55	42	17	17	17	55	65
TER	The Terrace	18	44	0	0	0	19	27	42	17	17	17	42	52
EVA	Evans Bay	18	44	0	0	0	19	55	42	17	17	17	55	65
IRA	8 Ira Street	18	44	0	0	0	19	55	42	17	17	17	55	65
HTI	Hataitai	19	44	0	0	0	19	21	42	17	17	17	42	52
PAL	Palm Grove	18	44	0	0	0	19	35	42	17	17	17	42	52
NAI	Nairn Street	18	44	0	0	0	19	0	42	17	17	17	42	52
FRE	Frederick St	16	44	0	0	0	19	18	42	17	17	17	42	52

5.3.3.5 CI component modification functionality

Finally, this functionality is also an additional benefit of the KCDSS to improve its customisation options. As discussed in the previous sections, all component data is uploaded during the scenario creation process, but this feature provides additional support to the users to add, modify or delete any of the CI components to have a variety of decision options.

Decision support capabilities

Component modification functionality is a useful feature because, after the creation of a scenario, the users can check the feasibility of additional CI components without any need to create a new scenario once again. The additional components then become part of the recovery calculation process and provide useful support to the decision-makers to compare the recovery results of the existing scenarios with the addition of new components. Figure 5-29 shows the screen to add a new substation. Similar types of forms are available to add components of other types. The users can enter the required information in the input forms, and subsequent error messages are displayed if the uploaded details are not in the proper format.

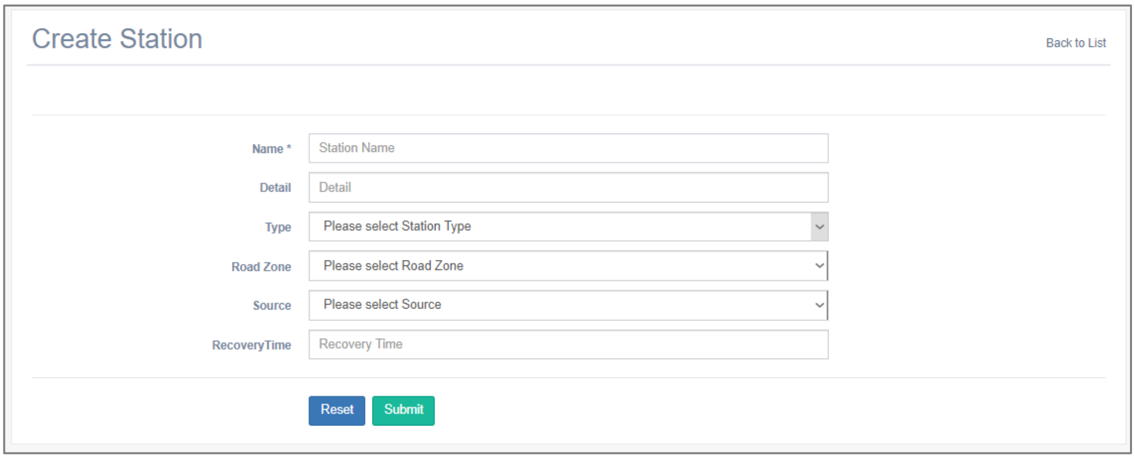

Figure 5-29. Form to manually create a new substation in the KCDSS.

Like the addition of new components, the component modification functionality of the KCDSS allows the users to modify or delete any of the existing components. Upon successful modification, the component data is updated in the database. Similar functionalities are provided by the KCDSS to modify the knowledge-base items, depending on the user access. An example screenshot of the *Substation* modification window is shown in Figure 5-30.

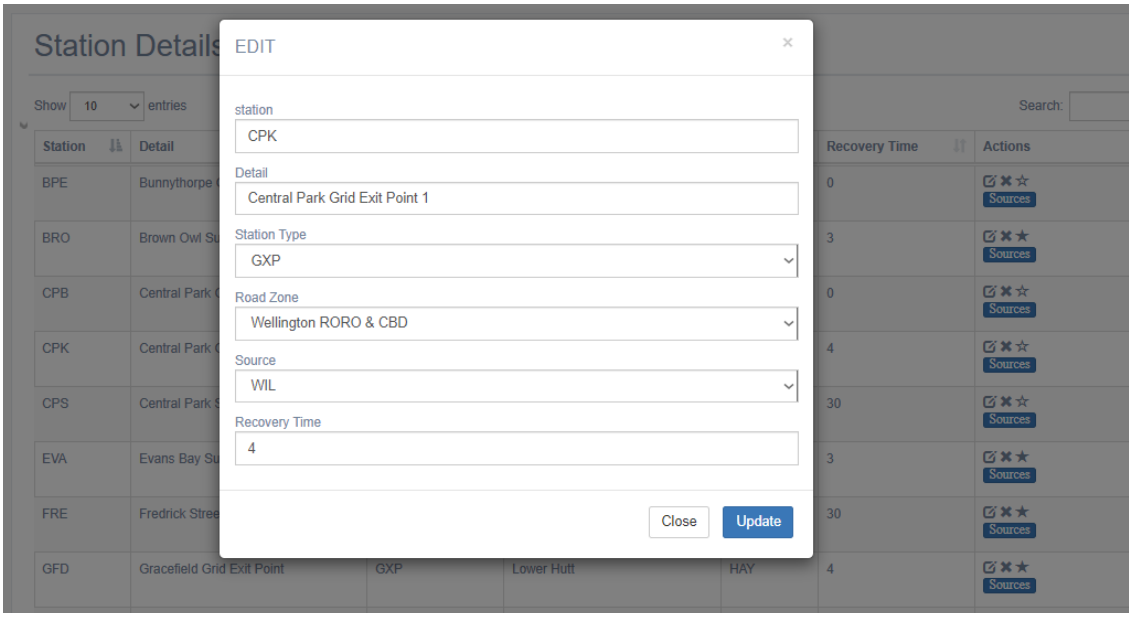

Figure 5-30. Form to modify an existing substation.

Through the various options of component modifications, the KCDSS becomes thoroughly customisable for testing new strategies with enhanced decision support. Therefore, with a variety of customisable options through a "what-if" analysis approach, the KCDSS provides useful support to the decision-makers through which they can test different redundancy options, check the possibilities of interconnections between CI networks and make plans of component modifications.

5.4 Chapter Summary

This chapter, explains and elaborates the development and implementation of the KCDSS by using a three-tier client-server software architecture. In the development process of this architecture, the presentation tier (user interface layer), business logic tier (application processing layer) and data tier (knowledge and database layer) are developed and maintained as independent modules. The layers of three-tier architecture are then implemented using the MVC pattern and the functional aspects of these layers have been discussed in detail. KCDSS implementation is based on the second phase of data collection, which is the elicitation of recovery strategies from CI network providers. These recovery strategies became part of the knowledge-base component of the KCDSS. Finally, the developed KCDSS was demonstrated through the creation of CI interdependency modelling scenarios. The demonstration of KCDSS shows a variety of customizable options that can help the decision-makers to modify and test their recovery strategies by using the topological and damage data of CI network components. The KCDSS is not only useful for the planning of a CI network to check the possibility of adding new components or removing the existing components but is also extremely useful during the response and recovery phases of a disaster to estimate the outage times of the modelled CI networks.

6 EVALUATION OF THE KCDSS

6.1 Introduction

This chapter elaborates on the process of evaluating the KCDSS artefact and the evaluation outcomes, which is also the fourth objective of this study. It starts with a discussion on the importance of evaluation in a DSR based study followed by a brief review of the artefact evaluation methods and finally the discussion of the evaluation process for this study.

Evaluation is a vital element for DSR study to justify the purpose of the designed artefacts (Herselman & Botha, 2015), and needs well-designed evaluation methods to demonstrate the utility, quality, and efficacy of a research project (Hevner et al., 2004). Evaluation is also essential to address the objectives of the research and it seeks to determine the relevance, efficiency and effectiveness of the built artefacts (Bazzano et al., 2017; Prat et al., 2014; Venable et al., 2012). In a DSR based study, the evaluation process is primarily concerned with the evaluation of the designed artefacts and theories developed throughout the research project (Hevner et al., 2004). According to Hevner et al. (2004), a DSR comprises two primary activities: *build* and *evaluate*. Though the importance of evaluation of the DSR artefacts is well supported in the literature (for example, Arnott & Pervan, 2014; Herselman & Botha, 2015; Hevner et al., 2004; Peffers et al., 2007; Pries-Heje et al., 2008; Venable et al., 2016), much of the existing works focus on the *build* activity. There also exist some design-science studies (for example, Pries-Heje et al., 2008; Sonnenberg & Vom Brocke, 2012) that deal specifically with the evaluation of design science research. A review of these studies indicates that design science researchers should define appropriate performance evaluation methods and related criteria based on the research objectives and the functionalities of the artefact.

6.2 Discussion of the evaluation process

The evaluation of a DSS needs a process of verification, validation and quality control to determine the usability and functionality of built artefacts and to examine the research assumptions, identify critical limitations and the reasons for generating specific types of results (Herselman & Botha, 2015). Verification is typically done throughout the software development process to make sure that software is being built correctly. Whereas, validation involves testing of the software product after its completion to validate all the functions are performing correctly (Osatuyi & Andoh-Baidoo, 2014). Thus, the KCDSS developed in this study is evaluated through:

i. Verification: Careful development of the source code to ensure the quality of the software design and architecture;
ii. Validation: testing and validating the functionalities of the KCDSS to ensure that each function works according to the end-users needs; and
iii. Evaluation: different experts evaluated the functionality, usability, reliability, performance and supportability aspects of KCDSS.

6.2.1 Verification of the KCDSS

The KCDSS is verified throughout its software development process to ensure that the source code is written in a standardized form with no errors and conforming to the syntax standards of the utilized programming languages. SQL Server and ASP.NET have advanced error-handling functions to check syntax during the deployment of the KCDSS. Error handling is an integral step for highlighting any errors in the developed source code and it is not possible to execute and deploy the KCDSS in case of any errors. For detection of any possible errors during the development of the user interface, the error handler for ASP.NET is used. Where necessary, some additional functions have been developed to identify any errors with executing database queries that were not already captured through the SQL server command line. After the KCDSS development, some syntax validators are utilized for checking the syntax of XHTML and CSS design of each page of the output to verify a correct depiction of the user interface to the end-users.

6.2.2 Validation of the KCDSS

The validation process involves testing mechanisms to validate that the inputs to the artefact are generating the outputs according to the expectations. For this purpose, individual modules of the artefact are validated using various tests (Shabi et al., 2017). Each of the three tiers of the KCDSS has been independently validated through the testing procedures. The input forms of the presentation tier have been tested individually to ensure that each module of the KCDSS accepts only the valid parameters. In case of a wrong or missing entry in the input forms, an error message is generated to indicate the description of the error to the KCDSS user. Similarly, all the possible dependencies and constraints in the database have also been validated. The validation for the knowledge-base was done by testing different rules in terms of their accuracy and completeness of the knowledge they represent.

To make sure that all the functional aspects of KCDSS are performing correctly, the researcher has used *Unit Testing* in this study. In Unit testing, a small piece of code is isolated from the rest of the code to validate whether it is generating the correct results (Runeson, 2006). KCDSS provides various features such as user login, scenario creation, outage results generation, display of results on graphical maps etc. All these features involve user inputs, submission of data to the database, retrieval of knowledge from the knowledge-base and calculation of results for which the following test cases have been developed and validated:

a) Login_Validation_Test

This test case is used to verify the username and password information of the user. If the provided information is correct, the user is allowed to access the KCDSS. If there is a mismatch in the username and password, the user is not allowed to log in.

b) Scenario_Validation_Test

This test was created to validate all the inputs of the Scenario creation functionality. As this process needs the uploading of several input files, therefore each of these files needs to be validated. Furthermore, the knowledge-base of recovery calculations is also validated to check all the input numbers are in an acceptable format.

c) Outage_Map_Validation_Test

In this test, the outage maps are validated to display appropriate supply zones of the modelled CI network. The numerical results of the CI network recovery for each supply zone are also validated to be displayed over the appropriate supply zones in the graphical outage maps.

d) Outage_Results_Validation_Test

This test was created to validate the recovery calculations. The repair times of all the individual CI network components are integrated to generate the aggregated results of a supply zone which need careful testing of all the results.

e) Component_Modification_Validation_Test

This function modifies CI network components during the run-time of the KCDSS. Therefore, a test was created to validate all the inputs as a minor error in any of the input values can affect all the recovery computations.

f) Knowledge-base_Modification_Validation_Test

The knowledge-base modification includes the update of repair calculations for the CI network components and therefore it needs careful monitoring. Therefore, this test was created to validate these modifications and to give warnings and errors if the input values are not in the right format.

These test cases have been validated using *NUnit*, which is the most popular open-source automated unit testing framework for .Net based software applications (Hamilton, 2004). The individual tests for each of the KCDSS functionalities have been written and compiled within the .Net software development environment and then loaded into the NUnit user interface. The tests were useful to identify coding errors and invalid results. The researcher then improved the invalid functions until successful completion of all the tests to validate that there is no more error in the respective functionalities and each of them is generating the accurate outcome. Figure 6-1 illustrates the final result of all the tests within the above-mentioned functionalities and indicates that all validation tests were passed without any errors.

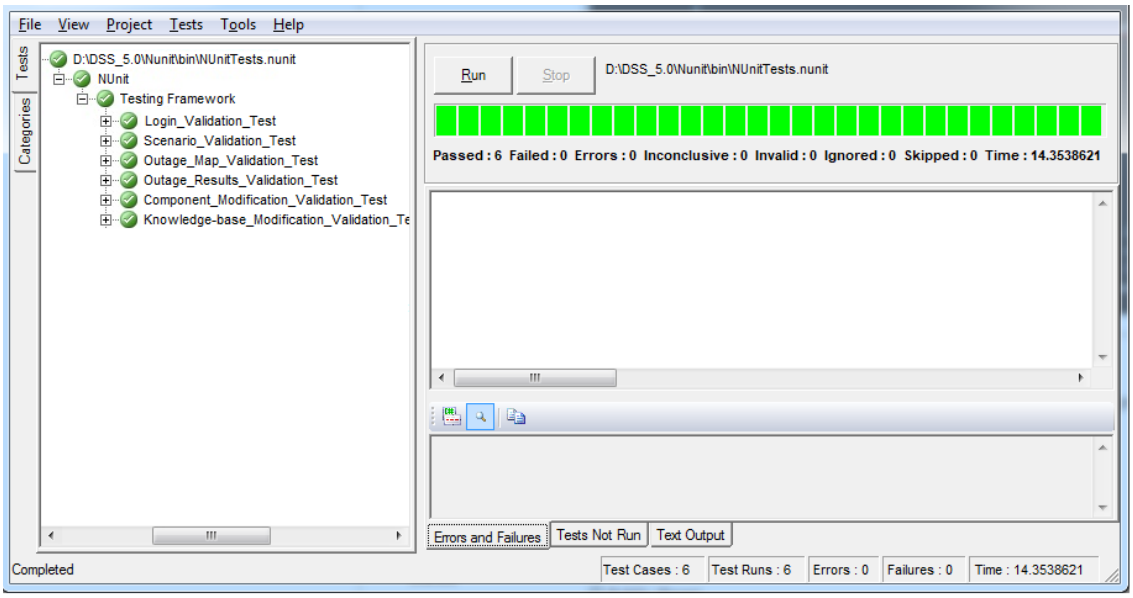

Figure 6-1. An interface screen of NUnit showing results of validation tests for six functionalities of the KCDSS

6.2.3 Evaluation of the KCDSS

The important aspect of a DSR based study is that evaluation is not only focused on evaluating the artefacts in the context of their contribution to the environment but also to evaluate their contribution of the knowledge to the knowledge-base (Sonnenberg & Vom Brocke, 2012). Therefore, it is argued by Pries-Heje et al. (2008) that the evaluation method should address the quality of an artefact's utility as well as the knowledge outcomes. An important challenge during the evaluation of the DSR artefacts is to determine a feasible way to design and conduct the evaluation by using appropriate strategies and methods. The existing literature identifies a variety of methods to do the evaluation and Hevner et al. (2004) summarized five classes of evaluation methods, which are:

a) **Observational methods**, which include case studies and field study;
b) **Analytical methods**, which include optimization, architecture analysis and static and dynamic analysis;
c) **Experimental methods**, which include a controlled experiment and simulation;

d) Testing methods, which include functional testing and structural testing. Both are also known as black-box testing and white-box testing; and

e) Descriptive methods, which include informed arguments and scenarios.

Nunamaker et al. (1990) termed computer simulations, field experiments and scientific simulations as experimentations and termed case studies, surveys and field studies as observations. These activities of experimentation and observation are instead termed artificial evaluation and naturalistic evaluation by Venable et al. (2012). The artificial evaluation uses laboratory and field experiments, simulations, criteria-based analysis, theoretical arguments, and mathematical proofs to evaluate the built artefacts in a non-realistic way. Naturalistic evaluation, on the other hand, includes interviews, case studies, field studies, surveys, ethnography, phenomenology, hermeneutic methods, and action research to explore the performance of artefacts in their real environment (Venable et al., 2016). Pries-Heje et al. (2008) proposed a strategic framework for evaluating the DSR artefacts using two dimensions: time and evaluation method (see Figure 6-2). The researcher has used this framework in this study to design the evaluation process.

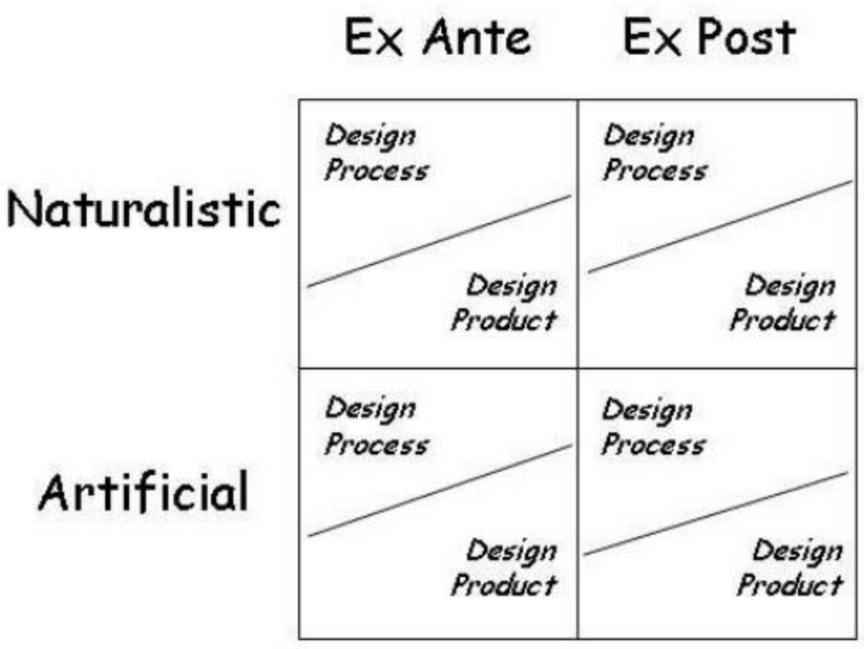

Figure 6-2. DSR evaluation framework (Source: Pries-Heje et al., 2008)

The advantage of using this framework is that it is designed not only to help researchers build strategies to evaluate the research outcomes but also to find ways to contribute to the knowledge-base. This framework seeks to answer some important questions, which are:

- What is been evaluated?
- How is it evaluated?
- When was it evaluated?
- Who is evaluating?

By choosing whether the researchers are evaluating a design process or a design product, they can determine *what* is evaluated. By choosing between naturalistic or artificial methods of evaluation, researchers can understand *how* to evaluate. *When* to evaluate may be decided based on ex-ante, ex-post, or both types of evaluation times. When the evaluation is done before the artefacts are constructed, it is termed as ex-ante evaluation and when it is done after the artefacts are constructed, it is termed as ex-post. Finally, the researchers need to identify the potential participants representing the real users, organizations or problems to finalize *who* is evaluating the research artefacts (Venable et al., 2016). These proposed questions by Pries-Heje et al. (2008) and their relevance with the current study are summarized in *Table 6-1*:

Table 6-1. Important aspects of the evaluation.

