A Design Science based Simulation Framework for Critical Infrastructure Interdependency

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ABSTRACT

Critical Infrastructures (CI) such as electricity, water, fuel, telecommunication and road networks are a crucial factor for secure and reliable operation of a society. In a non-emergency situation, most businesses operate on an individual infrastructure. However, after major natural disasters such as earthquakes, the conflicts and complex interdependencies among the different infrastructures can cause significant disturbances, as a failure can propagate from one infrastructure to another. This paper discusses the development of an integrated simulation framework that models dependencies of electricity network on the road network. The framework uses a damage map of electricity network components and integrates them with road access time to these damaged components for estimating the electricity outage time of a region. The results can be used for recovery planning, identification of vulnerabilities, and adding redundancies in an infrastructure network.

Keywords

Infrastructure, interdependency, electricity, road, restoration.

INTRODUCTION

Natural hazards such as earthquakes, volcanoes, tsunamis, landslides and forest fires can severely impact the well-being and sometimes survival of people within a country (Pondard & Daly, 2011). In densely populated areas these hazards have the potential to cause devastating social and economic loss. Accurate and timely acquisition of relevant information is important to respond and recover from an event. All immediate response and recovery actions have priority to save human lives and to relocate displaced people to some safer places. In this regard, critical services, also known as 'lifeline utility services' or 'critical infrastructures' (CI) also need to be operational as soon as possible (Trucco, Cagno, & De Ambroggi, 2012). CI, which include telecommunication, electricity, transportation, water supply, fuel and gas enable everyday activities including business continuity, mobilization and access to goods and communication. Unfortunately, hazards produce increased risk of CI service failures globally and the risks to CI are further amplified because of the complex interdependencies between modern networks, and an array of different failure modes that affect the functioning of an infrastructure (Shoji & Tabata, 2011; Wilkinson, Dunn, & Ma, 2012). Therefore, when emergency responders and stakeholders like safety engineers and building owners need to make decisions, they must have up to date information about any impacts of non-functional or damaged CIs and their interdependencies (Fogli & Guida, 2013).

Within New Zealand, the Civil Defence and Emergency Management (CDEM) Act 2002 sets out the essential infrastructures to be transport, water, wastewater, stormwater, energy and telecommunications services. Consequently, all infrastructure network providers have a responsibility to understand and develop resilience to hazards across various infrastructures both because of their operational interdependence, as well as their legislative responsibilities to function to their fullest possible level of service (Hughes & Healy, 2014).

Rinaldi et al. (2001) highlight the need to enhance interdependency analysis, arguing that it is impossible to analyse or understand the behaviour of a given infrastructure in isolation from the environment or other infrastructures. A significant amount of research demonstrates modelling and simulation as a tool to understand CI interdependencies. For instance, Agent-based Interdependency Modelling and Simulation (AIMS) 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, Baghi, Ghorbani, & Yari, 2007). Another simulation model is the Critical Infrastructure Modelling System (CIMS) that was developed at the Idaho National Laboratory (Dudenhoeffer & Manic, 2006). In CIMS, each physical infrastructure is represented by agents which could be both individual or collective entities such as organizations or groups. In the simulation framework, interdependencies between infrastructures and their relationships are represented as connected graphs. Furthermore, Critical Infrastructure Protection Initiative (CIPI) is a program coordinated by the Open Geospatial Consortium (OGC) (CIPI, 2002). The CIPI pilot project explored the possibility of emergency management through data sharing at various functional levels. It provided a basis to share geographical information and make different data standards interoperable, providing key data for infrastructure analysis. Critical Infrastructure Simulation by Interdependent Agents (CISIA) proposed by Panzieri et al. (2004, 2005), 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. Within New Zealand, national interdependent infrastructure research has been done by Zorn et al. (2016) who analyzed the vulnerability of interdependent infrastructures spatially through a system-of-systems based approach.

