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Estimation of electricity supply restoration time with interdependencies under cascading hazard risk approach

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ABSTRACT

The electricity infrastructure network functions as a system with several components interconnected and distributed over a region. When subjected to earthquake and its related cascading hazards, the vulnerable components undergo systemic failure resulting in outage of services. Restoration of power supply depends on the availability of road access to the damaged sites and hence interdependent on the road network restoration. In this paper, we present a detailed method to estimate restoration time with interdependencies that can be integrated with a broader cascading hazard risk probabilistic framework, developed in an earlier study by the authors.

The probabilistic cascading hazard risk framework begins with modelling of primary (e.g. earthquake) and cascading hazards to generate likely damage response of distributed infrastructure networks by accounting for uncertainties via Monte Carlo simulations and supports propagating uncertainties systematically. While this approach can generate thousands of damage realisations, we describe the restoration time estimation approach, by focusing on one potential damage realisation of electricity network considering its interdependencies on road recovery time, which can be repeated for simulations. In this paper, two infrastructures from Napier city are modelled and generated potential service outage maps of electricity network for a given restoration time for road network. Work is underway to generate full suite of damage realisations and quantify uncertainties in restoration times of the considered infrastructure networks.

1 INTRODUCTION

Natural hazard events have caused damage to critical infrastructure (CI) networks and resulted in wide-spread disruptions to essential utility services. In the recent past events in New Zealand, we have observed damage to various CI networks including electricity and road networks (e.g. Durante et al, 2018; Liu et al, 2017) and learnt potential vulnerable elements of the networks. Electricity supply is one of the fundamental commodities supporting livelihood and should be quickly restored. Even though the damage is local at the component level, their failure might trigger a domino effect on the functionality of other interconnected components geographically spread over a region leading to systemic vulnerability. However, the restoration heavily depends on road access availability to the damaged sites. So, resilience assessment of an infrastructure network needs to consider interdependencies on other networks that influence on restoration time estimates.

In dealing with natural hazards risk assessment, cascading hazards risk approach has recently gained importance, in particular, with the need for propagating uncertainties systematically from primary hazard to its triggered cascading hazards followed by uncertainties associated with damage fragilities of exposed assets. In an earlier study (Moratalla and Uma, 2023), a probabilistic cascading hazard risk framework was demonstrated to analyse a road network and estimate probabilities of damage to the network assets, and accessibility under a scenario earthquake and cascading hazards enabled by Monte Carlo simulations. The generated damage scenario realisations can be used for understanding consequences such as restoration time for services and accessibility issues. In this context, the framework was extended by including restoration modules for the road network that seamlessly connected with other modules and was applied to estimate regional restoration time for road network (Uma and Moratalla, 2024).

In this paper, we describe an approach to estimate restoration time for an interdependent infrastructure network. This method is adaptable to be integrated with previously presented probabilistic cascading hazard risk framework. To enable the reader, we first present the complete picture of cascade hazard risk approach with all modules required across the spectrum of hazard to damage to restoration time. Then, we focus to describe in detail, the proposed method for estimating restoration time for one possible scenario of damaged electricity network considering its interdependencies on the restoration of the road network, to enable discussions on the details of modelling. Work is underway to run a suite of damage realisations for both network assets and consider interdependencies in every simulation of restoration time with uncertainties and to use advanced artificial intelligence techniques for quantifying uncertainties (Harvey et al., 2017).

2 PROBABILISTIC CASCADING HAZARD RISK FRAMEWORK

The probabilistic cascading hazard risk framework is comprehensive and involves 3 stages: (i) *hazard modelling* deals with the primary hazard and the triggered cascading effects, including the associated uncertainties; (ii) *damage modelling* includes determining potential state of damage of a certain asset given hazard intensities, using fragility functions; (iii) *restoration modelling* involves estimating restoration time for the two networks with and without interdependencies (Figure 1). Given that there are various sources of uncertainties associated with all three stages, the methodology is capable of concatenating and propagating those uncertainties systematically. The framework adopts Monte Carlo simulations for introducing randomness in generating damage and restoration realizations and quantify uncertainties. As mentioned earlier, in Figure 1, all the blocks with blue outline are part of previous studies and explained in detail in references (Moratalla and Uma, 2023; Uma and Moratalla, 2024) and only an overview is presented in this paper. As we introduce the electricity network, a new task of demonstrating the effect of network interdependencies on restoration time (red outline box) is the focus of the present study.