Questions for evaluation	Answers
What is evaluated?	For this study, the design product (KCDSS prototype) is evaluated.
How is it evaluated?	A software quality model is used to evaluate the KCDSS prototype through a set of interviews with the relevant experts. Therefore, this evaluation process is done using a naturalistic approach.
When was it evaluated?	The artefact is evaluated ex-post (after the KCDSS was developed).
Who is evaluating?	The KCDSS is evaluated by a group of experts representing CI network providers and regional emergency management organizations.

In this study, a software quality model is selected for evaluating different quality attributes of the KCDSS and in-depth interviews were conducted with the selected experts to assess whether their needs are represented in the KCDSS. Due to the evaluation process, the experts became part of the design process and were given a feeling of confidence that their personal opinions had been integrated into the final design. Based on the criterion and snowball sampling methods, 15 experts were selected from various emergency management sectors in New Zealand. Table 6-2 summarise the background information of the selected participants for KCDSS evaluation.

Table 6-2. A summary of the chosen experts and their professions

Characteristics	Description
Years of experience	All the experts had more than 15 years of experience in their respective fields.
Industries represented	Emergency Response and Recovery, Lifeline Group, Lifeline Utility Providers and Emergency Management Research.
Professions of experts	Capability Development Manager, Asset Engineer, Senior Asset Manager, Senior Engineer, Manager Risk and Assurance, Lifeline Controller and Emergency Management Professionals

The selection of multiple experts in a study can also be useful to identify different opinions about the user interfaces and can yield better results through a combination of their feedback (Herselman & Botha, 2015). The selected experts had valuable experiences in their fields and the reason for selecting them from diverse emergency management organizations was to understand their decision-making needs from different perspectives. Although there are many existing methods for evaluating DSR artefacts, it is still a challenge to choose appropriate attributes to test an artefact. Hevner et al. (2004) identified utility, quality, and efficacy as attributes to be evaluated. Hevner et al. (2004, p. 85) further state that "artefacts can be evaluated in terms of functionality, completeness, consistency, accuracy, performance, reliability, usability, fit with the organization, and other relevant quality attributes". The following section gives a brief overview of some of the existing software quality models for evaluating a software artefact and the discussion of the evaluation of KCDSS through one of the selected models.

6.3 Software quality model for KCDSS evaluation

As mentioned in the previous section, the answer to "What is evaluated" is the "prototype" of KCDSS in this study. To evaluate a DSS prototype in general, an appropriate quality model is useful for the assessment of software quality (Al-Badareen et al., 2011). Software quality models consist of a set of features to determine a software's capability to satisfy end-user needs and requirements. Several quality models have been introduced and utilized in the literature. Boehm (1978) introduced a hierarchical software quality model in 1978 that consists of a) high-level or primary characteristics; b) intermediate-level; and c) lower-level or primitive characteristics. Boehm's quality model focuses on portability, reliability, testability, efficiency, human engineering, understandability and modifiability (Boehm et al., 1978). Jim McCall (1977) introduced the McCall software quality model in 1977 that addresses different quality attributes in three categories: a) product revision that consists of maintainability, flexibility and testability; b) product transition that consists of portability, reusability and interoperability; and c) product operation that consists correctness, reliability, usability, integrity and efficiency quality attributes (McCall et al., 1977). Dromey (1996) proposed to evaluate software quality attributes in four categories: a) correctness category that includes functionality and reliability; b) internal category consisting of maintainability and efficiency; c) contextual category consisting of reusability and portability; and d) descriptive category that includes usability attribute (Dromey, 1996). The ISO/IEC 9126:1991 (2001) model was introduced in 1991 as the ultimate software quality standard that was revised to ISO/IEC 9126-1:2001 and the latest revision of this standard is ISO/IEC 25010:2011 (ISO9126, 2001). This standard categorizes software quality into a) internal and external quality category that consists of functionality, reliability, usability, efficiency, maintainability and portability; and b) quality in use category that consists of effectiveness, productivity, safety and satisfaction attributes (ISO9126, 2001). Grady (1992) introduced a software quality model named FURPS model (FURPS stands for functionality, usability, reliability, performance and supportability). Each of these attributes consist of further sub-categories or subcomponents as summarized in Table 6-3.

Table 6-3. Main elements of the FURPS model (Source: Grady, 1992)

FURPS attributes	Subcomponents
Functionality	Main features
	Capabilities
	Generality
	Security
Usability	Simplicity
	Learnability
	Memorability
	Efficiency
	User documents
	Training materials
	Satisfaction level
	Usefulness
Reliability	Consistency
	Robustness
	Recoverability
	Predictability
Performance	Efficiency
	Speed
	Accuracy
Supportability	Configurability
	Compatibility
	Data versatility
	Model versatility
	Data Integration
	Model integration
	Adaptability

The different quality models discussed above provide a useful framework for software quality assessment. A few studies have been done to review these software quality models (see, for example, Al-Badareen et al., 2011; Deissenboeck et al., 2009; Miguel et al., 2014; Sadeghzadeh Hemayati & Rashidi, 2018). The reviews of these quality models suggest that although these software quality models provide their own set of attributes to test the software quality, their usefulness depends on the type of software or DSS and its provided functionalities (Oztekin, 2011; Sadeghzadeh Hemayati & Rashidi, 2018; Singhaputtangkul et al., 2013). Therefore, the software developers can choose either of these quality models based on their specific needs, capabilities, environment and the functional aspects of their software that they want to test.

In this study, the researcher has chosen the FURPS model as it suggests the attributes that are most relevant to this study. The functionality, usability, reliability, performance and supportability attributes of the FURPS model are further elaborated through 26 subcomponents that were useful to comprehensively test the various features, scenarios, capabilities and results generated by the KCDSS. During the evaluation process, each selected expert was interviewed through questionnaires (see Appendix C) having different questions covering the five attributes of the FURPS model. The Experts provided feedback using a five-point scale: Strongly Disagree, Disagree, Neutral, Agree and Strongly Agree using a formatted feedback form. The feedback was then computed using Likert's 5-point rating: Strongly Disagree = 1, Disagree = 2, Undecided = 3, Agree = 4 and Strongly Agree = 5 and the findings are presented using charts and spider graphs. A discussion of each of the five attributes of the FURPS model is presented in the following sections.

6.3.1 Evaluation of the functionality

According to the FURPS model, functional requirements determine the capabilities and features of a built system. In this study, the purpose of evaluating the functionality aspects of the KCDSS was to identify how well it supports the decision-makers to undertake activities and making decisions. During the evaluation, KCDSS was demonstrated through its essential features and decision support capabilities for different damage modelling scenarios. The questionnaires are designed through the identification of main components of the functionality aspect, as guided by Grady (1992) in the FURPS model, and listed in the Appendix C. These aspects included main features, capabilities, generality and security of the KCDSS to evaluate:

- main features for the intended usage;
- functional and error-free capabilities;
- generalizability for other scenarios;
- security from hackers; and
- support to the decision-makers for making better decisions.

The detailed questions being asked from the evaluators about the functionality aspects of the KCDSS are listed in Appendix C, and the average scores of their responses are illustrated in Figure 6-3.

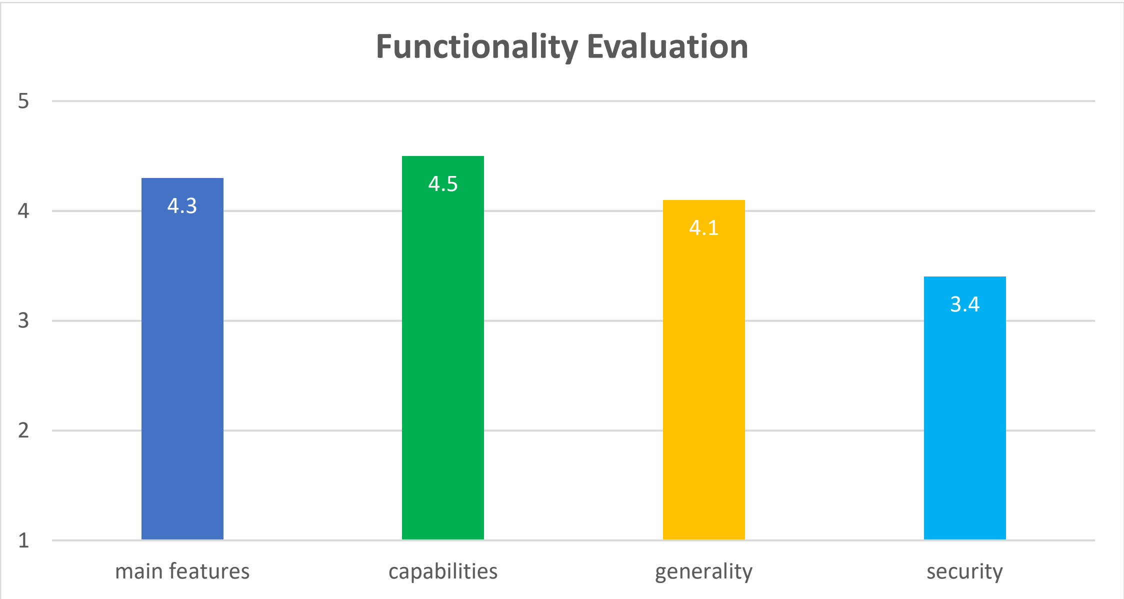

Figure 6-3. Results of functionality evaluation

The *main features* and *Capabilities* of the *Functionality* aspect of the KCDSS received a good response from the evaluators, which shows that the KCDSS was able to demonstrate the salient features required for the decision-makers to improve their decision-making capability. The response from one of the evaluators during the interview was:

> *It will be exciting to see how the KCDSS software responds to more data and different recovery knowledge when more CI networks will be added. Also, testing it with CI network data from different cities and comparing the results with the Wellington region could show preparation levels of different CI network providers to find out short-term and long-term infrastructure extendibility projects. [Evaluator-5]*

The *Security* component however got lower scores, mainly because most of the evaluators gave neutral comments about the security feature as the KCDSS hasn't been implemented in a real-world scenario as yet and although the user login mechanism has been a part of the KCDSS, the real test would be based on how the KCDSS would perform when exposed to the world through a web-based prototype. An evaluator discussed the security feature by saying:

> *I can't tell at this moment the security level of this software. Are you planning to implement it in a real-world scenario as web-based software?... Maybe future work to test real data will be useful to validate the current security features and extended features make it more secure. [Evaluator-9]*

6.3.2 Evaluation of the usability

Usability is a qualitative attribute of the user interface that assesses its simplicity, learnability, memorability, efficiency, user documents, training materials, satisfaction level and usefulness (Piemonti et al., 2017). Usability is defined by the International Organization of Standard (ISO 9241-11), as discussed by Jokela et al. (2003) is "the extent to which a product can be used by the specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use". Estimating usability attributes for the KCDSS helped the researcher to identify user interactions with the KCDSS and gain a better understanding of their behaviours, preferences, and needs. During the evaluation process, the evaluators were asked to provide their feedback after a demonstration of the KCDSS. They also tested the user interface by creating scenarios of their own choice to test the usability features in detail. The aspects through which the usability of the KCDSS has been evaluated are:

- The simplicity of use;
- clear and easy to understand the sequence of the interface screens;
- easy to learn functions and terminologies;
- efficiency to resolve the problems;
- helping material and training guidance;
- training of new users; and
- comfort and acceptability of usage.

The detailed questions being asked from the evaluators about the usability aspects of the KCDSS are listed in Appendix C, and the average scores of their responses are illustrated in Figure 6-4.

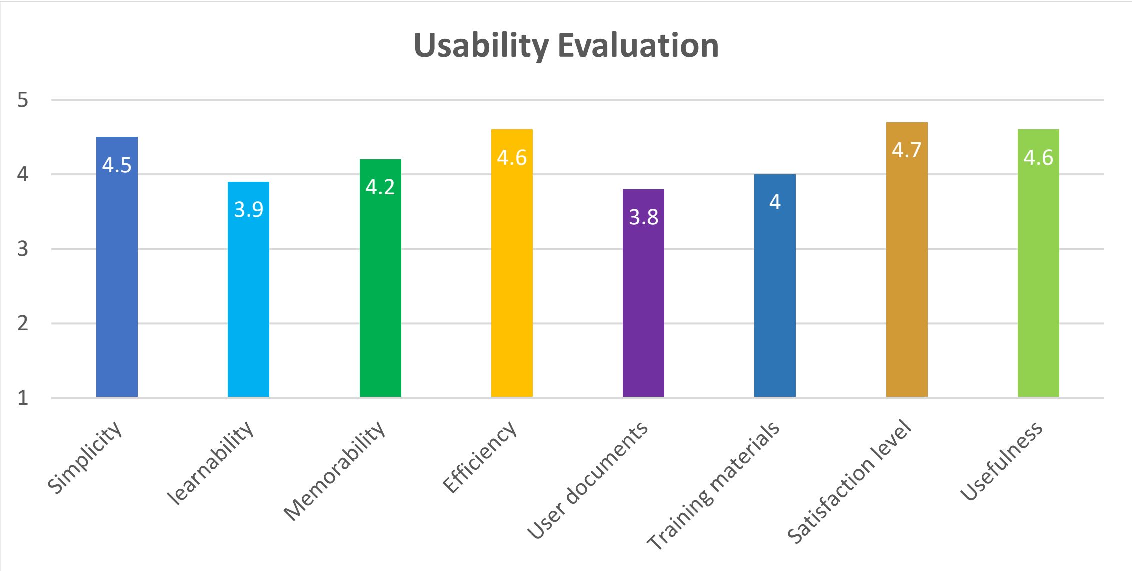

Figure 6-4. Results of usability evaluation

Within the *usability* feature, most of the evaluators were extremely satisfied with the *simplicity, efficiency, usefulness,* and *satisfaction level* of the KCDSS, which shows that the major usability aspects have been successfully fulfilled within the KCDSS. Evaluators however pointed out the lack of *user documentation* and *learnability* through the *training material.* One of the evaluators pointed out during the discussion that:

> *I think training material is very useful for the new users because at the beginning it is unclear how a user starts working and what are the accessible features and in which order. [Evaluator-15]*

Another evaluator suggested:

> *A demonstration through a video would be a useful idea so that the users can access the video any time and recall what they need to do if they are stuck at something. [Evaluator-1]*

The lack of training material was not considered as a limitation of the KCDSS because most of the evaluators were satisfied with the ease of use and simple user interface design. The reason for suggestions about adding the training material was to have an additional feature in the KCDSS for a user who would face difficulty understanding how to navigate to a particular function.

6.3.3 Evaluation of the reliability

The reliability feature in this study evaluates the capability of the KCDSS to maintain a specified level of performance when used to test different hazards and damage. Grady (1992) suggests evaluating reliability through consistency, robustness, recoverability and predictability. Evaluating the reliability and quality of a software system are somewhat similar. Normally, the focus of evaluating quality is to prevent any potential defects in a software artefact, whereas, reliability is the level of support provided to the users to prevent any potential failures when they use the end-product and successfully achieve their goals. The reliability aspects though which the KCDSS has been evaluated are:

- consistency in the outputs;
- minimized number of errors through the user interface;
- proper error messages and warning dialogs in all the screens;
- availability of operations that can be performed based on a user action;
- tolerance of the user errors and enough feedback when the user makes an error; and
- possibility of recovering from a user error.

The detailed questions being asked to the evaluators about the above-mentioned reliability aspects of the KCDSS are listed in Appendix C, and the average scores of their responses are illustrated in Figure 6-5.

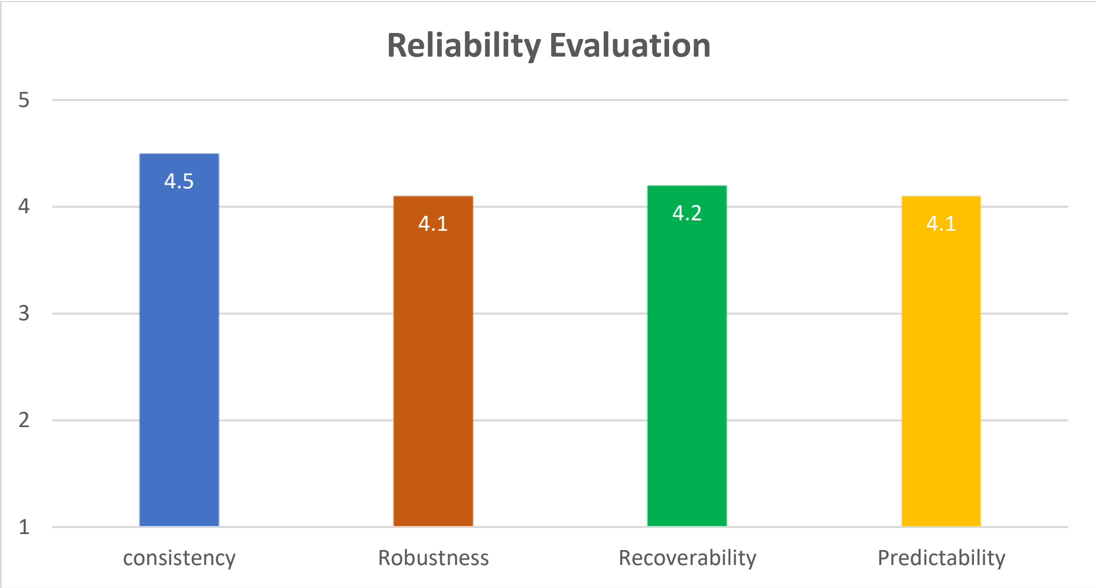

Figure 6-5. Results of reliability evaluation

Within the *Reliability* feature, the evaluators were overall satisfied with all the related questions. In some places, however, there were suggestions for improving the text of the warning and error dialogs, as they were unclear. The evaluators were generally happy to see that all the input fields of the KCDSS were properly maintained and the forms could not be submitted if the required data was not provided in the defined format. A response from one of the evaluators during the interview was:

> *The demonstration of scenario creation and outage results is smooth without any errors … I like the error dialog boxes at each step when a user gives invalid inputs. [Evaluator-7]*

Another evaluator suggested:

> *I like the backup and restore feature so that your users can recover the data at any stage. I am a little confused about the difference between data and results. Some explanation for each item on the screen will be very useful to avoid any confusion. [Evaluator-15]*

6.3.4 Evaluation of the performance

Performance is one of the core features of the KCDSS and Grady (1992) suggest evaluating it through efficiency, speed and accuracy to perform the computational operations to give the desired results. The KCDSS should be capable of providing a high level of productivity once the user gets familiar with using it. Efficiency in this aspect should also enable the users to achieve specified tasks in the minimum amount of computational time with accuracy and completeness. The aspects through which the performance of the KCDSS has been evaluated are:

- response time for generating the results;
- speed of handling a huge amount of CI network data; and
- accuracy of results as per user expectations.

The detailed questions being asked from the evaluators about the performance aspects of the KCDSS are listed in Appendix C, and the average scores of their responses are illustrated in Figure 6-6.

Figure 6-6. Results of performance evaluation

Performance is always one of the key features of any software system and the major aspects of functionality are efficiency and accuracy because if these features are compromised then the results can be of no use. Due to the uploading of a huge amount of data, the speed of generating the results can be compromised but if the accuracy is validated then speed cannot be an issue as most of the simulation programs generally take hours to process. An evaluator gave feedback about the performance of KCDSS by saying:

> *I am satisfied with the overall performance as the scenario [creation] and getting the outputs was smooth without any error … It is good to see that you have made the [results review] option to check the accuracy of the results. [Evaluator-2]*

Another evaluator said:

> *KCDSS works great in terms of efficiency and accuracy. I can understand that the simulation software generally takes some time to process the data and there was a lot of data processing in the background when you were demonstrating the scenarios. Therefore, as far as the results are accurate, speed can be compromised a little. [Evaluator-9]*

6.3.5 Evaluation of the supportability

Evaluation of the supportability of an artefact is a significant feature that is concerned with characteristics such as configurability, compatibility, data & model versatility, data & model integration and adaptability. Grady (1992) argues that these characteristics provide a useful way to evaluate customizable configuration options, compatibility with other software tools, possibility to integrate with other models for enhancing the results and usefulness of the KCDSS with changing datasets. The aspects through which the performance of the KCDSS has been evaluated are:

- options for data configurations;
- compatibility with other related software;
- handling of a versatile amount of data and models;
- integration of data of different formats and models of different kinds; and
- the adaptability of the user interface to various task requirements.

The detailed questions being asked from the evaluators about the supportability aspects of the KCDSS are listed in Appendix C, and the average scores of their responses are illustrated in Figure 6-7.