Based on the knowledge gained from careful analysis of the works mentioned above, this paper argues that although many aspects of an infrastructure such as organisation, behaviour, risks, threats and vulnerabilities have similarities, these models address the impact of interdependencies from different viewpoints. The understanding, characterizing and modelling of these systems is an immense task and the current efforts in this field are still in an early stage. There are multiple ways in which these models can be related, but there is no single taxonomy or classification that could suit all purposes and therefore the existing approaches have the following limitations:

- Most existing models are static and lack the ability to model temporal interactions across systems and system evolution over time. Therefore, there is a need for a time-stamped simulation so that stakeholders can view the cascading effects of a disaster and analyze regional recovery at different time periods.
- Most of the simulation approaches focus only on one infrastructure and its impact on the other infrastructures, without considering component level characteristics. In the case of interdependency analysis, one component can be entirely different from another, and their attributes should, therefore, be defined separately.
- There is a lack of comprehensive datasets and access to the relevant data which are needed to support different modelling approaches and analysis workflows.
- There is also a lack of an integrated methodological approach to model a CI and to assess the impacts of disruption while considering a wide range of stakeholder objectives.

To address these limitations, an integrated simulation framework is required that can deal with natural hazards by supporting guided decision-making to minimize the impacts of CI failures. The primary objective for developing such a simulation framework is to incorporate the diverse types of infrastructure interdependencies and strategic plans for the repair process and to provide a user-friendly environment for stakeholders to make better recovery decisions. The simulation framework for this study is a work-in-progress for developing a Decision Support System (DSS) through modelling of electricity, road and water networks. Till now, electricity and road networks have been modelled successfully, therefore the scope of this paper is only limited to these two networks. For this purpose, a case study scenario has been tested using our framework to create outage maps. This test case scenario drew on the Wellington region's electricity network in New Zealand. Road dependency was added during the restoration of significant components of the electricity network.

RESEARCH DESIGN

To design this research by addressing relevance and enhancing the rigor of research process, we have conducted this research using the Design Science Research (DSR) principles and used key recommendations provided by Hevner et al. (2004) and March and Smith (1995). DSR is different than philosophy and mathematics that build structures of logical propositions (Lesh & Sriraman, 2005). DSR states and predicts observable phenomena within a field of research to change the state of the world by introducing artificial construct ('artefact'), which can be further described as an artificial object made by humans to solve practical problems (Peffers, Tuunanen, Rothenberger, & Chatterjee, 2007). Artefacts are physical entities, drawings, a set of guidelines or an Information and Communication Technology (ICT) solution. CIs can also be considered as physical artefacts created by people (Hanid, 2014; Kehily & Underwood, 2015; Rickenberg, Gebhardt, & Breitner, 2013; Simon, 1996).

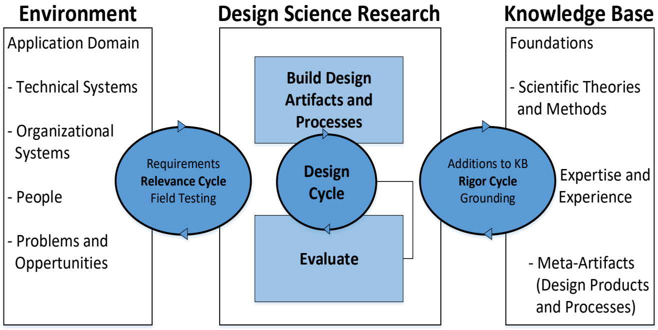


Figure 1. Design Science Research Cycles (Hevner, 2007)