2.1 Modelling of primary and cascading hazards

In our earlier studies (Moratalla and Uma, 2023), ground shaking generated by an earthquake source is referred to as a primary hazard. For modelling primary hazard, ground motion predictions equations recommended in OpenQuake (GEM, 2019) for the New Zealand Seismic Hazard Model (Gerstenberger et al., 2022) were used with appropriate values for various factors including shear-wave velocity (Vs30), to calculate shaking intensities at various sites away from the source. Monte Carlo simulations approach enables modelling uncertainties associated with 'between-events' and 'within the event' for each ground motion realization. As triggered by the primary hazard, the cascading hazards include liquefaction and lateral spreading resulting in permanent ground deformation in terms of vertical settlement and horizontal displacement respectively (Cubrinovski et al. 2012). In addition to this, debris run outs from earthquake-induced landslides with wet and dry conditions, and debris extensions from collapsed buildings on to network assets can also be considered as cascading hazards causing indirect damage to the exposed assets.

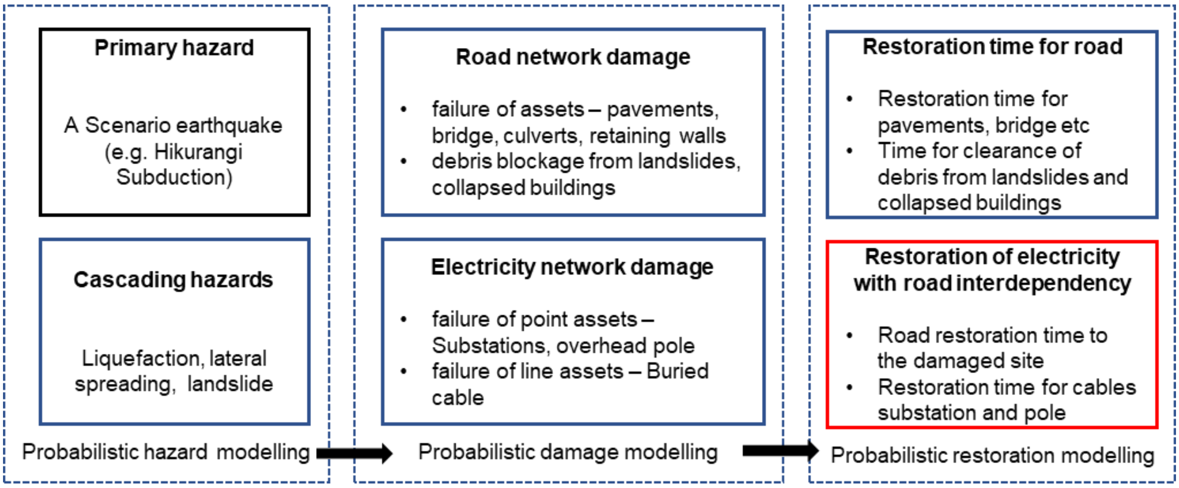

Figure 1 Schematic diagram representing the modelling stages of the cascading hazard risk framework.

2.2 Damage modelling

The framework supports modelling damage potential (probabilities) for individual assets of the networks through respective fragility functions. Discrete damage states such as slight, moderate, extensive and complete can be assigned enabling the assignment of appropriate restoration time/strategies. Where information on specific characteristics of the assets is lacking, generic fragility models available in HAZUS (FEMA, 2022) can be used. For assets that lack generic fragility functions (e.g. retaining walls), indicative performance measures from observed responses from reconnaissance reports of real events (Dismuke, 2012) have been used (Moratalla and Uma, 2023).

2.3 Restoration modelling

Estimation of time required to restore functional services is complex as it is influenced by many factors including resources availability as well as interdependencies on other networks and have large uncertainties. We have adopted available restoration models from HAZUS (FEMA, 2022) with continuous functions for some of the key assets of the network as it is convenient to integrate with damage/fragility models. Approaches for estimating restoration time for regional road network are presented by Uma and Moratalla (2024). For the electricity network, for individual assets, the restoration values (with a period range) were obtained in consultation with asset managers from an electricity distribution company.

2.4 Flow process to generate a single realisation

The modelling sequence of hazard characterisations, fragility analysis of significant components of the network, estimation of restoration time can be done within a Monte Carlo simulation framework to incorporate randomness in the process and the steps involved in each simulation are shown in Figure 2. For every simulation, damage scenarios for road and electricity network can be developed and used for estimating restoration time for the road network and with its interdependencies for the electricity network. In our proposed approach, we need an estimate of road access time to the sites of damaged electricity network. We define each suburb of the city as road zones and the road restoration time of each suburb is calculated as aggregated restoration time of the damaged road assets in that suburb. The road access time for sites of damaged electricity assets is calculated from a location where resources are to be despatched accounting for the restoration time of all the suburbs to cross. The access times for all the electricity components in each suburb is assumed to be the same.