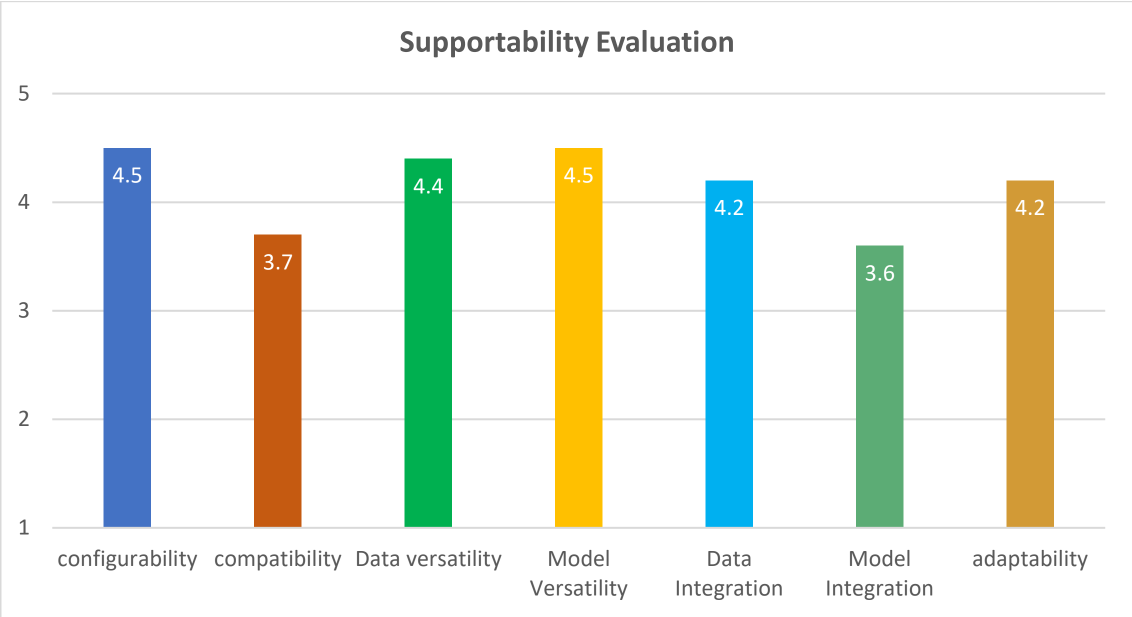

Figure 6-7. Results of supportability evaluation

Supportability features also got good average scores from the evaluators. Most of the evaluators were however unsure about the integration with other models and the compatibility of the KCDSS with other software systems. One of the evaluators gave the feedback about model integration by saying:

> *It is good to see that it [KCDSS] is compatible with other related models of Aotearoa New Zealand such as RiskScape and MERIT. You said that you have used damage results from RiskScape and made a CSV file manually. An automated process to convert data from RiskScape that can go directly into your DSS will be a very useful future work. [Evaluator-13]*

The electricity, potable water and road networks have different characteristics and because they belong to different CI network providers, therefore the data format is also not the same. But the evaluators appreciated that KCDSS was able to integrate models of different CI networks efficiently to generate the desired interdependency results. Apart from data and model integration, evaluators were very pleased to see the variety of configuration options in the KCDSS interface. The configuration options give users a confidence level that the system is flexible with user inputs and is easily modifiable to give a variety of options to the users. The response from one of the evaluators for the customizability was:

During the limited time of your studies, it is great to see that your software [KCDSS] has a lot of customization options, the versatility of integrating with different models and future possibilities for adding more CI networks. [Evaluator-5]

6.3.6 Discussion

The participants represented various fields of emergency response and recovery, lifeline group, lifeline utility providers and emergency management research and the attributes of testing the software quality of the KCDSS provided useful feedback to the researcher. The average scores of all these attributes were satisfactory and above the level of minimum acceptance, that is, 3. A summary of the results of 26 subcomponents of the FURPS model is illustrated in Figure 6-8.

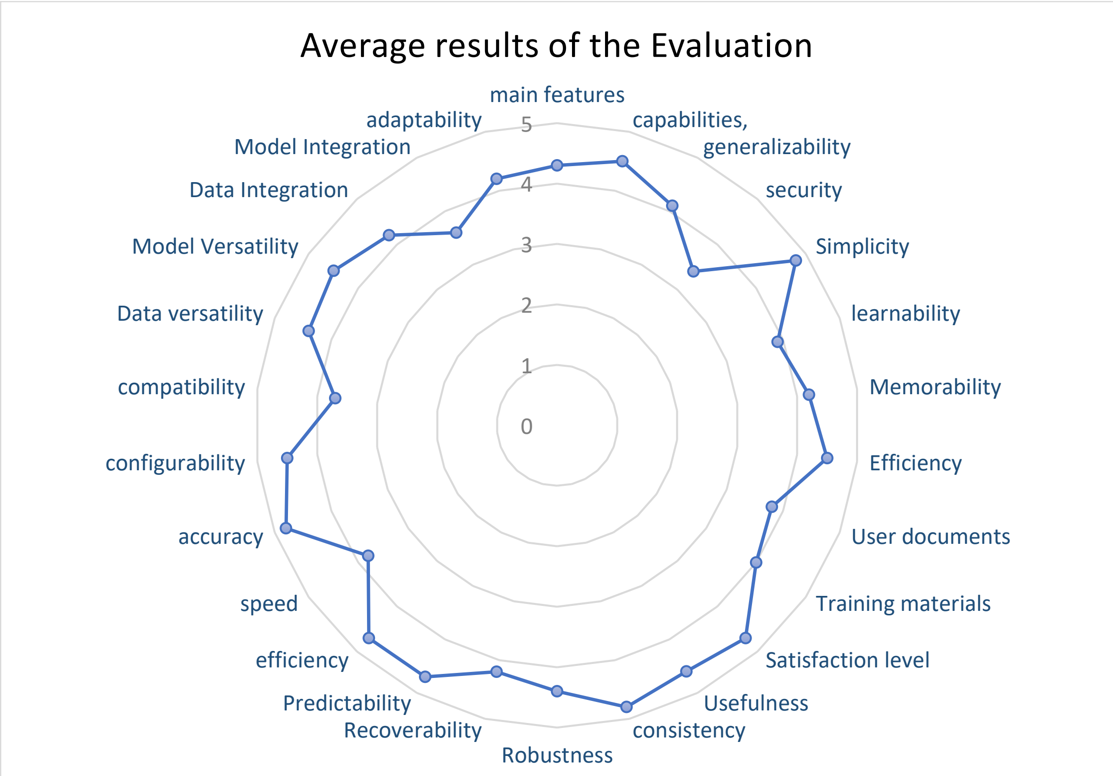

Figure 6-8. Average results of the complete evaluation process

These results are the average score of the responses of all fifteen evaluators and the average didn't vary too much that validates that the design and functionalities of the KCDSS are relatively easy to understand for people from different perspectives. The interview responses not only validated the functionality, usability, reliability, performance and supportability aspects of the KCDSS but also guided the researcher to find ways for future improvements. In conclusion, from the results of the evaluation, it is evident that KCDSS performed according to the expectation of evaluators from multidisciplinary backgrounds and the evaluation process resulted in the following major findings:

- KCDSS performed efficiently with existing data from CI networks in the Wellington region. A future extension of this work to include other CI networks from other regions of Aotearoa New Zealand will be very useful.
- Overall, the user interface was easy to understand. However, some screens need helping guides to about required inputs from the user.
- A video tutorial should be made to go through each step of the scenario creation and the process of getting outage results.
- A few improvements needed to use appropriate naming conventions in some of the user interface screens. If this KCDSS will be deployed in emergency management or a CI network providing organization, then they should be involved to carefully use the terminologies as per their organizational needs.
- KCDSS should be tested with more data to see the effects on the speed of getting the results. This will also be useful to determine the hardware requirements for smooth execution of KCDSS simulations and identification of areas to do coding optimization.
- An interface module can be developed in future to automatically retrieve topological and damage data from other software models such as RiskScape.
- Although KCDSS modelled CI network data for the Wellington region, due to its customizable and flexible development in MVC based three-tier architecture, this work is extendible in future without affecting its current state.

6.4 Chapter Summary

After KCDSS development, it has been evaluated to understand the validity, verification and capability of KCDSS to perform according to the user expectations. The KCDSS has been thoroughly verified during the software development stages to ensure that the source code was error-free. The syntax of the programming languages being used for the development of the KCDSS conformed to the quality standards. Testing all the input parameters has validated the presentation tier of the KCDSS. The validation and verification of the KCDSS made it efficient enough to be finally tested from a list of evaluators. The FURPS model was used to check the functionality, usability, reliability, performance and supportability aspects of the KCDSS. Out of twenty-six subcomponents of these five aspects, most received positive and encouraging feedback from the evaluators, which proves that the demonstration of the KCDSS has fulfilled the expectations of the decision-makers.

7 CONTRIBUTIONS AND FUTURE DIRECTIONS

7.1 Introduction

This chapter elaborates a summary of the work presented in different parts of this study, followed by a discussion of the research questions and the methods used to accomplish the research objectives and then highlights the contributions and impacts of this study to research and practice. Finally, it concludes with the limitations of this study and directions for future research.

The overall aim of this study was to design and develop a KCDSS using a computer-based impact assessment framework that assesses the functionality of CI networks by modelling their interdependencies to support the needs of stakeholders, such as the local government sector (e.g. emergency managers) and CI network providers in their decision-making processes.

In summary, Chapter 2 *(Literature Review)* identified the research gaps and challenges in the modelling of CI interdependencies and the use of proper DSS to enhance decision-making capabilities. It also explored the potential influence of recent modelling and simulation technologies to address the challenges associated with understanding CI interdependencies. Then, a detailed investigation of the use of KCDSS is presented by providing some real-world examples followed by a thorough literature review of the existing methods.

Chapter 3 *(Research Methodology)* used the research onion model to describe the perspectives and strategies that were adopted in this study to answer the research questions and to achieve the aim and objectives. The research was conducted with the pragmatist philosophical approach, thereby generating theory through an abductive approach, which started with an observation of the CI networks to find the simplest and most likely explanation for understanding their interdependencies. Driven by the Design Science Research (DSR) strategy, this study used a topology network-based approach as a conceptual artefact for understanding the CI component data and the dependencies between components of the same CI as well as between different CIs. Furthermore, a KCDSS has been developed as the second research artefact to contribute to knowledge about IS and disaster management by achieving the proposed objectives successfully and fulfilling the identified research gaps. Both the qualitative and quantitative data were collected through interviews and questionnaire methods as methodological choices for this study. As this study obtained qualitative information from experts in relevant CI network providers, a combination of purposeful sampling strategies (criterion and snowball) were employed.

Chapter *4 (Artefact - I: Framework for Integrated Impact Assessment of Critical Infrastructure Networks)* described the conceptual framework as the first artefact of this study. This chapter outlined the design of the impact assessment framework using modules of CI component representation, damage representation, network performance assessment and interdependency assessment. A topology network-based approach was chosen to represent the CI components of a test case scenario in the Wellington region. The CI network component interdependencies were represented using a generalized dependency matrix and the recovery calculation was explained using the Dijkstra algorithm for shortest path calculation. The integrated methodology of four different modules presented the phases and data needs for interdependency modelling between the three modelled CI networks.

Chapter 5 *(Artefact - II: Development of Knowledge-centred Decision Support System (KCDSS))* described the implementation of the integrated impact assessment framework using the knowledge-base of the adopted recovery strategies for the test case scenario in the Wellington region's CI networks. This chapter presented the overall implementation architecture of the KCDSS following a layered architecture pattern, which provided a modularization to simplify the implementation process. It also demonstrated different functionalities of the KCDSS through user interface screens.

Chapter 6 *(Evaluation of the KCDSS)* described the evaluation process of the KCDSS through the involvement of experts from various fields of emergency management. In-depth interviews and the FURPS analysis model were the main instruments used to evaluate the functionality, usability, reliability, performance, and supportability features of the KCDSS.

In summary, two research artefacts have been developed in this study that can contribute to both research and practice. The conceptual framework for integrated impact assessment is useful to understand the characteristics of individual CI networks and the failure propagation between interdependent CI networks. The KCDSS facilitates 'what-if' scenarios with a variety of control variables that allow decision-makers to test and verify their desired recovery strategies. The following section elaborates how the objectives of this study have been addressed and then further details the contributions of this study to research and practice.

7.2 Addressing the research objectives

This section summarises the findings and contributions of this study through the accomplishment of the research objectives that were described in the first Chapter.

Research Objective 1: Exploring fundamental concepts, requirements, existing methods, and current techniques of understanding the CI interdependencies

This objective was fulfilled through a review of literature that is summarized in Chapter 2. This process was guided by the research question *"What are the requirements and challenges for understanding CI interdependencies and issues of decision-making during an emergency scenario?"*. Based on the literature review, fundamental concepts related to the definitions of CI, dependencies, interdependencies, decision-making theory, decision support systems and finally the available approaches for modelling and simulation of CI interdependencies were explored.

A review of the literature guided the selection of an appropriate modelling and simulation approach to understanding the CI interdependencies. In this regard, existing studies have been explored that used a variety of techniques for modelling CI interdependencies (for example, Bloomfield et al., 2017; Griot, 2010; Ouyang & Dueñas-Osorio, 2011a; Panzieri et al., 2004; Pederson et al., 2006; Zorn et al., 2020). Given the inherent complexities of CI networks, no single technique or approach can answer all questions for any CI and no universal model can completely model the CI interdependencies (Eusgeld & Nan, 2009; Murray et al., 2008). The researcher, therefore, aimed to demonstrate how CI network recovery performance can be modelled, focusing on delivering results that can be useful for local and regional-level CI network providers within their decision-making contexts, such as:

- providing services delivered through CI network components (for example, the supply of electricity, water, fuel, natural gas and provision of transportation facilities roads, bridges, railway tracks, airports and wharves etc.);
- identification of the number of endangered CI network components due to the risk of major disruptions and development of appropriate mitigating strategies in a major region of interest; and
- development of action plans and risk assessment strategies to handle the vulnerabilities in CI networks.

The available literature indicated that the existing studies for modelling the CI interdependencies have adopted one of the five different methodological approaches, namely, (i) empirical, (ii) agent-based, (iii) system dynamics, (iv) economic theory and (v) a network-based approach. The researcher concluded in the literature review that it is not possible to develop a single solution to address all the key issues of CI interdependency modelling and the related decision-making contexts. Instead, there is a need for a more pragmatic and integrated approach to building and linking CI network models based on their regional characteristics. An integrated modelling approach proved to be useful to build a platform that allows the use of different methodological approaches depending on the stakeholders' needs, geographical concerns and regional characteristics of the CI networks to be modelled. Furthermore, the researcher identified some key aspects of network performance to enhance the decision-making of relevant stakeholders, such as:

- the spatial and temporal extent of the outage of services;
- knowledge of vulnerable components in the network;

- effects on network performance after adopting various intervention options;
- the effect of interdependencies affecting the network;
- the effect of changing recovery strategies for the damaged components; and
- the effect of changing the location for recovery resources.

Research Objective 2: Development of a conceptual CI performance framework to generate disruption measures in spatial and temporal context and to generate time-stamped outage maps.

This objective has been fulfilled through the development of an integrated impact assessment framework for the representation of CI components using a topology network-based approach and assessment of a CI network's functionality with and without dependency on the other modelled networks. This objective finds the answer to the research question *"What form would a framework take for a better representation of CI components and the assessment of their functionality?"*.

A variety of software systems, simulators and frameworks have addressed the fundamental issues related to a CI such as its organisation, behaviour, risks, threats and vulnerabilities (for example, Bagheri et al., 2007; Basu et al., 1998; Dudenhoeffer et al., 2006; Haghnevis et al., 2016; Panzieri et al., 2004). Although these simulation tools have made significant efforts to represent, simulate, and model the CI interdependencies, there is still a need for further investigation to provide new or innovative models and techniques that can meet the practical needs of decision-makers.

To develop a CI performance framework that can model the CI interdependencies by resolving the limitations in existing literature, it is argued that each CI need to be modelled starting from its macro components that have specific and easily recognisable roles. There needs to be a consistent description of the capabilities and behaviours of these components and fuzzy numbers can be used to code parameters and values to avoid any vague statements about their characteristics. Finally, there should be a provision for command and control systems to be integrated with real-time decision support to consider the impact of dependencies and interdependencies among the different CIs (Ani et al., 2019; Griot, 2010; Raskob et al., 2015).

Therefore, an integrated impact assessment framework is designed and presented in Chapter 4 that is developed using modules of CI component representation, damage representation, network performance assessment and interdependency assessment. These modules have been tested using data from a test case scenario of the Wellington Region's CI electricity, road, and potable water networks. The network models were constructed by acquiring various forms of data from different sources in two steps. The first step was to collect the network configuration, or relates to location details of the components, their basic feature and their connectivity link to other components. The second step was to acquire data on probable damage or status of failure to the CI network components. This information was sourced from the risk analysis tool named RiskScape, which models potential damage to the selected network components under a chosen level of earthquake hazard (Schmidt et al., 2011).

A vital aspect of the developed framework is that it is valid for both the component and network-level linkages. The component level linkage is achieved by linking different CI network component models through the identification of intra-dependencies between the components to understand the functionality of a single CI network. Similarly, the components of multiple CI network models have been linked together to model the interdependencies between different CI networks. A generalized dependency matrix has represented the CI network component interdependencies and the recovery calculation has been explained using the Dijkstra algorithm for shortest path calculation.

Research Objective 3: Development of an interactive DSS that hosts the processes of the conceptual framework and enables 'what-if' analysis for various scenarios within a simulation-based environment.

This research objective was accomplished through developing a KCDSS by keeping in view the research question *"What functional features should a DSS have to support decision-making* *during the recovery of CI networks?".* A review of literature is presented in Chapter 2 about existing efforts of developing DSSs that indicated several examples of DSS tools or software for various fields of emergency management (for example, Bell et al., 2007; Daly et al., 2015; Eguchi et al., 1997; Erdik & Fahjan, 2006; FEMA, 2003; Jain & McLean, 2003; Markus et al., 2004). The existing DSSs can be applied to various domains of emergency management and use different techniques and technologies such as artificial intelligence, network models and simulation strategies to achieve their desired goals (Ariav & Ginzberg, 1985; Choraś et al., 2010; H. Wang, 2013).

Through the review of existing literature, the researcher concluded that the available DSSs have some significant limitations, such as heavy reliance on GIS data (Aleskerov et al., 2005), need for a high level of expertise and training (Zografos et al., 2000), dependence on a high level of engagement and interpretation from the decision-makers (De Maio et al., 2011), reliance on human involvement to extract and interpret a large amount of CI interdependency data (Hormdee et al., 2007), and lack of support for variations in organisation-specific requirements (Tinguaro Rodríguez et al., 2010).

It is also highlighted by the researcher that for developing a DSS to model CI interdependencies, it is important to consider the needs and preferences of the relevant decision-makers that would become potential users of the DSS. As the damage to the CI networks directly or indirectly affects the population, therefore, it is also argued that the developed DSS should have the capability to self-learn, identify associations between various types of CI network data, and perform heuristic operations, when needed. Therefore, it was concluded that a Knowledge-centred Decision Support System (KCDSS) for modelling CI interdependencies can be a useful tool to provide specialized problem-solving expertise stored in a structural form of knowledge that would enhance the decision-making capabilities of its end-users.

The knowledge elicitation process gave insights about the CI network recovery strategies in a structured format, which was then transferred into the KCDSS to provide training and decision aiding facilities to the decision-makers. The elicitation of recovery strategies was useful for the researcher to understand available resources and personnel within the selected CI network providers, access to the repair equipment, region-specific needs to prioritize repairs of certain critical facilities and any alternate plans for a faster recovery process. For the elicitation of these recovery strategies, Critical Decision Method (CDM), was utilized, which is a Cognitive Task Analysis (CTA) method for requirement elicitation. A structured approach to analyse the CDM data proved to be useful to effectively organize a large amount of data. The first step of this approach was o create a decision chart to illustrate the decision process adopted by the participants on a paper timeline, followed by creating a narrative-based incident summary to elaborate the timeline design in a more meaningful way. Finally, a decision analysis table was developed through the identification of goals and strategies from the first two steps. The structured data was then modelled in the form of IF-THEN pairs using the Rule-Based Reasoning (RBR) approach.