As elaborated by Hevner (2007) in Figure 1, DSR consists of three overlapping research cycles. The Relevance Cycle connects relative environment of a research project's application domain with the DSR activities. In the context of this research, the application domain is emergency management, and the artefacts of modelled CIs need to be designed and evaluated according to the field requirements as specified by the relevant CI utility providers. The information gathering from various stakeholders through expert elicitation and field testing of the artefacts guided us to understand the problems and opportunities related to the proposed artefacts. The Rigor Cycle connects DSR activities with the knowledge base of existing scientific foundations, researchers' experiences, and expertise within the same field of the research project (Griot, 2010; Hasan & Foliente, 2015; Rinaldi et al., 2001). To ensure methodological rigor in this research, foundational information is gathered from the academic literature of appropriate theories for simulation of CI interdependency. In the middle, the Design Cycle is where the artefacts are built and later evaluated through interaction with relevant organizational and technical systems (Hevner, 2007). The design cycle is considerably dependent on the other two cycles for collecting relevant information and designing an artefact according to the needs of the environment. The design cycle starts with obtaining an awareness of the problem by engaging with the relevant stakeholders. This process was helpful to gain an in-depth understanding of the current state of the art of CI interdependencies in New Zealand that revealed actual problems and identification of research gaps in the field. After the identification of problem domain, subsequent research artefacts were constructed. The first artefact was the independent infrastructure model, which included only basic parameters, variables and constraints. It shows an outage scenario due to the failure of the individual infrastructure components. The next artefact modelled failure impacts of an infrastructure component on the components of the other infrastructures. The third artefact used a sectoral approach to identify the interdependencies between all the infrastructures to generate an outage map of the whole region. The final output of the three artefacts is evaluated to check whether it sufficiently meets the needs and expectations of the relevant end-users. After having specified the entire research process driven by the principles of DSR, a simulation framework is developed to accomplish the desired research objectives. Figure 2 illustrates the proposed research framework and the objectives of this research mapped over the three different cycles of the DSR model.

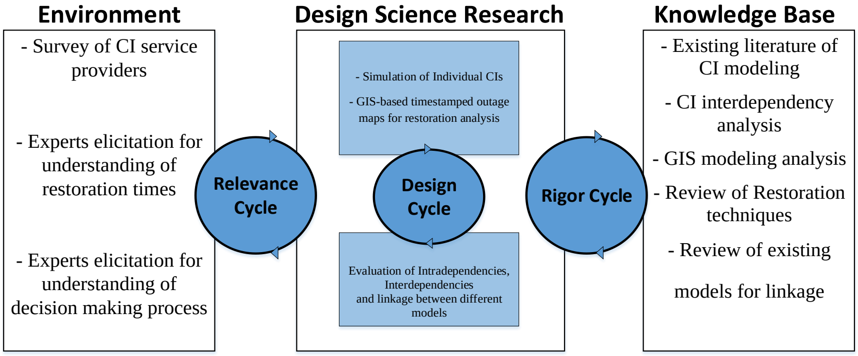


Figure 2. Illustration of simulation framework driven by the DSR's three-cycle view

SIMULATION FRAMEWORK

The first step in the development of any simulation framework is to gain a complete understanding of the problem. To achieve this, information was gathered through the study of existing documents, previous modelling results, interviews and questionnaires. A comprehensive review of the literature on the hierarchy of electricity and road networks was also carried out and used in the development of the test case scenario for the Wellington region. The researchers interacted with relevant stakeholders in the region including lifeline utility providers and emergency management organizations. It was found that there was a strong dependency of electricity network on the road network during the restoration of the significant components. To expand on this, the next sections introduce the underlying architecture of the electricity network, some assumptions about the restoration process and how restoration can occur through considering the road network dependency.

System Overview

Electricity systems are composed of three primary subsystems; generation units, transmission and distribution networks, as shown in figure 3. Generation units are responsible for the production of power. The generated power is then delivered to end users via transmission and distribution networks. Transmission networks transport high voltage power to distribution substations, and distribution networks supply the low voltage energy to end users (Erdener, Pambour, Lavin, & Dengiz, 2014). The electricity model developed in this test case scenario is designed to provide a realistic representation of the behaviour of a transmission network (in terms of cascading failure effects) when a failure occurs in any of the significant components. Analyzing cascading failures is very challenging due to the unexpected sequence of failures. These mainly depend on the initial failure and an appropriate restoration methodology is necessary to return the network to an operational state. The most significant components in a transmission network for this scenario are Grid Exit Points (GXP), substations, transmission structures and buried or overhead cables.