The computer-based KCDSS is implemented through ASP.NET MVC 5 with Entity Framework and SQL Server support that is capable of handling a large amount of data and instructions from the user. Its scope is defined as a recovery-time estimation tool that receives the CI network's topological and damage information through additional interfaces or sources. One of the key strengths of the KCDSS is that it works efficiently as a CI network recovery modelling tool and has been built by adopting the shortest path tree method, with user-friendly graphical interfaces. The flexibility of KCDSS to set up scenarios of a network with different damage realisations or configurations encourages users to run any number of 'what-if' scenarios and to generate necessary results to make an informed decision.

The various features of the KCDSS and its capabilities are demonstrated through a set of real CI networks in the Wellington region by analysing network performance independently and with interdependencies to generate outages of services in spatial and temporal aspects. The capabilities of KCDSS are versatile enough that CI network managers and decision-makers from the government and private sectors will be able to make informed decisions to address the likely impact of CI network failures.

Research Objective 4: Evaluating the KCDSS from a list of experts and identify areas for future development.

The evaluation of KCDSS is discussed in Chapter 6, which is guided by the research question *"What attributes must be considered for evaluating the functionality of the DSS?".* This chapter focused on understanding the capability of KCDSS to perform according to user expectations.

The literature review indicated that evaluation of a DSR artefact needs well-designed evaluation methods to demonstrate the utility, quality, and efficacy of a research project (Herselman & Botha, 2015; Hevner et al., 2004). Several researchers have emphasized the importance of evaluation for a DSR study (for example, Arnott & Pervan, 2014; Herselman & Botha, 2015; Hevner et al., 2004; Peffers et al., 2007; Pries-Heje et al., 2008; Venable et al., 2016). The researcher has also identified some guidelines for doing a DSR evaluation from the available literature (for example, Pries-Heje et al., 2008; Sonnenberg & Vom Brocke, 2012). It is argued that evaluation of a DSS needs a process of verification, validation and quality control to determine the usability and functionality of built artefacts and to examine the research assumptions, identify critical limitations and the reasons for generating specific types of results (Herselman & Botha, 2015). The researcher has verified the KCDSS artefact by careful development of the source code to ensure the quality of the software design and architecture and to make sure that all the functional aspects of KCDSS are performing correctly, the researcher has validated the KCDSS through the *Unit Testing* mechanism in this study. For this purpose, several tests have been created for individual functionalities of the KCDSS in an open-source automated unit testing framework, NUnit, which is a popular testing framework for .Net based software applications (Hamilton, 2004).

For explaining the KCDSS evaluation, the researcher has used a strategic framework proposed by Pries-Heje et al. (2008) that provide guidelines for evaluating the DSR artefacts using two dimensions: time and evaluation method. The researcher has used this framework in this study because it is designed not only to evaluate the research outcomes but also to find ways for contribution to the knowledge-base. Following the guidelines of this framework, the KCDSS prototype is evaluated ex-post using the FURPS (functionality, usability, reliability, performance and supportability) software quality model. Evaluation was done by a group of experts representing CI network providers and regional emergency management organizations. The functionality, usability, reliability, performance and supportability attributes of the FURPS model are further elaborated through 26 subcomponents that were useful to comprehensively test the various features, scenarios, capabilities and results generated by the KCDSS. From the results of the evaluation, the researcher concluded that KCDSS performed according to the expectation of evaluators from multidisciplinary backgrounds.

The following two sections of this chapter briefly explain the contributions of this study to the research community and for the practitioners in various related fields.

7.3 Research contributions

This study makes several contributions to existing knowledge related to CI interdependency modelling and knowledge-base development of the KCDSS. Following DSR as a research strategy, this study first proposed an integrated impact assessment framework using an iterative design process as its first research contribution. In this regard, the researcher reviewed and discussed some existing software packages from the recent past that have been developed to address various aspects of individual models (see, for example, Bebbington et al., 2008; Bell et al., 2007; Boulos et al., 2014; Buxton et al., 2015; Nan & Sansavini, 2016; Zorn & Shamseldin, 2016). However, it is essential to link these models to increase their uptake in hazard-impact assessments. At present, there is no such structured framework to link different models together and there is a need to understand the information needed in the flow from one model to the next, to facilitate integrated impact assessment of infrastructure networks (Paltrinieri et al., 2013). Furthermore, CI network modelling through identification of component-level dependencies proved to be beneficial to understand single and multiple CI network interdependencies. To overcome the existing limitations, the researcher utilized a topological network-based approach to model the interdependencies between different CI networks, and contributed to the existing knowledge through the following aspects:

a) Guidance for the research and practice about how to apply a topology network-based approach to represent CI interdependencies and to understand their functionalities;

b) Innovative procedures for collecting, analysing and representing quantitative data of CI components; and

c) Providing support for future research to understand both the component-level and network-level linkages for single and multiple CI networks.

The conceptual integrated impact assessment framework is developed in a modular form that is extendable in future to add new CI networks. Furthermore, software implementation and demonstration of CI interdependency results from this framework were presented through a KCDSS, which is proposed as the second research contribution of this study. Similar to the conceptual framework, the KCDSS is also developed in a modular three-tier architecture, which provides several contributions, such as:

a) The KCDSS is developed as an interactive and customizable graphical representation tool that is useful to support complex strategic decision-making problems;

b) The KCDSS provides a convenient and efficient platform for enhanced decision-making through a knowledge-base of real-life recovery strategies.

c) The knowledge elicitation and knowledge modelling has been comprehensively explained during the development of the KCDSS that will be beneficial for researchers involving in future similar research; and

d) The KCDSS will enhance the decision-making of regional lifelines groups, CI network organisations, local/regional CDEM organisations and the natural hazard impact modelling research community.

7.4 Research impacts

The research has been presented on several platforms including publications by Syed et al. (2018) at ISCRAM Asia Pacific 2018 and Syed et al. (2018) at NZSEE 2018 conferences. Two journal papers have recently been published in the NZSEE bulletin (see, Sadashiva et al., 2021; Syed et al., 2021). These articles will contribute to the existing knowledge of CI interdependency modelling. The researcher also presented in QuakeCoRE lightning talks, Disastrous Doctorates, JCDR's lunch presentations and different 3-minute thesis activities. The researcher has been funded throughout the studies from GNS Science and has been part of the GNS Science Report write-up process to further contribute towards the research and practice of CI interdependency modelling work. Two GNS Science reports have been published during this study that is discussed below:

1. **RiskScape and Wellington Electricity Restoration Uncertainty Analysis - GNS Science Report: 2019/08**

GNS Science Report by Syed et al. (2019), titled 'RiskScape and Wellington Electricity Restoration Uncertainty Analysis' is another research contribution. The work presented in this report was an extension of this study in which the electricity network was selected as a single CI network to test out the potential for propagating the uncertainty in damage state through outages and restoration time estimates. Choosing only the electricity network had the benefit that its restoration is dependent only on road access, not on other CI networks. In contrast, the restoration of many other CI networks requires electricity. This meant that automated modelling could be used (albeit with only one estimate of road access restoration). The researcher tested out three different methods ranging from Monte-Carlo (brute force) methods that require fully automated CI network outage and restoration models, through clustering techniques as an approach for the dimensional reduction to produce representative cases of damage that could then be used in an expert elicitation process. Monte-Carlo simulations depend on the modelling of many realisations of a scenario to be able to properly gauge the variance, and hence the uncertainty, encompassed by the modelling process. Clustering is a technique commonly associated with Artificial

Intelligence and Machine Learning that is used to analyse or transform data by grouping similar items close together in information space, while simultaneously maximizing the distance between dissimilar items. The important steps of this work include:

- The RiskScape tool was utilized for damage modelling to generate 1000 different representations of the Wellington Fault earthquake scenario in terms of the estimated damage sustained by the Wellington Electricity network due to each earthquake realisation.
- The RiskScape generated information is used as a basis for clustering in an attempt to reduce the number of sets of outage maps from 1000 to some more easily manageable number.
- The outage information is also used as a basis for clustering as above.
- All three (Monte Carlo, clustered damage, clustered outage times) sets of information are passed through the MERIT model providing three sets of economic trajectories (Harvey et al., 2017).

The researcher has proposed an extension to the use of clustering in the domain of hazard and risk modelling. It was justified in the report that clustering can be used to reduce the dimensionality of hazard/risk outputs in a useful fashion. One of the most well-known algorithms for clustering named the *k-means algorithm* has been adopted here, whereas the *Silhouette score* has been used as a basis for measuring the quality of the clustering results. The silhouette score is a measure of how similar observation is to its cluster compared to other clusters. It is a single score in the range -1 to +1 where a high positive value indicates a “good” clustering configuration and zero or negative values indicate “poor” clustering. The clustering approach was tested on two different types of output data utilizing the k-means algorithm:

- The direct damage state data output by RiskScape
- The processed recovery time data from the KCDSS

Clustering on the damage data outputs from RiskScape resulted in poorly resolved clusters and a silhouette score fractionally above 0. The recovery time data was better suited to clustering and consistently yielded better silhouette scores at all cluster numbers (k in the k-means). This work has revealed both extremes in that the damage state data resulted in poorly resolved clustering with only two clusters and the recovery time data resulted in better resolution for the clusters, but still, a reasonably large number of clusters (80) that would theoretically, incur a substantial time overhead for experts to review. It is maintained, however, that conceptually both clustered approaches offer substantial advantages over the raw Monte-Carlo results where experts cannot be expected to effectively process 1000 sets of results. In general, due to the interdependencies between CI networks, it will require either a complex computational model of the interdependencies or an iterative expert elicitation process. Even in the case of a complex model, experts would be needed to validate the outputs and check for inconsistencies. Therefore, clustering proved to be a useful means of reducing the breadth of damage realizations needed to represent the full range of potential recovery time outcomes.

2. **Modelling Interdependencies of Critical Infrastructure Network Recovery using a Decision Support System - GNS Science Report: 2020/18**

The researcher co-authored a GNS Science Report by Uma et al. (2020), titled ‘Modelling Interdependencies of Critical Infrastructure Recovery using a Decision Support System’. This report has mainly summarized the research outputs of this study including a demonstration of the different functionalities of the KCDSS. This work tested dummy electricity, road and potable water networks using placeholder values to see the feasibility of the KCDSS of handling CI network data for regions other than Wellington. The topological data files for the CI components were originally acquired in GIS shapefiles that were manually converted into CSV file format. To improve efficiency in terms of time and human error, an interface of an automated routine is developed to read the GIS shapefiles and extract necessary data to create input files compatible with the KCDSS requirements. The selection of topology network-based approach and implementation of KCDSS was discussed and a description of decision support capabilities was summarized for the relevant researchers to have a better understanding of the KCDSS features. Most of the research outputs and contributions of this report are already discussed in Section 7.3.

7.5 Practical contributions

Apart from the research or theoretical contributions, there are also some practical contributions from this study. The KCDSS has the potential to provide a formal communication channel for the enhancement of interactions between researchers and decision-makers. The KCDSS is an example of how the needs of decision-makers have been successfully implemented using a computer-based KCDSS and all the relevant stakeholders can get benefits for improved decision making.

The primary end-user target group of the KCDSS includes decision-makers dealing with in the field of emergency management (e.g. regional lifelines groups, CI network organisations and regional/local CDEM organisations). The stakeholders working in other related fields of disaster management can also utilize the KCDSS to understand the CI recovery process and various needs and challenges during emergency events. The key practical contributions from this study include:

1. **Protecting Wellington's Economy through Accelerated Infrastructure Investment Programme Business Case - WeLG's Programme Business Case**

A major role of this study was its contribution to the WeLG's Programme Business Case (Wellington Lifelines Group, 2019) by providing modelling results of the electricity network. The purpose of developing a PBC was to use a disciplined analytical approach to develop an integrated programme of CI projects across the lifeline sectors that would improve the resilience of the region. The Aotearoa New Zealand Treasury's Better Business Case process was used to guide the development of the PBC which is being undertaken in stages: Stage 1: Demonstration of Benefits of Programme (completed in April 2018). Stage 2: Financing and Timing (completed in September 2019). The remaining Commercial and Management cases which are also a part of the Better Business Case process will be developed individually by the lifeline organisations in the future.

The PBC project utilized a combination of a qualitative and a quantitative assessment process to demonstrate how economic disruptions at the regional and national level of a major natural disaster could be restricted by implementing an accelerated and phased programme of infrastructure resilience investments. To quantify the potential economic benefits that can be achieved by investing in the region’s infrastructure resilience, modelling works were carried on nine CI networks (e.g. potable water, road, electricity), for two main cases:

- Base Case: the CI networks with existing vulnerabilities exposed to a major natural hazard scenario.
- Improved Resilience Case: within the created model, specific investments are made to improve the resilience of the networks, and the upgraded networks are exposed to the same natural hazard scenario as in the base case.

The modelling workflow consists of the following three main components:

- Physical damage modelling - to understand the severity and extent of potential physical damage to the components exposed to a hazard
- Service outage modelling – to understand for how long the services will be lost (or operating at reduced levels of service) before the damaged components can be repaired or alternate arrangements made to restore the services to the customers
- Economic impact modelling – to understand the impact of service outages on regional and national economies at various times following the hazard event.

This work demonstrated that by making targeted and integrated CI investments before the next major earthquake in the region, the physical damage to the CI networks and disruption to the CI services can be reduced, thereby resulting in shorter service outage times and lesser economic disruption. The temporal service outage tables and maps generated from this work formed an essential input to evaluate and demonstrate the impact of the proposed resilience investments on the regional and national economies.

2. **Towards Robust Decision-Making in Natural Hazard Risk Management: Uncertainty Quantification for RiskScape-MERIT Modelling - Natural Hazard and Research Platform (NHRP) Project (NHRP, 2017)**

One of the research outputs through the RiskScape and Wellington Electricity restoration uncertainty analysis, discussed in the previous section was also part of a practical contribution of this study. The uncertainty analysis became part of a project of Natural Hazard and Research Platform (NHRP), titled *'Towards Robust Decision-Making in Natural Hazard Risk Management: Uncertainty Quantification for RiskScape-MERIT Modelling'* (Harvey et al., 2017). This project aimed to enhance Aotearoa New Zealand's ability to make robust decisions in natural hazard risk management by developing the capability to calculate direct and indirect socio-economic impacts that incorporate the inherent uncertainties in both natural hazard events and socio-economic modelling.

As discussed earlier, the objective of the PBC program was to create a proof-of-concept for linking information and integrating CI network models to undertake state-of-the-art simulation modelling of disaster events to support risk management decision-making. This project was a combined effort of RiskScape and Post Disaster Cities (PDC) projects of GNS Science along with MERIT modelling tool of Market Economics. The extension of PBC work included uncertainty in the modelling work. This project extended the existing work to enable the assessment of the sources of uncertainty in the modelling, test out different methods for propagating uncertainty through the RiskScape-MERIT modelling pipeline and determine the key uncertainties.

In the PBC project, the RiskScape model was used to estimate potential damage to buildings, humans, and CI network components in the case of an Mw7.5 Wellington Fault earthquake. Wellington's CI network providers were approached to get the CI network component data layers. The researcher's involvement in the PDC project contributed to determining outages and restoration times for the electricity network from the damage to individual network components, considering the restoration strategies including the interdependencies on other CI networks for recovery. This process involved extensive expert elicitation and iterative work to refine. Although

RiskScape is inherently probabilistic and able to produce multiple realisations of damage states, only one damage realisation was used in the PBC project due to the complexities of the expert elicitation process and the CI network interdependencies.

Therefore, this project was an extension to the PBC project by including multiple damage realisations from RiskScape. The electricity network was selected as a single CI network to test out the potential for propagating the uncertainty in damage state through outages and restoration time estimates as discussed in the previous section. The uncertainty results were propagated through to MERIT to determine the usefulness and applicability of the outputs from the clustering technique. This project also considered the natural hazard and socio-economic factors that have the greatest influence on the economic impacts of an event; and surveyed the natural hazard and economic factor uncertainties in the modelling pipeline to identify the probable prioritisation options for future refinement.

The improvements throughout this project in the modelling calibration, validation and computational efficiency greatly improved MERIT's capacity for modelling economic impacts of disruption events, not limited to natural hazard-related disruptions. Results generated from the researcher's KCDSS guided MERIT to know where to best put data and model refinements. It will also help practitioners identify where intervention efforts should be invested. The project also identified a set of plausible, diverse economic futures that will help decision-makers assess today's CI networks' investment decisions against a range of possible futures: fragmented future, techno-global future, and green-oriented future. The ability to consider multiple future scenarios will help decision-makers make more robust decisions considering options against a range of features. The researcher's contribution in this project also added value and new capabilities to the RiskScape and MERIT modelling tools and will improve the effective integration of these tools for multidisciplinary, integrated natural hazard impact assessment. The integration of RiskScape and MERIT models has been tested and this project seeks to create a step-change in this modelling by incorporating uncertainty estimation.

7.6 Limitations and future research directions

Despite the research and practical contributions made in this study, several limitations also need to be acknowledged. One of the major challenges for this study was the collection of CI component data from a variety of network providers. Apart from converting the topological data to make uniform input files, the sensitivity of sharing the CI data from the potable water network due to the data restrictions was another challenge. To overcome this issue, placeholder component data for the potable water network was designed and utilized as input to the KCDSS. The connectivity of potable water network with electricity and road networks was also based on assumed placeholder connectivity links. The successful inclusion of a potable water network and its connectivity with the other existing networks verified that more CI networks, such as telecommunication, natural gas or fuel networks can also be added to the KCDSS in future extensions of this work.

The topological data files for the CI components were first obtained in GIS shapefiles and the researcher converted them into CSV format as discussed in Chapter 4. In a future extension of this work, this manual data conversion process can be replaced with an interface module within the KCDSS that will directly obtain the topological data from GIS shapefiles. A preliminary exercise has been done already on a test network and has been discussed in the GNS Science Report by Uma et al. (2020). Similarly, after computation of the recovery times for CI networks, the resultant outage maps have been shown in the user interface of the KCDSS and the outage results can only be exported in CSV file format. Another interface module can be added in future to the KCDSS to automatically generate the results in GIS shapefile format. In this way, the output files would also include the georeferencing information of the supply zones.

Although the KCDSS can upload multiple damage realisations from any risk-modelling tool, the recovery calculations remain constant for all those realisations. It means that the same repair times will be applied to all the damage realizations. The inclusion of multiple damage realizations in the KCDSS was to model uncertainties in the modelling process. The same process can be applied to model uncertainties in recovery computation by providing a range of recovery times instead of constant values. Furthermore, an analysis of restoration processes can provide useful information about the critical CI network components or road connections that are driving the spatial and temporal variations for recovery and increasing the outage times.

The KCDSS has been developed on a topological network-based approach and therefore does not account for any flow of CI network services. A possible extension of the KCDSS can include the electricity or potable water service demand and available supply in the business as usual and during an emergency event to give more accurate results from the customer's point of view. Such an approach would enable connections between the loss of electricity or potable water demand and their corresponding outage that were currently not the scope of this study but might be useful in future related studies within the regional and national hazard and risk management organizations.

7.7 Conclusion

This study has drawn upon the use of DSR strategy and contributed to both the rigor and relevance, by developing and evaluating innovative research artefacts through an operational KCDSS. The first research artefact in this study is a topological network-based integrated impact assessment framework that was developed to understand the characteristics of large amounts of component data from multiple CI networks to model their interdependencies. The characteristics of these networks include the source to destination connectivity, categorization of components based on various types and location information for the understanding of the probable damage in case of a modelled hazard scenario.

The impact assessment framework was implemented with available CI network data to subsequently propose and implement a KCDSS as the second research artefact. The knowledge-base development of repair assumptions and recovery strategies for the damaged CI network components developed in this study can be considered as another important research contribution. The knowledge-based development process should be able to guide the knowledge elicitation and transfer of knowledge when implementing a KCDSS in a way that would improve the decision-making capabilities of the end-users.

This study also contributes to the existing research within the field of CI network interdependencies through peer-reviewed publications and science reports. The outage results generated from the KCDSS can also become a useful contribution for the practical utilization of some of the ongoing projects in Aotearoa New Zealand. With the above research and practical contributions, the outcomes of this study will support Aotearoa New Zealand's ability to make robust decisions in natural hazard risk management by developing the capability to calculate direct and indirect impacts in both natural hazard and socio-economic modelling. The contributions to the existing research and practice will also add value and new capabilities to existing and future hazard and economic modelling tools and will improve their effective integration for multidisciplinary, integrated natural hazard impact assessment.

REFERENCES

Ahmed, D. M., & Sundaram, D. (2011). Design science research methodology: An artefact-centric creation and evaluation approach. *Proceedings of the 22nd Australian Conference on Information Systems*.

Ahmed, D. M., Sundaram, D., & Piramuthu, S. (2010). Knowledge-based scenario management - Process and support. *Decision Support Systems*, *49*(4), 507–520. https://doi.org/10.1016/j.dss.2010.06.004

Al-Badareen, A. B., Selamat, M. H., A. Jabar, M., Din, J., & Turaev, S. (2011). Software quality models: A comparative study. *Communications in Computer and Information Science*, *179 CCIS*(PART 1), 46–55. https://doi.org/10.1007/978-3-642-22170-5_4

Alcaraz, C., & Zeadally, S. (2015). Critical infrastructure protection: Requirements and challenges for the 21st century. *International Journal of Critical Infrastructure Protection*, *8*, 53–66. https://doi.org/10.1016/j.ijcip.2014.12.002

Aleskerov, F., Say, A. I., Toker, A., Akin, H. L., & Altay, G. (2005). A cluster-based decision support system for estimating earthquake damage and casualties. *Disasters*, *29*(3), 255–276. https://doi.org/10.1111/j.0361-3666.2005.00290.x

Alutaibi, K. (2017). *Decision support for emergency response in interdependent infrastructure systems* [Doctoral dissertation, The University of British Columbia, Vancouver, Canada]. https://doi.org/10.14288/1.0343988

Ani, U. D., Watson, J. D. M., Nurse, J. R. C., Cook, A., & Maple, C. (2019). A review of critical infrastructure protection approaches: Improving security through responsiveness to the dynamic modelling landscape. *Proceedings of PETRAS/IET Conference Living in the Internet of Things: Cybersecurity of the IoT,* 1–16. http://arxiv.org/abs/1904.01551

Anil, E. B., Akinci, B., Garrett, J. H., & Kurc, O. (2016). Information requirements for earthquake damage assessment of structural walls. *Advanced Engineering Informatics, 30*(1), 54–64. https://doi.org/10.1016/j.aei.2015.12.002

Anzaldi, G., Rubion, E., Corchero, A., Sanfeliu, R., Domingo, X., Pijuan, J., & Tersa, F. (2014). Towards an enhanced knowledge-based Decision Support System (DSS) for integrated water resource management (IWRM). *Procedia Engineering*, *89*, 1097–1104. https://doi.org/10.1016/j.proeng.2014.11.230

Arain, F. (2015). Knowledge-based approach for sustainable disaster management: Empowering emergency response management team. *Procedia Engineering*, *118*, 232–239. https://doi.org/10.1016/j.proeng.2015.08.422

Ariav, G., & Ginzberg, M. J. (1985). DSS design: a systemic view of decision support. *Communications of the ACM*, *28*(10), 1045–1052. https://doi.org/10.1145/4372.4374

Arnott, D., & Pervan, G. (2012). Design science in decision support systems research: An assessment using the Hevner, March, Park, and Ram guidelines. *Journal of the Association for Information Systems (JAIS)*, *13*(11), 923–949.

Arnott, D., & Pervan, G. (2014). A critical analysis of decision support systems research revisited: The rise of design science. *Journal of Information Technology*, *29*(4), 269–293. https://doi.org/10.1057/jit.2014.16

Arnott, D., & Pervan, G. (2018). An assessment of DSS design science using the Hevner, March, Park and Ram guidelines. *Information Systems Foundations: The Role of Design Science*, 255–284. https://doi.org/10.22459/isf.12.2010.12

Asghar, S., Damminda, A., & Churilov, L. (2005). A dynamic integrated model for disaster management decision support systems. *International Journal of Simulation Systems, Science & Technology*, *6*(10–11), 95–114.

Aung, Z. Z., & Watanabe, K. (2009). A framework for modeling interdependencies in Japan's critical infrastructures. In C. Palmer & S. Shenoi (Eds.), *Critical Infrastructure Protection III* (pp. 243–257). Springer.

Bagheri, E., Baghi, H., Ghorbani, A. A., & Yari, A. (2007). An agent-based service-oriented simulation suite for critical infrastructure behavior analysis. *International Journal of Business Process Integration and Management*, *2*(4), 312–326. https://doi.org/10.1504/IJBPIM.2007.017756

Bagui, S., & Earp, R. (2003). *Database design using Entity-Relationship diagrams* (2nd ed.). Auerbach Publications.

Banerjee, J., Basu, K., & Sen, A. (2018). Analysing robustness in intra-dependent and inter-dependent networks using a new model of interdependency. *International Journal of Critical Infrastructures*, *14*(2), 156–181. https://doi.org/10.1504/IJCIS.2018.091938

Basu, N., Pryor, R., & Quint, T. (1998). ASPEN: A microsimulation model of the economy. *Computational Economics*, *12*(3), 223–241. https://doi.org/10.1023/A:1008691115079

Bazzano, A. N., Martin, J., Hicks, E., Faughnan, M., & Murphy, L. (2017). Human-centred design in global health: A scoping review of applications and contexts. *PloS One*, *12*(11), e0186744. https://doi.org/10.1371/journal.pone.0186744

Bebbington, M., Cronin, S. J., Chapman, I., & Turner, M. B. (2008). Quantifying volcanic ash fall hazard to electricity infrastructure. *Journal of Volcanology and Geothermal Research*, *177*(4), 1055–1062. https://doi.org/10.1016/j.jvolgeores.2008.07.023

Becu, N., Bousquet, F., Barreteau, O., Perez, P., & Walker, A. (2003). A methodology for eliciting and modelling stakeholders' representations with agent based modelling. In D. Hales, B. Edmonds, E. Norling, & J. Rouchier (Eds.), *Multi-Agent-Based Simulation III. MABS 2003. Lecture Notes in Computer Science: Vol. 2927* (pp. 131–148). Springer. https://doi.org/10.1007/978-3-540-24613-8_10

Bell, R. G., Reese, S., & King, A. B. (2007). Regional RiskScape: A multi-hazard loss modelling tool . *Proceedings of the Coastal Communities Natural Disasters, Auckland, New Zealand, April*, 1–4.

Bloomfield, R. E., Popov, P., Salako, K., Stankovic, V., & Wright, D. (2017). Preliminary interdependency analysis: An approach to support critical-infrastructure risk-assessment. *Reliability Engineering and System Safety*, *167*, 198–217. https://doi.org/10.1016/j.ress.2017.05.030

Bočkarjova, M., Steenge, A. E., & Veen, A. van der. (2004). On direct estimation of initial damage in the case of a major catastrophe: derivation of the "basic equation". *Disaster Prevention and Management*, *13*(4), 330–336.

Boehm, B. W., Brown, J. R., Kaspar, H., Lipow, M., McLeod, G., & Merritt, M. (1978). *Characteristics of software quality*. North Holland Publishing Co.

Bogdan, R., & Biklen, S. K. (2007). *Qualitative research for education: An introduction to theory and methods* (5th ed.). Pearson.

Bonczek, R. H., Holsapple, C. W., & Whinston, A. B. (1980). Future directions for developing decision support systems. *Decision Sciences*, *11*(4), 616–631. https://doi.org/10.1111/j.1540-5915.1980.tb01165.x

Borshchev, A., Karpov, Y., & Kharitonov, V. (2002). Distributed simulation of hybrid systems with AnyLogic and HLA. *Future Generation Computer Systems*, *18*(6), 829–839. https://doi.org/10.1016/S0167-739X(02)00055-9

Boulos, P. F., Jacobsen, L. B., Heath, J. E., & Kamojjala, S. R. I. (2014). Real-time modeling of water distribution systems: A case study. *Journal AWWA*, *106*(9), 391–401. https://doi.org/10.5942/jawwa.2014.106.0076

Brown, T. (2006). Multiple modeling approaches and insights for critical infrastructure protection. In D. Skanata & D. Byrd (Eds.), *Computational Models of Risks to Infrastructure* (pp. 23–33). IOS Press.

References

Buxton, R., Mcdonald, G., Seville, E., Daly, M., & Smith, N. (2015). It has MERIT! The development of a system dynamic tool for modelling the economic effects of infrastructure outages. *IPWEA 2015*.

Çagnan, Z., & Davidson, R. (2003). Post-earthquake lifeline service restoration modeling. *Sixth U.S. Conference and Workshop on Lifeline Earthquake Engineering (TCLEE)*, 255–264. https://doi.org/doi:10.1061/40687(2003)27

Canzani, E., Kaufmann, H., & Lechner, U. (2017). An operator-driven approach for modeling interdependencies in critical infrastructures based on critical services and sectors. In G. Havarneanu, R. Setola, H. Nassopoulos, & S. Wolthusen (Eds.), *Critical Information Infrastructures Security* (pp. 308–320). Springer.

Casalicchio, E., Galli, E., & Tucci, S. (2010). Agent-based modelling of interdependent critical infrastructures. *International Journal of System of Systems Engineering*, *2*(1), 60. https://doi.org/10.1504/IJSSE.2010.035381

Cavallini, S., d'Alessandro, C., Volpe, M., Armenia, S., Carlini, C., Brein, E., & Assogna, P. (2014). A system dynamics framework for modeling critical infrastructure resilience. *IFIP Advances in Information and Communication Technology*, *441*. https://doi.org/10.1007/978-3-662-45355-1_10

Chen, A. S., Hammond, M. J., Djordjević, S., Butler, D., Khan, D. M., & Veerbeek, W. (2016). From hazard to impact: Flood damage assessment tools for mega cities. *Natural Hazards*, *82*, 857–890. https://doi.org/10.1007/s11069-016-2223-2

Chen, P. P.-S. (2002). The Entity Relationship Model - Toward a unified view of data. In M. Broy & E. Denert (Eds.), *Software Pioneers: Contributions to Software Engineering* (pp. 311–339). Springer. https://doi.org/10.1007/978-3-642-59412-0_18

Cheng, A., Kessler, D., Mackinnon, R., Chang, T. P., Nadkarni, V. M., Hunt, E. A., Duval-Arnould, J., Lin, Y., Cook, D. A., Pusic, M., Hui, J., Moher, D., Egger, M., & Auerbach,

M. (2016). Reporting guidelines for health care simulation research: Extensions to the CONSORT and STROBE satements. *Simulation in Healthcare: The Journal of the Society for Simulation in Healthcare, 11*(4), 238–248. https://doi.org/10.1097/SIH.0000000000000150

Cheng, Q. (2017). A new mathematical framework and spatial decision support system for modeling cascade interdependency of critical infrastructure during geo-disasters. *Journal of Earth Science*, *28*(1), 131–146. https://doi.org/10.1007/s12583-017-0746-4

Choraś, M., Kozik, R., Flizikowski, A., & Hołubowicz, W. (2010). Ontology applied in decision support system for critical infrastructures protection. In N. García-Pedrajas, F. Herrera, C. Fyfe, J. M. Benítez, & M. Ali (Eds.), *Trends in Applied Intelligent Systems. IEA/AIE 2010. Lecture Notes in Computer Science, vol 6096* (pp. 671–680). Springer. https://doi.org/10.1007/978-3-642-13022-9_67

Chou, C. C., & Tseng, S. M. (2010). Collection and analysis of critical infrastructure interdependency relationships. *Journal of Computing in Civil Engineering*, *24*(6), 539–547. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000059

Coyne, I. T. (1997). Sampling in qualitative research. Purposeful and theoretical sampling; merging or clear boundaries? *Journal of Advanced Nursing*, *26*(3), 623–630. https://doi.org/10.1046/j.1365-2648.1997.t01-25-00999.x

Creswell, J. W. (2014). *Research design: Qualitative, quantitative, and mixed methods approaches* (4th ed.). Sage.

Daly, M., Buxton, R., McDonald, G., Smith, N., Kim, J.-H., Wright, K. C., & Timar, L. (2015). Single infrastructure failures: Capturing outage information for MERIT modelling the economics of resilient infrastructure tool. *IPWEA 2015*.

De Maio, C., Fenza, G., Gaeta, M., Loia, V., & Orciuoli, F. (2011). A knowledge-based framework for emergency DSS. *Knowledge-Based Systems*, *24*(8), 1372–1379.

https://doi.org/10.1016/j.knosys.2011.06.011

De Nicola, A., Villani, M. L., Brugnoli, M. C., & D'Agostino, G. (2016). A methodology for modeling and measuring interdependencies of information and communications systems used for public administration and eGovernment services. *International Journal of Critical Infrastructure Protection*, *14*, 18–27. https://doi.org/10.1016/j.ijcip.2016.06.001

Deissenboeck, F., Juergens, E., Lochmann, K., & Wagner, S. (2009). Software quality models: Purposes, usage scenarios and requirements. *Proceedings of International Conference on Software Engineering*, 9–14. https://doi.org/10.1109/WOSQ.2009.5071551

Digioia, G., Foglietta, C., Panzieri, S., & Falleni, A. (2012). Mixed holistic reductionistic approach for impact assessment of cyber attacks. *Proceedings of 2012 European Intelligence and Security Informatics Conference*, 123–130. https://doi.org/10.1109/EISIC.2012.30

Dijkstra, E. W. (1959). A note on two problems in connexion with graphs. *Numer. Math*, *1*(1), 269–271. https://doi.org/10.1007/BF01386390

Dromey, R. G. (1996). Cornering the chimera. *IEEE Software*, *13*(1), 33–43. https://doi.org/10.1109/52.476284

Du Bois, E. (2013). *A designerly methodology for software development* [Doctoral dissertation, Delft University of Technology]. https://doi.org/10.4233/uuid:6f8f9802-f174-4be9-b51e-741315add1be

Duah, D. Y. A., Ford, K., & Syal, M. (2014). Expert knowledge elicitation for decision-making in home energy retrofits. *Structural Survey, 32*(5), 377–395. https://doi.org/10.1108/SS-01-2014-0004

Duah, D. Y. A., & Syal, M. (2016). Intelligent decision support system for home energy retrofit adoption. *International Journal of Sustainable Built Environment*, *5*(2), 620–634. https://doi.org/10.1016/j.ijsbe.2016.05.003

Dudenhoeffer, D. D., Permann, M. R., & Manic, M. (2006). CIMS: A framework for infrastructure interdependency modeling and analysis. In L. F. Perrone, F. P. Wieland, J. Liu, B. G. Lawson, D. M. Nicol, & R. M. Fujimoto (Eds.), *2006 Winter Simulation Conference* (pp. 478–485).

Dueñas-Osorio, L., Craig, J. I., & Goodno, B. J. (2007). Seismic response of critical interdependent networks. *Earthquake Engineering & Structural Dynamics*, *36*(2), 285–306. https://doi.org/10.1002/eqe.626

Dueñas-Osorio, L., & Hernandez-Fajardo, I. (2008). Flow-based reliability assessment of infrastructure systems. *Proceedings of 14th World Conference on Earthquake Engineering (14WCEE)*, 1–8. https://www.iitk.ac.in/nicee/wcee/article/14_06-0039.PDF

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

Dunn, S., Wilkinson, S., Fu, G., & Dawson, R. (2013). Modelling infrastructure systems for resilience and sustainability. In P. Campbell & P. Perez (Eds.), *Proceedings of the International Symposium of Next Generation Infrastructure*.

Eguchi, R. T., Goltz, J. D., Seligson, H. A., Flores, P. J., Biais, N. C., Heaton, T. H., & Bortugno, E. (1997). Real-time loss estimation as an emergency response decision support system: The Early Post-Earthquake Damage Assessment Tool (EPEDAT). *Earthquake Spectra*, *13*(4), 815–832. https://doi.org/10.1193/1.1585982

Elliott, R., & Timulak, L. (2005). Descriptive and interpretive approaches to qualitative research. In J. Miles & P. Gilbert (Eds.), *A Handbook of Research Methods for Clinical and Health Psychology* (pp. 147–159). Oxford University Press. https://psycnet.apa.org/record/2006-02282-011

Erdener, B. C., Pambour, K. A., Lavin, R. B., & Dengiz, B. (2014). An integrated simulation model for analysing electricity and gas systems. *International Journal of Electrical Power*

& Energy Systems, *61*, 410–420. https://doi.org/10.1016/j.ijepes.2014.03.052

Erdik, M., & Fahjan, Y. (2006). Damage scenarios and damage evaluation. In C. S. Oliveira, A. Roca, & X. Goula (Eds.), *Assessing and managing earthquake risk. Geotechnical, Geological And Earthquake Engineering, vol 2.* (pp. 213–237). Springer. https://doi.org/10.1007/978-1-4020-3608-8_10

ESRI online documentation. (2017). *Shapefiles—ArcGIS Online Help | Documentation*. https://doc.arcgis.com/en/arcgis-online/reference/shapefiles.htm

Eusgeld, I., Henzi, D., & Kröger, W. (2008). *Comparative evaluation of modeling and simulation techniques for interdependent critical infrastructures*. Swiss Federal Institute of Technology.

Eusgeld, I., & Nan, C. (2009). Creating a simulation environment for critical infrastructure interdependencies study. *Proceedings of IEEE International Conference on Industrial Engineering and Engineering Management*, 2104–2108. https://doi.org/10.1109/IEEM.2009.5373155

Eusgeld, I., Nan, C., & Dietz, S. (2011). System-of-systems approach for interdependent critical infrastructures. *Reliability Engineering and System Safety*, *96*(6), 679–686. https://doi.org/10.1016/j.ress.2010.12.010

Farshidi, S., Jansen, S., de Jong, R., & Brinkkemper, S. (2018). A decision support system for software technology selection. *Journal of Decision Systems*, *27*, 98–110. https://doi.org/10.1080/12460125.2018.1464821

FEMA. (2003). *HAZUS-MH 2.1 earthquake model technical manual.* https://www.fema.gov/media-library-data /20130726-1820-25045-6286/hzmh2_1_eq_tm.pdf.

Filip, F. G. (2008). Decision support and control for large-scale complex systems. *Annual Reviews in Control*, *32*(1).

Flanagan, J. C. (1954). The Critical Incident Technique. *Psychological Bulletin*, *51*(4), 327–358. https://doi.org/10.1037/h0061470

Fogli, D., & Guida, G. (2013). Knowledge-centered design of decision support systems for emergency management. *Decision Support Systems*, *55*(1), 336–347. https://doi.org/10.1016/j.dss.2013.01.022

Furuta, K., Komiyama, R., Kanno, T., Fujii, H., Yoshimura, S., & Yamada, T. (2016). Resilience analysis of critical infrastructure. In X. Zhuang & C. A. Sakurai (Eds.), *Proceedings of the Recent Advances in Information Science* (pp. 21–28).

Galbusera, L., Giannopoulos, G., Argyroudis, S., & Kakderi, K. (2018). A boolean networks approach to modeling and resilience analysis of interdependent critical infrastructures. *Computer-Aided Civil and Infrastructure Engineering*, *33*(12), 1041–1055. https://doi.org/10.1111/mice.12371

Gavrilova, T., & Andreeva, T. (2012). Knowledge elicitation techniques in a knowledge management context. *Journal of Knowledge Management*, *16*(4), 523–537. https://doi.org/10.1108/13673271211246112

Gentles, S. J., Charles, C., & Ploeg, J. (2015). Sampling in qualitative research: Insights from an overview of the methods literature. *The Qualitative Report*, *20*(11), 1772–1789. https://doi.org/10.46743/2160-3715/2015.2373

Get Ready. (n.d.). *New Zealand ShakeOut - Wellington Earthquake Hazards*. Retrieved August 11, 2016, from http://www.shakeout.govt.nz/wellington/

Giovinazzi, S., Pollino, M., Kongar, I., Rossetto, T., Caiaffa, E., Di Pietro, A., La Porta, L., Rosato, V., & Tofani, A. (2017). Towards a decision support tool for assessing, managing and mitigating seismic risk of electric power networks. In O. Gervasi, B. Murgante, S. Misra, G. Borruso, C. M. Torre, A. M. A. C. Rocha, D. Taniar, B. O. Apduhan, E. Stankova, & A. Cuzzocrea (Eds.), *Proceedings of the Computational Science and Its*

Applications -- ICCSA 2017 (pp. 399–414). Springer.