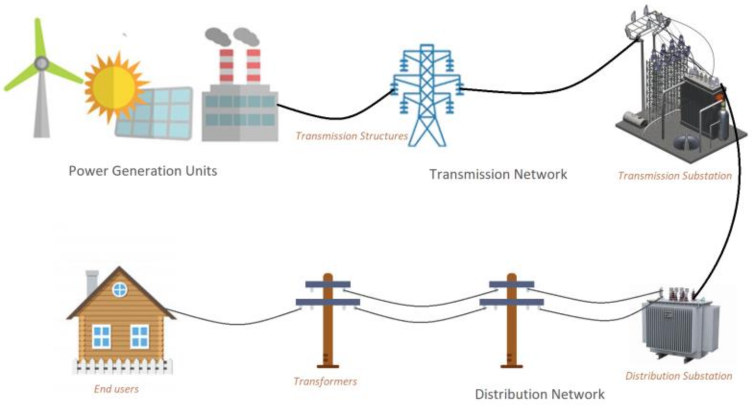
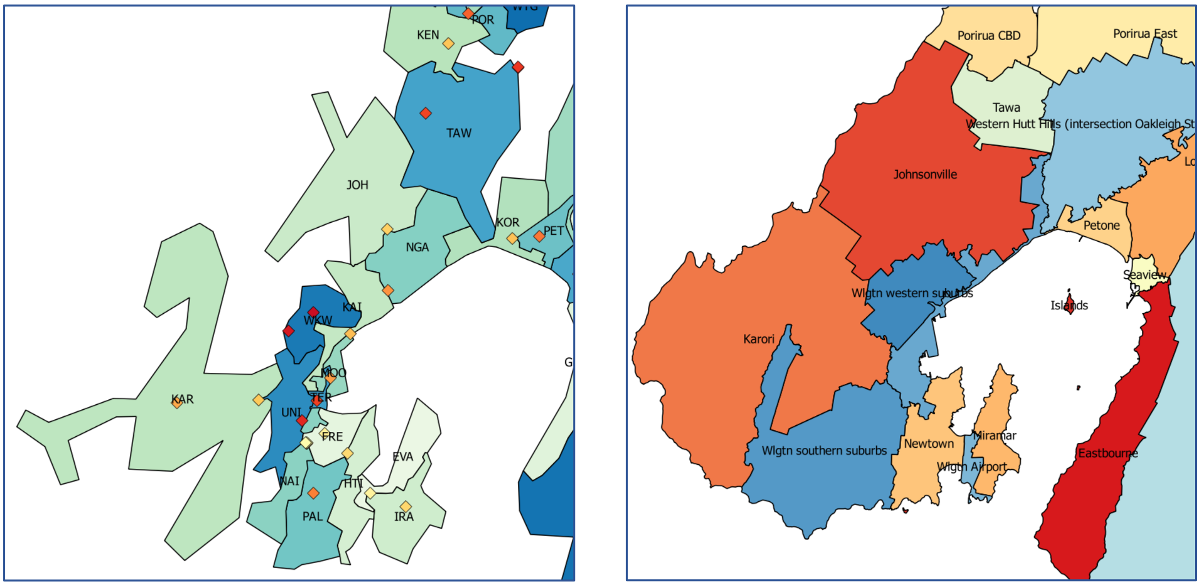


Figure 3. The basic structure of an electricity network

Wellington's metropolitan power supply is provided via a hierarchical system of 220kV, 110kV, 33kV, 11kV and 400V network components. Transpower New Zealand supply a series of grid exit points (GXPs) and from here Wellington Electricity (WE) control supply to commercial and domestic users. Different 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 has defined regional boundaries or zones in which they supply electricity.