GNS Science. (n.d.). *GNS Science*. Retrieved September 16, 2016, from https://www.gns.cri.nz/

Gonzalez, R., & Dahanayake, A. (2007). A concept map of information systems research approaches. In M. Khosrow-Pour (Ed.), *Proceedings of the 2007 IRMA International Conference* (pp. 845–848). https://www.irma-international.org/viewtitle/33198/?isxn=9781599049298

Grady, R. B. (1992). *Practical software metrics for project management and process improvement*. Prentice Hall.

Griot, C. (2010). Modelling and simulation for critical infrastructure interdependency assessment: A meta-review for model characterisation. *International Journal of Critical Infrastructures*, *6*(4), 363–379. https://doi.org/10.1504/IJCIS.2010.037453

GWRC. (n.d.). *Greater Wellington Regional Council*. Retrieved January 24, 2017, from http://www.gw.govt.nz/

Haghnevis, M., Askin, R. G., & Armbruster, D. (2016). An agent-based modeling optimization approach for understanding behavior of engineered complex adaptive systems. *Socio-Economic Planning Sciences*, *56*, 67–87. https://doi.org/10.1016/j.seps.2016.04.003

Haimes, Y., & Jiang, P. (2001). Leontief-based model of risk in complex interconnected infrastructures. *Journal of Infrastructure Systems*, *7*(1), 1–12. https://doi.org/10.1061/(ASCE)1076-0342(2001)7:1(1)

Hamilton, B. (2004). *NUnit Pocket Reference: Up and Running with NUnit*. O’Reilly Media, Inc.

Harenčárová, H. (2015). Structured analysis of critical decision method data-emergency medicine case study. *Human Affairs*, *25*(4), 443–459. https://doi.org/10.1515/humaff-2015-0036

Harvey, E., Smith, N., Vergara, M. J., Buxton, R., Uma, S., Syed, Y. I., & Horspool, N. (2017).

Towards robust decision-making in natural hazard risk management: Uncertainty quantification for RiskScape-MERIT modelling (NHRP Contest 2017-191031). M. E Research (Market Economics Ltd.).

Hasan, S., & Foliente, G. C. (2015). Modeling infrastructure system interdependencies and socioeconomic impacts of failure in extreme events: Emerging R&D challenges. *Natural Hazards*, *78*(3), 2143–2168. https://doi.org/10.1007/s11069-015-1814-7

He, X., & Cha, E. J. (2018). Modeling the damage and recovery of interdependent critical infrastructure systems from natural hazards. *Reliability Engineering and System Safety*, *177*, 162–175. https://doi.org/10.1016/j.ress.2018.04.029

Herselman, M., & Botha, A. (2015). Evaluating an artifact in design science research. *Proceedings of the 2015 Annual Research Conference on South African Institute of Computer Scientists and Information Technologists - SAICSIT '15*, 1–10. https://doi.org/10.1145/2815782.2815806

Hevner, A. R. (2007). A three cycle view of design science research. *Scandinavian Journal of Information Systems*, *19*(2), 87–92. https://doi.org/http://aisel.aisnet.org/sjis/vol19/iss2/4

Hevner, A. R., March, S. T., Park, J., & Ram, S. (2004). Design science in information systems research. *MIS Quarterly*, *28*(1), 75–105. https://doi.org/10.2307/25148625

Hickey, A. M., & Davis, A. M. (2003). Elicitation technique selection: How do experts do it? *Proceedings of the IEEE International Conference on Requirements Engineering*, 169–178. https://doi.org/10.1109/ICRE.2003.1232748

Hoffman, R. R., Crandall, B., & Shadbolt, N. (1998). Use of the critical decision method to elicit expert knowledge: A case study in the methodology of cognitive task analysis. *Human Factors*, *40*(2), 254–276. https://doi.org/10.1518/001872098779480442

Hormdee, D., Kanarkard, W., Adams, R. G., Davey, N., & Taweepworadej, W. (2007). Risk management for chemical emergency system based on GIS and Decision Support System

(DSS). *Proceedings of TENCON 2006 - IEEE Region 10 Conference*. https://doi.org/10.1109/TENCON.2006.343940

Hosseininezhad, Z., Alidoosti, A., & Jamshidi, A. (2012). Integrated framework for modeling of critical infrastructure interdependency in emergency condition. *Proceedings of the Annual International Conference. International Institute for Infrastructure, Renewal and Reconstruction & Kumamoto University*, 329–338.

Huang, C. N., Liou, J. J. H., & Chuang, Y. C. (2014). A method for exploring the interdependencies and importance of critical infrastructures. *Knowledge-Based Systems*, *55*, 66–74. https://doi.org/10.1016/j.knosys.2013.10.010

Iivari, J. (2007). A paradigmatic analysis of information systems as a design science. *Scandinavian Journal of Information Systems*, *19*(2), 39–64. https://doi.org/10.1.1.218.2636

Inan, D. I., & Beydoun, G. (2017). Disaster knowledge management analysis framework utilizing agent-based models: Design science research approach. *Procedia Computer Science*, *124*, 116–124. https://doi.org/10.1016/j.procs.2017.12.137

ISO9126. (2001). *ISO - ISO/IEC 9126-1:2001 - Software engineering — Product quality — Part 1: Quality model*. https://www.iso.org/standard/22749.html

Ives, B., Hamilton, S., & Davis, G. B. (1980). A framework for research in computer-based management information systems. *Management Science*, *26*(9), 910–934. https://doi.org/10.1287/mnsc.26.9.910

Jain, S., & McLean, C. (2003). A framework for modelling and simulation for emergency response. In S. Chick, P. J. Sánchez, D. Ferrin, & D. J. Morrice (Eds.), *Proceedings of the 2003 Winter Simulation Conference* (pp. 1068–1076). https://doi.org/10.1109/WSC.2003.1261532

Järvinen, P. (2007). Action research is similar to design science. *Quality and Quantity*, *41*(1), 37–54. https://doi.org/10.1007/s11135-005-5427-1

Johansen, C., & Tien, I. (2017). Probabilistic multi-scale modeling of interdependencies between critical infrastructure systems for resilience. *Sustainable and Resilient Infrastructure*, 1–15. https://doi.org/10.1080/23789689.2017.1345253

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

Jokela, T., Iivari, N., Matero, J., & Karukka, M. (2003). The standard of user-centered design and the standard definition of usability: Analyzing ISO 13407 against ISO 9241-11. *Proceedings of the Latin American Conference on Human-Computer Interaction*, 53–60.

Jonker, J., & Pennink, B. W. (2009). Qualitative Research. In *The Essence of Research Methodology: A Concise Guide for Master and PhD Students in Management Science* (pp. 77–96). Springer. https://doi.org/10.1007/978-3-540-71659-4_5

Jonkeren, O. E., Ward, D., Dorneanu, B., & Giannopoulos, G. (2012). Economic impact assessment of critical infrastructure failure in the EU : A combined systems engineering – inoperability input-output model. *Proceedings of the 20th International Input-Output Conference*, 1–21.

Kantartzis, A., & Malesios, C. (2018). A decision support system web - Application for the management of forest road network. *Journal of Environmental Science and Engineering A*, *7*(1), 8–21. https://doi.org/10.17265/2162-5298/2018.01.002

Keen, P. G. W. (1987). Decision support systems: The next decade. *Decision Support Systems*, *3*(3), 253–265. https://doi.org/10.1016/0167-9236(87)90180-1

Kellner, M. I., Madachy, R. J., & Raffo, D. M. (1999). Software process simulation modeling: Why? What? How? *Journal of Systems and Software*, *46*(2), 91–105. https://doi.org/10.1016/S0164-1212(99)00003-5

References

Kelly, S. (2015). Estimating economic loss from cascading infrastructure failure: A perspective on modelling interdependency. *Infrastructure Complexity*, *2*(1). https://doi.org/10.1186/s40551-015-0010-y

Kiel, J., Petiet, P., Nieuwenhuis, A., Peters, T., & Van Ruiten, K. (2016). A decision support system for the resilience of critical transport infrastructure to extreme weather events. *Transportation Research Procedia*, *14*, 68–77. https://doi.org/10.1016/j.trpro.2016.05.042

Kim, Y., & Kang, W. H. (2013). Network reliability analysis of complex systems using a non-simulation-based method. *Reliability Engineering and System Safety*, *110*, 80–88. https://doi.org/10.1016/j.ress.2012.09.012

Klashner, R., & Sabet, S. (2007). A DSS design model for complex problems: Lessons from mission critical infrastructure. *Decision Support Systems*, *43*(3), 990–1013. https://doi.org/10.1016/j.dss.2005.05.027

Klein, G., Calderwood, R., & Macgregor, D. (1989). Critical decision method for eliciting knowledge. *IEEE Transactions on Systems, Man and Cybernetics*, *19*(3), 462–472. https://doi.org/10.1109/21.31053

Knutas, A., Pourzolfaghar, Z., & Helfert, M. (2017). A meta-level design science process for integrating stakeholder needs - demonstrated for smart city services. *Proceedings of the International Conference on Computer-Human Interaction Research and Applications (CHIRA 2017)*, 75–84. https://doi.org/10.5220/0006512500750084

König, S., & Schauer, S. (2019). Cascading threats in critical infrastructures with control systems. In Z. Franco, J. J. Gonzalez, & J. H. Canós (Eds.), *Proceedings of the 16th International Conference on Information Systems for Crisis Response and Management (ISCRAM)* (pp. 1252–1259).

Krasner, G. E., & Pope, S. T. (1988). A description of the Model-View-Controller user interface paradigm in the smalltalk-80 system. *Journal Of Object Oriented Programming*, *1*(3), 26–

49.

Lam, C. Y., & Tai, K. (2018). Modeling infrastructure interdependencies by integrating network and fuzzy set theory. *International Journal of Critical Infrastructure Protection*, *22*, 51–61. https://doi.org/10.1016/j.ijcip.2018.05.005

Laprie, J.-C., Kanoun, K., & Kaâniche, M. (2007). Modelling interdependencies between the electricity and information infrastructures. In F. Saglietti & N. Oster (Eds.), *Computer Safety, Reliability, and Security* (pp. 54–67). Springer.

Le Blanc, L. A., & Tawfik Jelassi, M. (1989). DSS software selection: A multiple criteria decision methodology. *Information and Management*, *17*(1), 49–65. https://doi.org/10.1016/0378-7206(89)90054-2

Lee, S., Hwang, S., Park, M., & Lee, H. S. (2018). Damage propagation from component level to system level in the electricity sector. *Journal of Infrastructure Systems*, *24*(3), 1–13. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000437

Lin, S.-L., Uma, S., Nayyerloo, M., Buxton, R., & King, A. (2014). Engineering characteristics of building performance with Detailed Engineering Evaluation (DEE) data from the Canterbury earthquake sequence. *ASEC 2014: Structural Engineering in Australasia*, 1–8.

Liu, Shaofeng, & Zaraté, P. (2014). Knowledge based decision support systems: A survey on technologies and application domains. In P. Zaraté, G. E. Kersten, & J. E. Hernández (Eds.), *Group Decision and Negotiation. A Process-Oriented View. GDN 2014. Lecture Notes in Business Information Processing: Vol 180* (pp. 62–72). Springer.

Liu, Shushu. (2010). Unified call method of stored procedure for oracle in .NET. In C. Taiyuan (Ed.), *Proceedings of the 2010 International Conference on Computer Application and System Modeling* (Vol. 11). https://doi.org/10.1109/ICCASM.2010.5623276

Lovrencic, S., & Klicek, B. (2004). Which technique to use when eliciting knowledge from an expert. *Journal of Information and Organizational Sciences*, *28*(1), 109–122.

Lu, J., Bai, D., Zhang, N., Yu, T., & Zhang, X. (2016). Fuzzy case-based reasoning system. *Applied Sciences*, *6*(7). https://doi.org/10.3390/app6070189

Luiijf, E., Burger, H. H., & Klaver, M. H. A. (2003). Critical (information) infrastructure protection in the netherlands. In U. E. Gattiker (Ed.), *EICAR Conference Best Paper Proceedings, European Institute for Computer Anti-Virus Research* (pp. 9–19).

Luiijf, E., Nieuwenhuijs, A., Klaver, M., van Eeten, M., & Cruz, E. (2009). Empirical findings on critical infrastructure dependencies in europe. In R. Setola & S. Geretshuber (Eds.), *Critical Information Infrastructure Security* (pp. 302–310). Springer.

Macal, C. M., & North, M. J. (2008). Agent-based modeling and simulation: AMBS examples. In S. J. Mason, R. R. Hill, L. Mönch, O. Rose, T. Jefferson, & J. W. Fowler (Eds.), *Proceedings of the 2008 Winter Simulation Conference* (pp. 101–112).

Maria, A. (1997). Introduction to modelling and simulation. In S. Andradottir, K. J. Healy, D. H. Withers, & B. L. Nelson (Eds.), *Proceedings of the 1997 Winter Simulation Conference* (pp. 7–13). https://doi.org/10.1109/WSC.1997.640371

Markus, M., Fiedrich, F., Leebmann, J., Schweier, C., & Steinle, E. (2004). Concept for an integrated disaster management tool. *Proceedings of the 13th World Conference on Earthquake Engineering*.

Marshall, C., & Rossman, G. B. (2015). *Designing qualitative research* (6th ed.). Sage Publications.

Masucci, D., Palazzo, C., Foglietta, C., & Panzieri, S. (2016). Enhancing decision support with interdependency modeling. *IFIP Advances in Information and Communication Technology*, *485*, 169–183. https://doi.org/10.1007/978-3-319-48737-3_10

Masucci, V., Adinolfi, F., Servillo, P., Dipoppa, G., & Tofani, A. (2009). Ontology-based critical infrastructure modeling and simulation. *IFIP Advances in Information and Communication Technology*, *311*, 229–242. https://doi.org/10.1007/978-3-642-04798-

5_16

McCall, J., Richards, P. A., & Walters, G. (1977). *Factors in software quality: Concept and definitions of software quality - Final technical report* (N. T. I. RADC-TR-77-369 (ed.); pp. 1–168). Springfield.

McCarthy, N., Neville, K., Pope, A., Gallagher, A., Nussbaumer, A., & Steiner, C. M. (2016). The creation of a training model to support decision-making of emergency management practitioners: a design research study. *Journal of Decision Systems*, *25*, 558–565. https://doi.org/10.1080/12460125.2016.1187409

McDaniels, T., Chang, S., Peterson, K., Mikawoz, J., & Reed, D. (2007). Empirical framework for characterizing infrastructure failure interdependencies. *Journal of Infrastructure Systems*, *13*(3), 175–184. https://doi.org/10.1061/(ASCE)1076-0342(2007)13:3(175)

MCDEM. (2002). *Civil Defence Emergency Management Act 2002 (CDEM Act)*. http://www.legislation.govt.nz/act/public/2002/0033/51.0/DLM149789.html

Meduri, Y. (2016). Multi-stakeholder participation in disaster recovery: A case study. *Procedia Engineering*, *159*, 179–185. https://doi.org/10.1016/j.proeng.2016.08.153

Mendonça, D., Beroggi, G. E. G., & Wallace, W. A. (2001). Decision support for improvisation during emergency response operations. *International Journal of Emergency Management*, *1*(1), 30–39. https://doi.org/10.1504/IJEM.2001.000507

Menoni, S., Pergalani, F., Boni, M. ., & Petrini, V. (2002). Lifelines earthquake vulnerability assessment: A systemic approach. *Soil Dynamics and Earthquake Engineering*, *22*(9–12), 1199–1208. https://doi.org/10.1016/S0267-7261(02)00148-3

Miguel, J. P., Mauricio, D., & Rodriguez, G. (2014). A review of software quality models for the evaluation of software products. *International Journal of Software Engineering & Applications*, *5*(6), 31–53. https://doi.org/10.5121/ijsea.2014.5603

Mitsova, D. (2018). Integrative interdisciplinary approaches to critical infrastructure interdependency analysis. *Risk Analysis*. https://doi.org/10.1111/risa.13129

Mittra, S. S. (1986). *Decision support systems: Tools and techniques*. Wiley. https://dl.acm.org/citation.cfm?id=6777

Morton, S., & S, M. (1971). *Management decision systems: Computer-based support for decision making*. Harvard University Press.

Mowll, R. (2012). *Lifeline utilities restoration times for metropolitan Wellington following a Wellington fault earthquake*. Wellington Lifelines Group.

Mowll, R., Brunsdon, D. R., Wilde, F., & Leslie, P. D. (2013). Understanding the impact of a major earthquake on Wellington Lifelines. *Bulletin of the New Zealand Society for Earthquake Engineering (NZSEE)*, *46*(2), 109–115.

Müller, L., Gangadharaiah, R., Klein, S. C., Perry, J., Bernstein, G., Nurkse, D., Wailes, D., Graham, R., El-Kareh, R., Mehta, S., Vinterbo, S. A., & Aronoff-Spencer, E. (2019). An open access medical knowledge base for community driven diagnostic decision support system development. *BMC Medical Informatics and Decision Making*, *19*(1), 1–7. https://doi.org/10.1186/s12911-019-0804-1

Murray, A. T., Matisziw, T. C., & Grubesic, T. H. (2008). A methodological overview of network vulnerability analysis. *Growth and Change*, *39*(4), 573–592. https://doi.org/10.1111/j.1468-2257.2008.00447.x

Nan, C., & Sansavini, G. (2016). Developing an agent-based hierarchical modeling approach to assess human performance of infrastructure systems. *International Journal of Industrial Ergonomics*, *53*, 340–354. https://doi.org/10.1016/j.ergon.2016.04.002

Nan, C., & Sansavini, G. (2017). A quantitative method for assessing resilience of interdependent infrastructures. *Reliability Engineering and System Safety*, *157*, 35–53. https://doi.org/10.1016/j.ress.2016.08.013

Neville, K., O'Riordan, S., Pope, A., Rauner, M., Maria Rochford, Madden, M., Sweeney, J., Nussbaumer, A., McCarthy, N., & O'Brien, C. (2016). Towards the development of a decision support system for multi-agency decision-making during cross-border emergencies. *Journal of Decision Systems*, *25*, 381–396. https://doi.org/10.1080/12460125.2016.1187393

Neville, K., Pope, A., O'Riordan, S., & Ó'Lionáird, M. (2018). Evaluating an emergency management decision support system with practitioner-driven scenarios: Action design research. *Proceedings of the Thirty Ninth International Conference on Information Systems*, 1–17.

New Zealand Parliament. (2016). *Major New Zealand earthquakes since 1855*. https://www.parliament.nz/en/pb/research-papers/document/00PLEcoRP2016031/major-new-zealand-earthquakes-since-1855

Newman, J. P., Maier, H. R., Riddell, G. A., Zecchin, A. C., Daniell, J. E., Schaefer, A. M., van Delden, H., Khazai, B., O'Flaherty, M. J., & Newland, C. P. (2017). Review of literature on decision support systems for natural hazard risk reduction: Current status and future research directions. *Environmental Modelling and Software*, *96*, 378–409. https://doi.org/10.1016/j.envsoft.2017.06.042

NHRP. (2017). *Contests 2017 Projects & Final Reports*. https://www.naturalhazards.org.nz/NHRP/Funding/Contest-2017/More-information/2017-Final-Reports

NIWA. (n.d.). *NIWA Taihoro Nakurangi - RiskScape software*. Retrieved October 2, 2016, from https://www.niwa.co.nz

Nunamaker, J. F., Chen, M., & Purdin, T. D. M. (1990). Systems development in information systems research. *Journal of Management Information Systems*, *7*(3), 89–106. https://doi.org/10.1080/07421222.1990.11517898

Oliva, G., Panzieri, S., & Setola, R. (2010). Agent-based input-output interdependency model.