As mentioned earlier, modern infrastructure systems are vulnerable not only through disruption of components within their own system but also because of dependencies with other networks. Among electricity and road networks, there are some obvious and clear dependency links. The relative importance of the links can change, however, depending on whether we are in a normal operating situation or whether we are in a post-event period where the emphasis is on recovery and reinstatement. In normal situations, electricity network is considered the primary source for most other infrastructure networks, but in the recovery process, road networks take a higher level of importance because road access controls the ease with which repair and reinstatement operations can take place. Therefore, to understand the electricity outage time of a region, it is important to first know the road access time to access the damaged components. In figure 4 (a), we have shown a zone map of the electricity network in such a way that each zone is covered by a single substation. In figure 4 (b), we have similarly divided the whole region into different road access zones.



a) **b)**

Figure 4. Zone maps of a) Electricity Network and b) Road Network

The zone boundaries for both of these zone maps are drawn for testing the functionality of this simulation framework after the consultation with relevant transport and city council authorities. The division of road zones is based on the road structure and accessible locations within a defined area. After defining the zones, a matrix was created to include access times from each zone to the other and for this test case scenario, we allocated placeholder road access times to simulate an example earthquake scenario. To start the recovery process of electricity network components, the road access time is computed from the source, where repair equipment is present to the destination, where the damaged components are located. Following this, an aggregated recovery time is calculated based on some predefined assumptions for the two networks as explained in the next subsection.

Restoration Assumptions

To successfully model the electricity network and to understand the recovery process with the inclusion of road outages for each electricity substation zone, assumptions were made to establish a common understanding of restoration times. Without these base assumptions, the analysis of the restoration times could become overly complicated, to the point where the realistic assessment would become impossible. These assumptions are that:

- The majority of the expected damage would be caused by the initial fault rupture and earthquake. Significant aftershocks would potentially cause further damage and therefore potentially lengthen restoration times.
- The scope of this test case is to model only the transmission network from generation units to the substation level. For the recovery of assets in the distribution network that, a predefined restoration time has been assigned after recommendations from the experts.
- The majority of necessary skilled resource and associated equipment would also be locally available, and there would be enough repair staff for work to proceed in multiple locations at a time.
- The repair times and strategies for various types of cables like Paper Insulated Aluminum Sheathed (PIAS) and cross-linked polyethylene (XLPE) may be different because some could be solid fluid-filled therefore harder to repair (Erdener et al., 2014). If the number of damaged cables exceeds a predefined value, then the repair work on those cables could be abandoned and the existing cables could be replaced with emergency overhead lines for the continuity of electricity services to the customers.
- There are different priority substation zones in which the emergency overhead lines are replaced first. These priority zones are based on the significance of buildings depending on the services they provide like hospitals, fire brigade offices, police stations and other emergency management organisations.
- The road outage times would be computed based on the assumed number of days between different road zones during the response and recovery stages after an event.
- Every component of the electricity network would be mapped to a predefined road zone to understand the road access time to reach the damaged site before starting the repair work.

These assumptions are related specifically to the Wellington region for this test case scenario, but the framework has the capability to model any city with new assumptions as well. Based on the assumptions mentioned above, we developed an integrated research methodology to link electricity and road networks and then tested the methodology with some placeholder data to create example outage maps.

Integrated Methodology for Linking Electricity and Road Networks

As described in the previous section, the simulation framework in this study is developed to compute the recovery times of electricity services through an understanding of their dependency on the road network. To accomplish this task, we have developed an integrated research methodology for using one of the models as a subset of the other model. As shown in figure 5, both the models have specific inputs and outputs. The road network model is integrated into the electricity network model as a subroutine so that electricity model uses the outputs of the road access times between various road zones to generate some realistic restoration times.

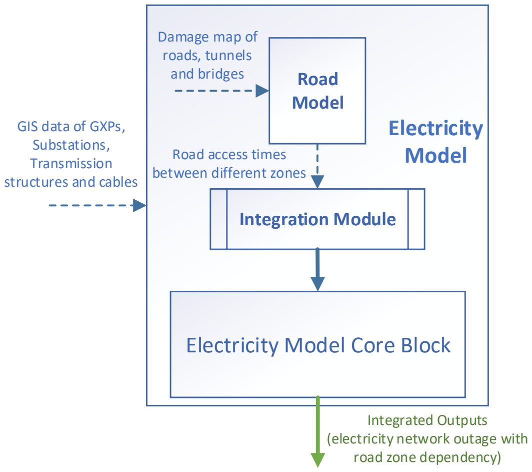
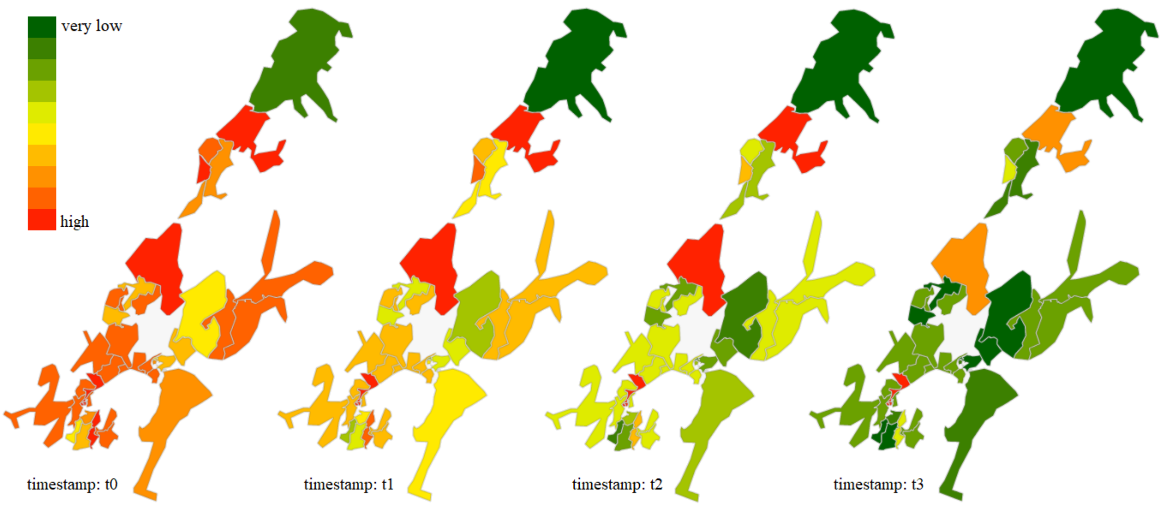


Figure 5. An integrated methodology for modelling electricity and road networks

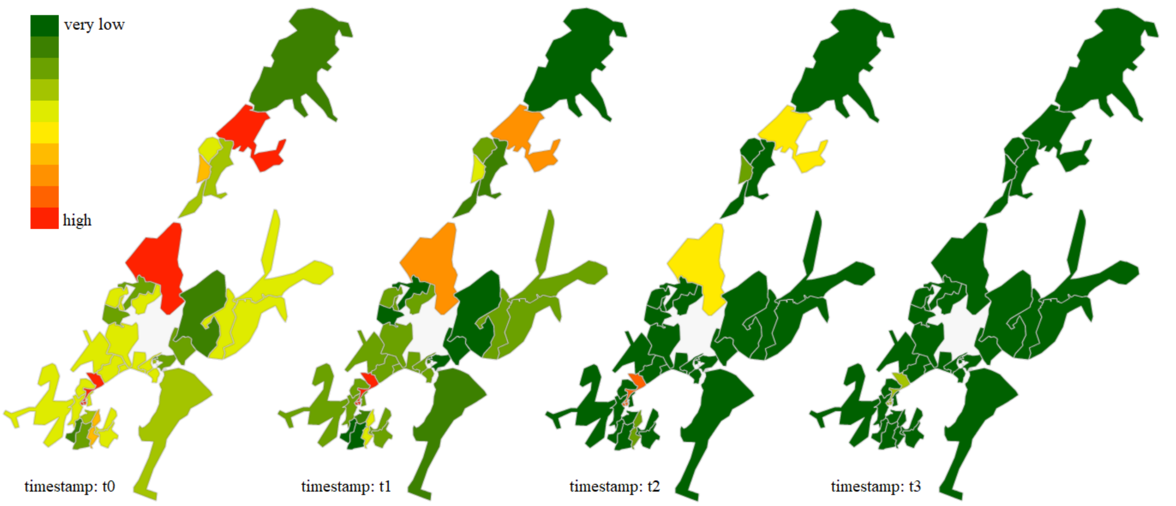
Further explanation about this integrated methodology is presented through a step by step process. This process has been developed on the restoration assumptions defined earlier in this paper. The 6-step integration methodology is described below:

- Step 1: In this scenario, input to the road model is a damage map of the core network components including *roads, tunnels and bridges*. This damage map was developed using an example earthquake scenario using placeholder values. The output is a *road matrix depicting the number of days required for travelling from one region to another in the response and recovery phases of a disaster* considering the probable damage to each of the road network components.
- Step 2: The input of the electricity model is represented through a damage map of selected core components including *GXPs, substations, cables and transmission structures*. Again, the damage map was generated using an example earthquake scenario. To test the framework, we assigned different damage states and corresponding repair times for each of the components to compute restoration time of a substation zone. The output is *timestamped outage map of a substation zone based on the failure of the different components.* This conversion of damage data to the restoration time is done within the framework and is based on the restoration assumptions defined earlier in this paper.
- Step 3: Road model is used as source model whose road outage times are used by electricity model to do an analysis of the electricity outage due to the dependency on road network.
- Step 4: The linking parameter to link both the models is the *road outage time between different road zones.*
- Step 5: The simulation framework first combines road zones with substation zones and then uses the road outage times to determine the amount of time needed for damaged electricity components to recover. Different parts of the damaged components e.g. electricity cables can be spread across different road zones. Therefore, the recovery time for each part of the damaged component is computed based on its corresponding road access time and finally an aggregated restoration time is computed for all damaged components within a substation zone.
- Step 6: After the successful integration of the models, the combined outage map is generated for the interdependency analysis between the road network and the electricity network.

After applying the above-mentioned methodology, we generated some example timestamped outage maps for the Wellington region as shown in figure 6. As mentioned earlier, the region is divided into different substation zones, and the zones in red colour need higher number of days to recover and the zones in green colour are either fully recovered or need very low number of days to recover. In the initial timestamp, i.e. t0, most of the substation zones have damages and the subsequent timestamps show recovery of the whole region gradually. The outage maps in figure 6 (a) and (b) reveal a substantial increase in electricity outage time due to the road network dependency. The comparison of both the maps show that if there is no dependency on the road network then the electricity zones can recover quickly as compared to when there is road network dependency. The reason for this delay is that all the repair equipment and repair staff need transportation access to the damaged sites and if there is no or partial road access available then definitely the time needed to repair electricity network's components would increase.



(a) with road network dependency



(b) without road network dependency

Figure 6. Electricity network outage maps on different timestamps (a) with and (b) without road network dependency

The simulation framework is developed in a way that the electricity and road network of any other city can also be modelled in the same manner if the damage information of the components is provided in the proper format. The outage times can be seen at different timestamps for any day by moving a timeline bar to understand the recovery process and the amount of time needed for the region to recover completely. The resultant outage maps not only show the recovery time of a substation zone, but the simulation framework also has the capability to show the detailed damage information of all the components that provide electricity to a substation from a GXP. This detailed analysis could be useful for identification of vulnerabilities within the electricity network. Moreover, the relevant stakeholders who would use this framework could customize the restoration assumptions and repair strategies to compare different recovery options and their corresponding outage maps.

CONCLUSION

This study identifies the interactions and dependencies of the electricity network on the road network. To achieve this, an integrated research methodology was used to link electricity and road networks during a test case scenario. The results illustrate how analyzing two infrastructure systems in an integrated manner can provide valuable information about system vulnerability and impact analysis. The electricity network is very much dependent on the functionality of a road network for the initiation of repair work. This simulation framework can be used in real-world scenarios if damage maps of electricity and road networks are available and appropriate repair strategies are incorporated as recovery assumptions. In the future, to extend this work and provide more information for the relevant emergency management stakeholders and decision makers, more infrastructure network models will be integrated into the simulation framework. Importantly, this work supports the development of CI response and recovery actions that help to save lives and ensure people have the necessary utilities to survive a disaster or emergency event.

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