International Journal of Critical Infrastructure Protection, *3*(2), 76–82. https://doi.org/10.1016/j.ijcip.2010.05.001

Orchiston, C., Mitchell, J., Wilson, T., Langridge, R., Davies, T., Bradley, B., Johnston, D., Davies, A., Becker, J., & McKay, A. (2018). Project AF8: developing a coordinated, multi-agency response plan for a future great Alpine Fault earthquake. *New Zealand Journal of Geology and Geophysics*, 1–14. https://doi.org/10.1080/00288306.2018.1455716

Osatuyi, B., & Andoh-Baidoo, F. K. (2014). Towards a community-centered knowledge management architecture for disaster management in sub-saharan africa. In K.-M. Osei-Bryson, G. Mansingh, & L. Rao (Eds.), *Knowledge Management for Development: Domains, Strategies and Technologies for Developing Countries* (pp. 17–41). Springer. https://doi.org/10.1007/978-1-4899-7392-4_2

Ouyang, M. (2013). Comparisons of purely topological model, betweenness based model and direct current power flow model to analyze power grid vulnerability. *Chaos*, *23*(2). https://doi.org/10.1063/1.4807478

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

Ouyang, M., & Dueñas-Osorio, L. (2011a). An approach to design interface topologies across interdependent urban infrastructure systems. *Reliability Engineering and System Safety*, *96*(11), 1462–1473. https://doi.org/10.1016/j.ress.2011.06.002

Ouyang, M., & Dueñas-Osorio, L. (2011b). Efficient approach to compute generalized interdependent effects between infrastructure systems. *Journal of Computing in Civil Engineering*, *25*(5), 394–406. https://doi.org/10.1061/(asce)cp.1943-5487.0000103

Ouyang, M., Hong, L., Mao, Z. J., Yu, M. H., & Qi, F. (2009). A methodological approach to analyze vulnerability of interdependent infrastructures. *Simulation Modelling Practice and Theory*, *17*(5), 817–828. https://doi.org/10.1016/j.simpat.2009.02.001

Oztekin, A. (2011). A decision support system for usability evaluation of web-based information systems. *Expert Systems with Applications*, *38*(3), 2110–2118. https://doi.org/10.1016/j.eswa.2010.07.151

Paltrinieri, N., Breedveld, L., Wilday, J., & Cozzani, V. (2013). Identification of hazards and environmental impact assessment for an integrated approach to emerging risks of CO2 capture installations. *Energy Procedia*, *37*(1876), 2811–2818. https://doi.org/10.1016/j.egypro.2013.06.166

Pant, R., Thacker, S., & Hall, J. W. (2017). System-of-systems framework for global infrastructure vulnerability assessments. *Proceedings of the Green Growth Knowledge Platform (GGKP), Annual Conference*. https://doi.org/http://dx.doi.org/

Panzieri, S., Setola, R., & Ulivi, G. (2004). An agent based simulator for critical interdependent infrastructures. *Securing Critical Infrastructures*.

Panzieri, S., Setola, R., & Ulivi, G. (2005). An approach to model complex interdependent infrastructures. *IFAC Proceedings Volumes*, *38*(1), 404–409. https://doi.org/10.3182/20050703-6-CZ-1902.00068

Patton, M. Q. (2014). *Qualitative Evaluation and Research Methods* (4th ed.). SAGE Publications. https://doi.org/10.1002/nur.4770140111

PCCIP. (1997). Critical foundations: Protecting America´s infrastructure. *President's Commission on Critical Infrastructure Protection (PCCIP)*. https://www.fas.org/sgp/library/pccip.pdf

Pederson, P., Dudenhoeffer, D., Hartley, S., & Permann, M. (2006). Critical infrastructure interdependency modeling: A survey of US and international research. In *Idaho National Laboratory*. https://doi.org/10.2172/911792

References

Peerenboom, J. P., & Fisher, R. E. (2007). Analyzing cross-sector interdependencies. *Proceedings of the 2007 40th Hawaii International Conference on System Sciences (HICSS'07)*, 1–9. https://doi.org/10.1109/HICSS.2007.78

Peffers, K., Tuunanen, T., Rothenberger, M. A., & Chatterjee, S. (2007). A design science research methodology for information systems research. *Journal of Management Information Systems*, *24*(3), 45–78. https://doi.org/10.2753/MIS0742-1222240302

Peters, M. A. (2017). Research Methods. In M. A. Peters (Ed.), *Encyclopedia of Educational Philosophy and Theory* (p. 2032). Springer Singapore. https://doi.org/10.1007/978-981-287-588-4_100915

Piemonti, A. D., Macuga, K. L., & Babbar-Sebens, M. (2017). Usability evaluation of an interactive decision support system for user-guided design of scenarios of watershed conservation practices. *Journal of Hydroinformatics*, *19*(5), 701–718. https://doi.org/10.2166/hydro.2017.017

Pinnaka, S., Yarlagadda, R., & Cetinkaya, E. K. (2015). Modelling robustness of critical infrastructure networks. *Proceedings of the 11th International Conference on the Design of Reliable Communication Networks, DRCN 2015*, 95–98. https://doi.org/10.1109/DRCN.2015.7148995

Pop, D. P., & Altar, A. (2014). Designing an MVC model for rapid web application development. *Procedia Engineering*, *69*, 1172–1179. https://doi.org/10.1016/j.proeng.2014.03.106

Porcellinis, S. De, Setola, R., Panzieri, S., & Ulivi, G. (2008). Simulation of heterogeneous and interdependent critical infrastructures. *International Journal of Critical Infrastructures*, *4*(1/2), 110–128. https://doi.org/10.1504/IJCIS.2008.016095

Portante, E. C., Kavicky, J. A., Craig, B. A., Talaber, L. E., & Folga, S. M. (2017). Modeling electric power and natural gas system interdependencies. *Journal of Infrastructure*

Systems, *23*(4), 1–18. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000395

Power, D. (2002). *Decision support systems: Concepts and resources for managers*. Faculty Book Gallery.

Prasanna, R., & Huggins, T. J. (2016). Factors affecting the acceptance of information systems supporting emergency operations centres. *Computers in Human Behavior*, *57*, 168–181. https://doi.org/10.1016/j.chb.2015.12.013

Prat, N., Comyn-Wattiau, I., & Akoka, J. (2014). Artifact evaluation in information systems design science research - A holistic view. *Proceedings of 18th Pacific Asia Conference on Information Systems, (PACIS 2014), Paper 23*. http://aisel.aisnet.org/pacis2014/23/

Pries-Heje, J., Baskerville, R., & Venable, J. (2008). Strategies for design science research evaluation. *Proceedings of the European Conference on Information Systems*. https://aisel.aisnet.org/ecis2008/87

Puuska, S., Rummukainen, L., Timonen, J., Lääperi, L., Klemetti, M., Oksama, L., & Vankka, J. (2018). Nationwide critical infrastructure monitoring using a common operating picture framework. *International Journal of Critical Infrastructure Protection*, *20*, 28–47. https://doi.org/10.1016/j.ijcip.2017.11.005

Rahman, H. A., Armstrong, M., Hydro, B. C., & Marti, J. (2011). Infrastructure interdependencies simulation through matrix partitioning technique. *International Journal of Critical Infrastructures*, *7*(2), 91–116. https://doi.org/10.1504/IJCIS.2011.041534

Ramirez, A. O. (2000). Three-Tier Architecture. *Linux Journal*. https://www.linuxjournal.com/article/3508

Raskob, W., Wandler, S., & Deines, E. (2015). Agent-based modelling to identify possible measures in case of critical infrastructure disruption. In L. Palen, M. Buscher, T. Comes, & A. Hughes (Eds.), *12th International Conference on Information Systems for Crisis Response and Management (ISCRAM 2015)* (pp. 1–6).

http://idl.iscram.org/files/wolfgangraskob/2015/1182_WolfgangRaskob_etal2015.pdf

Reenskaug, T. (1979). *MVC XEROX PARC 1978-79*. https://folk.universitetetioslo.no/trygver/themes/mvc/mvc-index.html

Rickenberg, T., Gebhardt, A., & Breitner, M. H. (2013). A decision support system for the optimization of car sharing stations. *Proceedings of the ECIS 2013 Completed Research*. https://aisel.aisnet.org/ecis2013_cr/207

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

Rolland, E., Patterson, R. A., Ward, K., & Dodin, B. (2010). Decision support for disaster management. *Operations Management Research*, *3*(1), 68–79. https://doi.org/10.1007/s12063-010-0028-0

Rosato, V., Di Pietro, A., La Porta, L., Pollino, M., Tofani, A., Marti, J. R., & Romani, C. (2016). A decision support system for emergency management of critical infrastructures subjected to natural hazards. In C. G. Panayiotou, G. Ellinas, E. Kyriakides, & M. M. Polycarpou (Eds.), *Critical Information Infrastructures Security* (pp. 362–367). Springer.

Runeson, P. (2006). A survey of unit testing practices. *IEEE Software*, *23*(4), 22–29. https://doi.org/10.1109/MS.2006.91

Rutledge, D., Mcdonald, G., Cameron, M., Mcbride, G., Poot, J., Scrimgeour, F., Price, R., Phyn, D., Delden, H. Van, Huser, B., Small, B., Wedderburn, L., & Fenton, T. (2007). Development of spatial decision support systems to support long-term, integrated planning. In L. Oxley & D. Kulasiri (Eds.), *Proceedings of International Congress on Modelling and Simulation* (pp. 308–314). Modelling and Simulation Society of Australia and New Zealand.

Sadashiva, V. K., Mowll, R., Uma, S., Lin, S. L., Heron, D. W., Horspool, N. A., Nayyerloo, M., Williams, J., Syed, Y. I., Buxton, R., King, A. B., Lukovic, B., Berryman, K. R., & Daly, M. C. (2021). Improving Wellington region' s resilience through integrated infrastructure resilience investments. *Bulletin of the New Zealand Society for Earthquake Engineering (NZSEE)*, *54*(2), 117–134.

Sadeghzadeh Hemayati, M., & Rashidi, H. (2018). Software quality models: A comprehensive review and analysis. *Journal of Electrical and Computer Engineering Innovations, 6*(1), 59–76. https://doi.org/10.22061/JECEI.2019.1076

Sahu, P. K. (2013a). Research design. In *Research Methodology: A guide for researchers in Agricultural Science, Social Science and other related fields* (pp. 25–33). Springer. https://doi.org/10.1007/978-81-322-1020-7_4

Sahu, P. K. (2013b). Sampling design. In *Research Methodology: A guide for researchers in Agricultural Science, Social Science and other related fields* (pp. 45–61). Springer. https://doi.org/10.1007/978-81-322-1020-7_6

Sànchez-Marrè, M., Gibert, K., Sojda, R. S., Steyer, J. P., Struss, P., Rodríguez-Roda, I., Comas, J., Brilhante, V., & Roehl, E. A. (2008). Intelligent environmental decision support systems. In *Developments in Integrated Environmental Assessment* (Vol. 3, pp. 119–144). Elsevier. https://doi.org/10.1016/S1574-101X(08)00608-X

Santos, J. R. (2006). Inoperability input-output modeling of disruptions to interdependent economic systems. *Systems Engineering*, *9*(1), 20–34. https://doi.org/10.1002/sys.20040

Saunders, M., Lewis, P., & Thornhill, A. (2015). *Research methods for business students* (7th ed.).

Schmidt, J., Matcham, I., Reese, S., King, A., Bell, R., Henderson, R., Smart, G., Cousins, J., Smith, W., & Heron, D. (2011). Quantitative multi-risk analysis for natural hazards: A framework for multi-risk modelling. *Natural Hazards*, *58*(3), 1169–1192. https://doi.org/10.1007/s11069-011-9721-z

Schuldt, H. (2009). Multi-Tier Architecture. In L. LIU & M. T. ÖZSU (Eds.), *Encyclopedia of Database Systems* (pp. 1862–1865). Springer. https://doi.org/10.1007/978-0-387-39940-9_652

Setola, R., & Theocharidou, M. (2016). Modelling dependencies between critical infrastructures. In *Studies in Systems, Decision and Control* (Vol. 90, pp. 19–41). Springer. https://doi.org/10.1007/978-3-319-51043-9_2

Shabi, J., Reich, Y., & Diamant, R. (2017). Planning the verification, validation, and testing process: A case study demonstrating a decision support model. *Journal of Engineering Design*, *28*(3). https://doi.org/10.1080/09544828.2016.1274964

Shafinah, K., Selamat, M. H., Abdullah, R., Nik Muhamad, A. M., & Awang Noor, A. G. (2010). System evaluation for a decision support system. *Information Technology Journal*, *9*(5), 889–898. https://doi.org/10.3923/itj.2010.889.898

Shamsaie, A., Habibi, J., & Ghassemi, F. (2007). Tierpeer: A three-tier framework for P2P applications. *International Journal of Computer Science and Network Security*, *7*(2).

Simon, H. (1996). *The Sciences of the Artificial* (3rd ed.). MIT Press. https://doi.org/10.1016/S0898-1221(97)82941-0

Singhaputtangkul, N., Low, S. P., Teo, A. L., & Hwang, B. G. (2013). Knowledge-based decision support system quality function deployment (KBDSS-QFD) tool for assessment of building envelopes. *Automation in Construction*, *35*, 314–328. https://doi.org/10.1016/j.autcon.2013.05.017

Sonnenberg, C., & Vom Brocke, J. (2012). Evaluation patterns for design science research artefacts. *Communications in Computer and Information Science*, *286*, 71–83. https://doi.org/10.1007/978-3-642-33681-2_7

Sprague, R. H., & Carlson, E. D. (1982). *Building effective decision support systems*. Prentice Hall. https://dl.acm.org/citation.cfm?id=578156

Statistics New Zealand. (2020). *Home | Stats NZ*. https://www.stats.govt.nz/

Syed, Y. I., Buxton, R., & Horspool, N. (2019). *RiskScape and Wellington Electricity restoration uncertainty analysis* (GNS Science Internal Report 2019/08). GNS Science, Avalon, Lower Hutt.

Syed, Y. I., Uma, S., & Prasanna, R. (2018). A simulation framework to model interdependencies between electricity and road infrastructure networks. *New Zealand Society for Earthquake Engineering*, 1–7.

Syed, Y. I., Uma, S., Prasanna, R., Stock, K., & Blake, D. (2018). A design science based simulation framework for critical infrastructure interdependency. In K. Stock & D. Bunker (Eds.), *Proceedings of ISCRAM Asia Pacific 2018: Innovating for Resilience – 1st International Conference on Information Systems for Crisis Response and Management Asia Pacific* (pp. 516–524).

Syed, Y. I., Uma, S., Prasanna, R., & Wotherspoon, L. M. (2021). 'End to end' linkage structure for integrated impact assessment of infrastructure networks under natural hazards. *Bulletin of the New Zealand Society for Earthquake Engineering (NZSEE)*, *54*(2), 153–162.

Tang, A. P., & Zhao, A. P. (2012). A decision supporting system for earthquake disaster mitigation. *Proceedings of 2012 International Conference on Intelligent Systems Design and Engineering Applications*, 748–751. https://doi.org/10.1109/ISdea.2012.743

Taylor, P. (1998). The three-tier architecture: An object-oriented perspective. In *Distributed applications engineering: Building new applications and managing legacy applications with distributed technologies* (pp. 79–94). Springer. https://doi.org/10.1007/978-1-4471-1550-2_4

Thompson, S., Altay, N., Iii, W. G. G., & Lapetina, J. (2006). Improving disaster response efforts with decision support systems. *International Journal of Emergency Management*, *3*(4), 250. https://doi.org/10.1504/IJEM.2006.011295

Tinguaro Rodríguez, J., Vitoriano, B., & Montero, J. (2010). A natural-disaster management DSS for humanitarian non-governmental organisations. *Knowledge-Based Systems*, *23*(1), 17–22. https://doi.org/10.1016/j.knosys.2009.07.009

Tinguaro Rodríguez, J., Vitoriano, B., & Montero, J. (2012). A general methodology for data-based rule building and its application to natural disaster management. *Computers and Operations Research*, *39*(4), 863–873. https://doi.org/10.1016/j.cor.2009.11.014

Tolk, A., Ihrig, M., Page, E. H., Szabo, C., Heath, B. L., Padilla, J. J., Dante Suarez, E., Weirich, P., & Yilmaz, L. (2013). Epistemology of modeling and simulation. In R. Pasupathy, S.-H. Kim, A. Tolk, R. Hill, & M. E. Kuhl (Eds.), *Proceedings of the 2013 Winter Simulation Conference* (pp. 1152–1166). https://doi.org/10.1109/WSC.2013.6721504

Tolone, W. J., Johnson, E. W., Lee, S.-W., Xiang, W.-N., Marsh, L., Yeager, C., & Blackwell, J. (2009). Enabling system of systems analysis of critical infrastructure behaviors. In R. Setola & S. Geretshuber (Eds.), *Critical Information Infrastructure Security* (pp. 24–35). Springer.

Transpower New Zealand. (n.d.). *Transpower New Zealand*. Retrieved February 16, 2018, from https://www.transpower.co.nz/

Trucco, P., Cagno, E., & De Ambroggi, M. (2012). Dynamic functional modelling of vulnerability and interoperability of Critical Infrastructures. *Reliability Engineering and System Safety*, *105*, 51–63. https://doi.org/10.1016/j.ress.2011.12.003

Uma, S., Syed, Y. I., Karalliyadda, S., & Prasanna, R. (2020). *Modelling interdependencies of critical infrastructure network recovery using a decision support system* (GNS Science Report 2020/18). GNS Science, Avalon, Lower Hutt.

UNDRR. (2015). *Sendai Framework for Disaster Risk Reduction*. https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030

Unen, H. C., Sahin, M., & Elnashai, A. S. (2011). Assessment of interdependent lifeline networks performance in earthquake disaster management. *Proceedings of the 8th International ISCRAM Conference*, 1–5. http://idl.iscram.org/files/canuenen/2011/365_CanUenen_etal2011.pdf

Venable, J., Pries-Heje, J., & Baskerville, R. (2016). FEDS: A framework for evaluation in design science research. *European Journal of Information Systems*, *25*(1), 77–89. https://doi.org/10.1057/ejis.2014.36

Venable, J., Pries-Heje, J., & Baskerville, R. (2012). A comprehensive framework for evaluation in design science research. In K. Peffers, M. Rothenberger, & B. Kuechler (Eds.), *Design Science Research in Information Systems. Advances in Theory and Practice* (pp. 423–438). Springer.

Ventura, C. E., García, H. J., & Martí, J. M. (2010). Understanding interdependencies among critical infrastructures. *Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering*.

Vitoriano, B., Rodríguez, J. T., Tirado, G., Martín-Campo, F. J., Ortuño, M. T., & Montero, J. (2015). Intelligent decision-making models for disaster management. *Human and Ecological Risk Assessment: An International Journal*, *21*(5), 1341–1360. https://doi.org/10.1080/10807039.2014.957947

Vivacqua, A., Garcia, A. C., Canós, J., Comes, M., & Vieira, V. (2016). Collaboration and decision making in crisis situations. *Proceedings of the 19th ACM Conference on Computer Supported Cooperative Work and Social Computing Companion*, 503–508. https://doi.org/10.1145/2818052.2855520

Voorhees, D. P. (2020). Introduction to Model-View-Controller. In *Guide to efficient software design: An MVC approach to concepts, structures, and models* (pp. 175–179). Springer. https://doi.org/10.1007/978-3-030-28501-2_14

Waka Kotahi NZTA. (n.d.). *Waka Kotahi NZ Transport Agency*. Retrieved January 24, 2017, from https://www.nzta.govt.nz/

Wang, H. (2013). A rule-based decision support system for critical infrastructure management. *Human and Ecological Risk Assessment*, *19*(2), 566–576. https://doi.org/10.1080/10807039.2013.755102

Wang, J., Lawson, G., & Shen, Y. (2014). Automatic high-fidelity 3D road network modeling based on 2D GIS data. *Advances in Engineering Software*, *76*, 86–98. https://doi.org/10.1016/j.advengsoft.2014.06.005

Wellington Electricity. (n.d.). *Wellington Electricity*. Retrieved January 24, 2017, from https://welectricity.co.nz/

Wellington Lifelines Group. (2019). *Protecting Wellington's economy through accelerated infrastructure investment programme business case.* Wellington Lifelines - Regional Resilience Project. https://wremo.nz/assets/Uploads/191111-Wellington-Lifelines-PBC-MAIN-20191009.pdf

Wellington Water. (n.d.). *Wellington Water*. Retrieved January 24, 2017, from https://wellingtonwater.co.nz/

Wijegunaratne, I., & Fernandez, G. (1998). The three-tier application architecture. In *Distributed applications engineering: Building new applications and managing legacy applications with distributed technologies* (pp. 41–78). Springer. https://doi.org/10.1007/978-1-4471-1550-2_3

Williams, D. W., & Wood, M. S. (2015). Rule-based reasoning for understanding opportunity evaluation. *Academy of Management Perspectives*, *29*(2). https://doi.org/10.5465/amp.2013.0017

Wilson, G., Wilson, T. M., Deligne, N. I., & Cole, J. W. (2014). Volcanic hazard impacts to critical infrastructure: A review. *Journal of Volcanology and Geothermal Research*, *286*, 148–182. https://doi.org/10.1016/j.jvolgeores.2014.08.030

Wong, B. L. W. (2004). Data analysis for the Critical Decision Method. In D. Diaper & N. Stanton (Eds.), *Task Analysis for Human-Computer Interaction*. Mahwah, NJ: Lawrence Erlbaum Associates.

WREMO. (n.d.). *WREMO*. Retrieved January 23, 2017, from http://www.getprepared.org.nz/

XMind. (n.d.). *XMind*. Retrieved June 15, 2019, from https://www.xmind.net

Yang, L., Prasanna, R., & King, M. (2014). GDIA: Eliciting information requirements in emergency first response. *Requirements Engineering*, *20*(4), 345–362. https://doi.org/10.1007/s00766-014-0202-2

Yao, X., Han, C., Chen, Q., & Meng, L. (2018). Vulnerability distribution model of critical infrastructures based on topological system simulation. In I. Smith & B. Domer (Eds.), *Advanced Computing Strategies for Engineering* (pp. 498–515). Springer.

Yin, R. K. (2014). *Case study research: Design and methods* (5th ed.). Sage Publications.

Zakaria, F., Garcia, H. A., Hooijmans, C. M., & Brdjanovic, D. (2015). Decision support system for the provision of emergency sanitation. *Science of the Total Environment*, *512–513*, 645–658. https://doi.org/10.1016/j.scitotenv.2015.01.051

Zaraté, P., & Liu, S. (2016). A new trend for knowledge-based decision support systems design. *International Journal of Information and Decision Sciences*, *8*(3), 305–324. https://doi.org/10.1504/IJIDS.2016.078586

Zhang, C., Liu, X., Jiang, Y. P., Fan, B., & Song, X. (2014). A two-stage resource allocation model for lifeline systems quick response with vulnerability analysis. *European Journal of Operational Research*, *250*, 855–864. https://doi.org/10.1016/j.ejor.2015.10.022

Zhang, P., & Peeta, S. (2011). A generalized modeling framework to analyze interdependencies among infrastructure systems. *Transportation Research Part B: Methodological*, *45*(3), 553–579. https://doi.org/10.1016/j.trb.2010.10.001

Zhang, Y., Yang, N., & Lall, U. (2016). Modeling and simulation of the vulnerability of interdependent power-water infrastructure networks to cascading failures. *Journal of Systems Science and Systems Engineering*, *25*(1), 102–118. https://doi.org/10.1007/s11518-016-5295-3

Zhou, Y. xi, Liu, G. jun, Fu, E. jiang, & Zhang, K. fei. (2009). An object-relational prototype of GIS-based disaster database. *Procedia Earth and Planetary Science*, *1*(1), 1060–1066. https://doi.org/10.1016/j.proeps.2009.09.163

Zio, E. (2016). Challenges in the vulnerability and risk analysis of critical infrastructures. *Reliability Engineering and System Safety*, *152*, 137–150. https://doi.org/10.1016/j.ress.2016.02.009

Zlatev, Z., Veres, G., & Sabeur, Z. (2013). Agile data fusion and knowledge base architecture for critical decision support. *International Journal of Decision Support System Technology*, *5*(2), 1–20. https://doi.org/10.4018/jdsst.2013040101

Zografos, K. G., Vasilakis, G. M., & Giannouli, I. M. (2000). Methodological framework for developing decision support systems (DSS) for hazardous materials emergency response operations. *Journal of Hazardous Materials*, *71*(1–3), 503–521. https://doi.org/10.1016/S0304-3894(99)00096-5

Zorn, C., Pant, R., Thacker, S., & Shamseldin, A. Y. (2020). Evaluating the magnitude and spatial extent of disruptions across interdependent national infrastructure networks. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems Part B: Mechanical Engineering*, *6*(2), 1–35. https://doi.org/10.1115/1.4046327

Zorn, C., & Shamseldin, A. Y. (2016). Quantifying directional dependencies from infrastructure restoration data. *Earthquake Spectra*, *32*(3), 1363–1381. https://doi.org/10.1193/013015EQS015M

APPENDIX A

HUMAN ETHICS NOTIFICATIONS

Date: 05 July 2017

Dear Yasir Syed

Re: Ethics Notification - **4000018086** - **Development of a Decision Support System through Modelling of Critical Infrastructure Interdependencies**

Thank you for your notification which you have assessed as Low Risk.

Your project has been recorded in our system which is reported in the Annual Report of the Massey University Human Ethics Committee.

The low risk notification for this project is valid for a maximum of three years.

If situations subsequently occur which cause you to reconsider your ethical analysis, please contact a Research Ethics Administrator.

Please note that travel undertaken by students must be approved by the supervisor and the relevant Pro Vice-Chancellor and be in accordance with the Policy and Procedures for Course-Related Student Travel Overseas. In addition, the supervisor must advise the University's Insurance Officer.

A reminder to include the following statement on all public documents:
"This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named in this document are responsible for the ethical conduct of this research.

If you have any concerns about the conduct of this research that you want to raise with someone other than the researcher(s), please contact Dr Brian Finch, Director - Ethics, telephone 06 3569099 ext 86015, email humanethics@massey.ac.nz. "

Please note, if a sponsoring organisation, funding authority or a journal in which you wish to publish requires evidence of committee approval (with an approval number), you will have to complete the application form again, answering "yes" to the publication question to provide more information for one of the University's Human Ethics Committees. You should also note that such an approval can only be provided prior to the commencement of the research.

Yours sincerely

B J Finch

Dr Brian Finch
Chair, Human Ethics Chairs' Committee and Director (Research Ethics)

APPENDIX B

INTERVIEW GUIDE FOR KNOWLEDGE ELICITATION

Development of a Decision Support System through Modelling of Critical Infrastructure Interdependencies

INFORMATION SHEET

Researcher(s) Introduction
My name is Syed Yasir Imtiaz, and I am doing a PhD. in Emergency Management from Joint Centre for Disaster Research (JCDR), Massey University, Wellington. My study is funded by the GNS project of Post Disaster Cities (PDC) and as part of this project, I am also working on developing a report on "Framework for an integrated end to end impact assessment of infrastructure networks under natural hazards".

Project Description and Invitation
This study aims to develop a Decision Support System (DSS) through a computer-based simulation framework to model Critical Infrastructures (CI) interdependencies. The simulation framework after successfully modelling the CI interdependencies will be used as an interface between RiskScape; a multi-hazard risk analysis tool and MERIT (Measuring the Economics of Resilient Infrastructure Tool); an integrated decision support model to quantify the economic consequences resulting from the infrastructure damage. As part of the knowledge elicitation process, the researcher wants to understand different recovery strategies adopted by regional CI network providers. The researcher is using the Critical Decision Method (CDM) for his interviews which will be very useful and easy for the participants to narrate their experiences of handling real-life CI damage recovery tasks interactively.

You are requested to participate in the research project as your participation would be greatly helpful for the researcher and your support in this regard is much appreciated.

Participant Identification and Recruitment
Personnel involved in various infrastructure modelling works for different types of natural hazards within New Zealand are invited to participate.

Project Procedures
Taking part will involve a semi-structured interview which will take **one to two hours** of your time depending on your choice and availability. Given that your participation may take place during work time, it may be appropriate to seek approval from your line manager before participation.

Data Management
Data will be stored securely in password-protected electronic files for five years after completion of the project and will be deleted permanently afterwards.

Participant's Rights
Your participation is entirely voluntarily, and you are under no obligation to accept this invitation. If you decide to participate, you are free to ask questions about the study at any time. Also, you have the right to decline to answer any particular question during the interview, withdraw from the study, ask any questions about the study at any time during participation, and be given access to a summary of the project findings when it is concluded. Your participation in the interview will remain anonymous. Interviews will be recorded and transcriptions will be shared with you for verification and approval. Only the researcher will have access to your individual views, comments, and responses. Later these individual interviews will be combined for analysis and the publication of any findings.

Project Contacts
If you have any concerns or questions about the project, you may contact the student and his primary supervisor through the contact details given below:

Syed Yasir Imtiaz
Joint Centre for Disaster Research (JCDR)
T18 Wellington Campus
Massey University
94 Tasman Street
Wellington
Tel: +6448015799 Ext: 63725
Mob: +64 21 08373000
Email: y.syed@massey.ac.nz

Dr Raj Prasanna
Joint Centre for Disaster Research
T20 Wellington Campus
Massey University
94 Tasman Street
Wellington
Tel: +6448015799 Ext: 63618
Email: r.prasanna@massey.ac.nz

This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named in this document are responsible for the ethical conduct of this research.

If you have any concerns about the conduct of this research that you want to raise with someone other than the researcher(s), please contact Dr Brian Finch, Director (Research Ethics), by email humanethics@massey.ac.nz.

PARTICIPANT CONSENT FORM – INDIVIDUAL

Development of a Decision Support System through Modelling of Critical Infrastructure Interdependencies

Researcher: Syed Yasir Imtiaz, Joint Centre for Disaster Research, School of Psychology, Massey University

- I have read the Information Sheet and have had the details of the study explained to me. My questions have been answered to my satisfaction, and I understand that I may ask further questions at any time.
- I understand that any information I provide will be kept confidential and accessible only to the researcher and his supervisors.
- I understand that the data I provide will not be used for any other purpose or released to others.
- I understand that all the data will be destroyed within five years after the completion of the project.

Please underline or circle your choices below:

I agree/do not agree with the interview being sound recorded.

I wish/do not wish to have my recordings returned to me.

I agree/do not agree to participate in this study under the conditions set out in the Information Sheet.

Signature: .... **Date:** ....

Full Name: ....

Interview Guide

Title: Development of a Decision Support System through modelling of Critical Infrastructure Interdependencies

Part 1: Participant's demographic information

This section consists of a few introductory questions related to the demographic information of the participants. Please answer each question according to the information needed. All the information will be kept anonymous and only for research purposes.

1.1 Please indicate your age

☐ 18-30 years

☐ 31-40 years

☐ 41-50 years

☐ 51-60 years

☐ More than 61 years

1.2 Please write the name of your current organization

____

1.3 Please indicate the industry/ field your organization represents

____

1.4 Please indicate your job role in this organization

____

1.5 Please indicate your experience in this organization as this job role

☐ 0-2 years

☐ More than 2 and up to 5 years

☐ More than 5 and up to 10 years

☐ More than 10 and up to 15 years

☐ More than 15 years

Part 2: Event Details

Briefly explain what you would do if you are informed about an electricity outage in multiple locations after an earthquake in the region. You have to make decisions about the management of your available resources and the initial steps needed for the recovery process.

Part 3: Timeline Construction

Based on the above Incident, please provide your feedback on the below timeline that the researcher has developed while you were narrating the incident. It shows how various events happened from the time your team arrived at the scene to the time the resources were recovered fully

Sketch of the Timeline

Part 4: Decision Points Identification

Based on the timeline, the following information, decisions and actions are identified. Please give your feedback for improvements.

Information	**Decision**	**Action**
I.1	D.1	A.1
I.2	D.2	A.2
I.3	D.3	A.3
I.4	D.4	A.4
I.5	D.5	A.5
I.6	D.6	A.6
I.7	D.7	A.7
I.8	D.8	A.8

APPENDIX C

INTERVIEW GUIDE FOR KCDSS EVALUATION

Development of a Decision Support System through modelling of Critical Infrastructure Interdependencies

INFORMATION SHEET

Researcher(s) Introduction
My name is Syed Yasir Imtiaz, and I am doing a PhD in Emergency Management from Joint Centre for Disaster Research (JCDR), Massey University, Wellington. My study is funded by the GNS project of Post Disaster Cities (PDC) and as part of this project, I am also working on developing a report on “Framework for an integrated end to end impact assessment of infrastructure networks under natural hazards”.

Project Description and Invitation

This study aims to develop a Decision Support System (DSS) through a computer-based simulation framework to model Critical Infrastructures (CI) interdependencies. The DSS can model the interdependencies between electricity, water and road networks and provides its end-users with a variety of customization options to apply, test and evaluate their recovery strategies. The DSS is flexible to accept the damage models for the CI assets from natural hazards risk modelling tools like RiskScape or HAZUS etc. Corresponding recovery strategies can then be applied through a user-friendly interface of the DSS. Different Scenarios based on the variety of recovery strategies can be tested and compared to see whether it is useful to apply a strategy or not. So, this DSS is useful for both the preparedness and recovery phases of a disaster.

You are requested to participate in the evaluation phase of this study project to test and give feedback about the performance, reliability, efficiency and usefulness of the DSS. During the evaluation, a demo of the DSS functionalities and features will be presented and the participants would be asked to give feedback about the user interface and capabilities of the DSS. This feedback would be useful for the researcher to validate some of the important features of the DSS as well as finding possibilities for future improvements.

Your participation in the evaluation will be highly valuable to improve the findings and outcomes of this study.

Participant Identification and Recruitment
Personnel involved in various fields of emergency management and the experts working on management of CI in lifeline utility organizations within New Zealand are invited to participate.

Project Procedures
Taking part will involve a semi-structured interview which will take **one hour** of your time depending on your choice and availability.

Data Management
Data will be stored securely in password-protected electronic files for five years after completion of the project and will be deleted permanently afterwards.

Participant’s Rights
Your participation is entirely voluntarily, and you are under no obligation to accept this invitation. If you decide to participate, you are free to ask questions about the study at any time. Also, you have the right to: decline to answer any particular question during the interview, withdraw from the study, ask any questions about the study at any time during participation, and be given access to a summary of the project findings

when it is concluded. Your participation in the interview will remain anonymous. Interviews will be recorded and transcriptions will be shared with you for verification and approval. Only the researcher will have access to your individual views, comments, and responses. Later these individual interviews will be combined for analysis and the publication of any findings.

Project Contacts
If you have any concerns or questions about the project, you may contact the student and his primary supervisor through the contact details given below:

Syed Yasir Imtiaz
Joint Centre for Disaster Research (JCDR)
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Email: r.prasanna@massey.ac.nz

This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named in this document are responsible for the ethical conduct of this research.

If you have any concerns about the conduct of this research that you want to raise with someone other than the researcher(s), please contact Dr Brian Finch, Director (Research Ethics), by email humanethics@massey.ac.nz.

PARTICIPANT CONSENT FORM – INDIVIDUAL

Development of a Decision Support System through Modelling of Critical Infrastructure Interdependencies

Researcher: Syed Yasir Imtiaz, Joint Centre for Disaster Research, School of Psychology, Massey University

- I have read the Information Sheet and have had the details of the study explained to me. My questions have been answered to my satisfaction, and I understand that I may ask further questions at any time.
- I understand that any information I provide will be kept confidential and accessible only to the researcher and his supervisors.
- I understand that the data I provide will not be used for any other purpose or released to others.
- I understand that all the data will be destroyed within five years after the completion of the project.

Please underline or circle your choices below:

I agree/do not agree with the interview being sound recorded.

I wish/do not wish to have my recordings returned to me.

I agree/do not agree to participate in this study under the conditions set out in the Information Sheet.

Signature: .... **Date:** ....

Full Name: ....

Evaluation of the KCDSS

Part 1: Participant's demographic information

This section consists of a few introductory questions related to the demographic information of the participants. Please answer each question according to the information needed. All the information will be kept anonymous and only for research purposes.

1.1 Please indicate your age

- ☐ 18-30 years
- ☐ 31-40 years
- ☐ 41-50 years
- ☐ 51-60 years
- ☐ More than 61 years

1.2 Please write the name of your current organization

____

1.3 Please indicate the industry/ field your organization represents

____

1.4 Please indicate your job role in this organization

____

1.5 Please indicate your experience in this organization as this job role

- ☐ 0-2 years
- ☐ More than 2 and up to 5 years
- ☐ More than 5 and up to 10 years
- ☐ More than 10 and up to 15 years
- ☐ More than 15 years

Part 2: Evaluation Questionnaire

This section evaluates the software quality of the KCDSS based on the five attributes of functionality, usability, reliability, performance and supportability. The researcher will be giving a demonstration of the KCDSS in the process of asking different questions. Please assess the above-mentioned five attributes by considering yourself as the user of KCDSS and give your feedback in the indicated five scales of satisfaction levels.

2.1 Functionality of the KCDSS

This section evaluates the KCDSS through different aspects of its functionality.

		Strongly disagree	**Disagree**	**Neutral**	**Agree**	**Strongly agree**
F1.	KCDSS has all the necessary main features for its intended tasks	☐	☐	☐	☐	☐
F2.	All the capabilities of the KCDSS are fully functional and error-free	☐	☐	☐	☐	☐
F3.	KCDSS is generalizable to be used for other scenarios and is not specific or limited	☐	☐	☐	☐	☐
F4.	Security features are implemented to keep the KCDSS secure from the hackers	☐	☐	☐	☐	☐
F5.	KCDSS supports decision-makers to undertake activities and make decisions	☐	☐	☐	☐	☐

2.2 Usability of the KCDSS

This section evaluates the KCDSS through different aspects of its usability.

		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
U1.	KCDSS is simple to use and if complexity is a requirement in certain places, it is explained in a simpler way	☐	☐	☐	☐	☐
U2	The sequence of the screens is clear	☐	☐	☐	☐	☐
U3	The overall functionality of the KCDSS is easy to learn	☐	☐	☐	☐	☐
U4	Easy to remember the terminologies used in the Menu	☐	☐	☐	☐	☐
U5	KCDSS works efficiently in resolving real-world problems	☐	☐	☐	☐	☐
U6	Users can easily reuse the KCDSS after some time of not having used it, without having to learn everything all over again.	☐	☐	☐	☐	☐
U7	Proper help facilities and guidance is present	☐	☐	☐	☐	☐
U8	Training guidance and material is provided within the KCDSS	☐	☐	☐	☐	☐
U9	KCDSS gives a proper way to train the new users	☐	☐	☐	☐	☐
U10	The user feels satisfied when using the KCDSS in terms of comfort and acceptability	☐	☐	☐	☐	☐
U11	KCDSS functions according to the user requirements	☐	☐	☐	☐	☐
U12	Users can solve real-world problems using this KCDSS in an acceptable way	☐	☐	☐	☐	☐
U13	KCDSS has a practical utility with the right kind of functionality according to the user needs	☐	☐	☐	☐	☐

2.3 Reliability of the KCDSS

This section evaluates the KCDSS through different aspects of its reliability.

		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
R1.	The outputs generated from KCDSS are consistent	☐	☐	☐	☐	☐
R2	User interface minimises the possibility for errors to occur	☐	☐	☐	☐	☐
R3	Error messages are helpful	☐	☐	☐	☐	☐
R4	Warning dialogs are generated where necessary	☐	☐	☐	☐	☐
R5	KCDSS recovers efficiently from the user errors	☐	☐	☐	☐	☐
R6	Users can easily do the corrective action once an error has been recognized	☐	☐	☐	☐	☐
R7	KCDSS supports its user to determine the effects of future actions based on past interaction history	☐	☐	☐	☐	☐
R8	A list of related operations is available for the users, based on their actions	☐	☐	☐	☐	☐
R9	KCDSS is tolerant to user errors and provides enough feedback when a user makes an error	☐	☐	☐	☐	☐
R10	If users make an error, they can recover from it easily	☐	☐	☐	☐	☐

2.4 Performance of the KCDSS

This section evaluates the KCDSS through different aspects of its performance.

		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
P1.	The response time of the KCDSS is acceptable	☐	☐	☐	☐	☐
P2	KCDSS can maintain its speed even with a large amount of data	☐	☐	☐	☐	☐
P3	KCDSS generated accurate results as per user expectations	☐	☐	☐	☐	☐

2.5 Supportability of the KCDSS

This section evaluates the KCDSS through different aspects of its supportability.

		Strongly disagree	Disagree	Neutral	Agree	Strongly agree
S1.	KCDSS provides proper options of configurations	☐	☐	☐	☐	☐
S2	KCDSS is compatible with other related software that can give input to the KCDSS or can get output from the KCDSS	☐	☐	☐	☐	☐
S3	A versatile amount of data and models can be used with the KCDSS	☐	☐	☐	☐	☐
S4	Data of different formats and models of different kinds can be integrated to generate the desired results	☐	☐	☐	☐	☐
S5	KCDSS UI can adapt to various task requirements	☐	☐	☐	☐	☐
S6	KCDSS provides its users with the ability to customize input and output methods	☐	☐	☐	☐	☐

Thank you for your participation in this evaluation