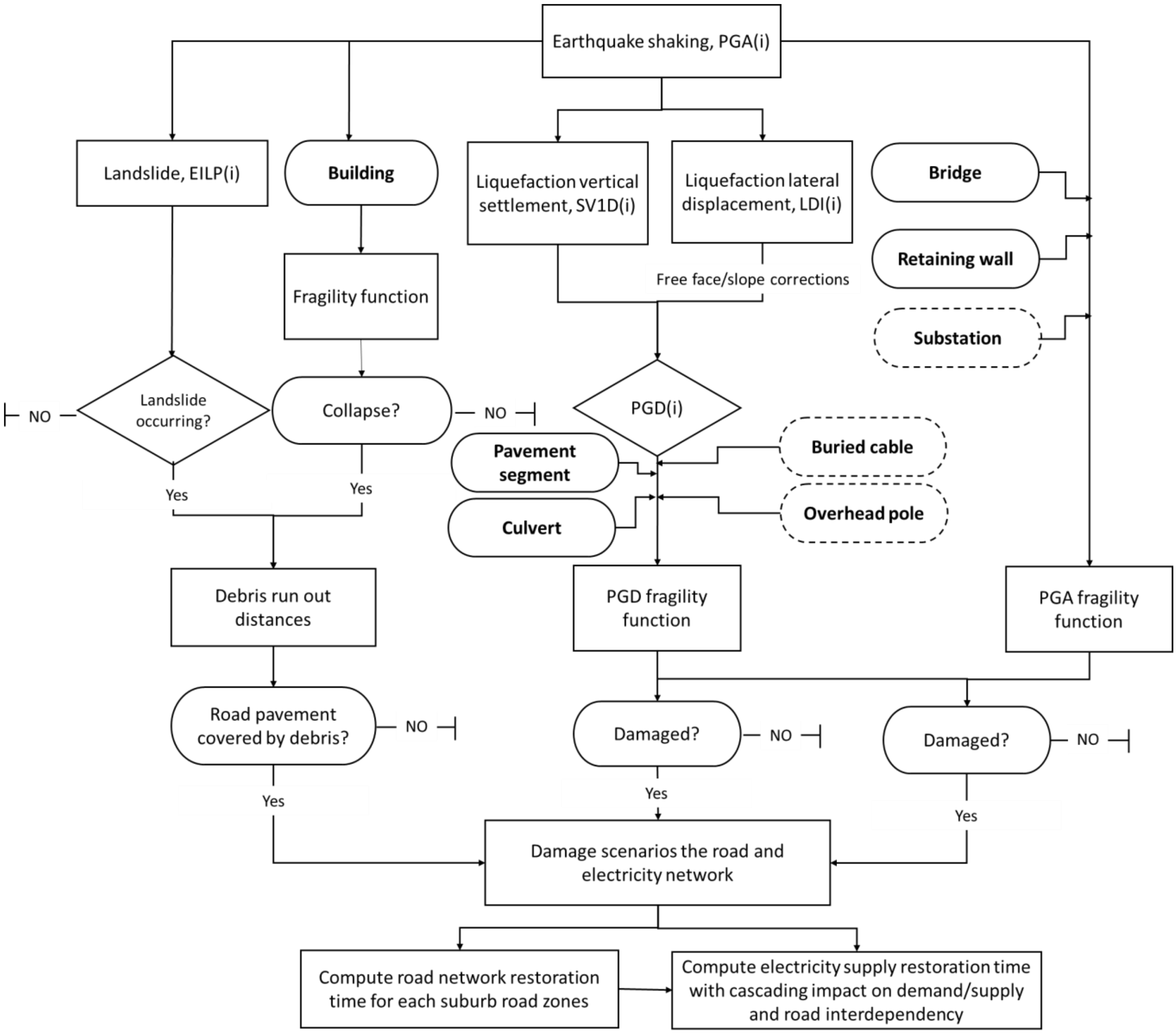

Figure 2. Steps in a single Monte Carlo simulation to generate damage and restoration realisation

It is worth mentioning that with thousands of simulations, a range of restoration time (outage time for services) can be generated and then processed for quantifying uncertainties in restoration time.

3 CASE STUDY WITH ELECTRICITY AND ROAD NETWORK IN NAPIER CITY

This case study considers Napier city electricity network and road network. We have considered every suburb (in Napier City of Hawkes Bay region) to represent a road zone and there are 22 suburbs. As noted earlier, for the purpose of demonstrating our proposed approach to estimate restoration time of electricity network with interdependency on the availability of road access, we begin with initial information of: (i) a typical damage scenario for electricity network which is randomly generated, as a representative of one single damage realisation from the probabilistic approach performance (Figure 3 a) showing different degree of damage to the components; and (ii) access time to various suburbs from the resource location (Figure 3 b). Note that recovery time for each road zone is estimated with reasonable judgements from our previous study

(Moratalla and Uma, 2023) based on the maximum number of blockages realised in each suburb and then the shortest access time from the resource location (Taradale) is calculated. Here, it is assumed that the road zone recovery is happening in parallel and hence the access time equals the longest recovery time of the connecting suburb from the origin to destination suburb.

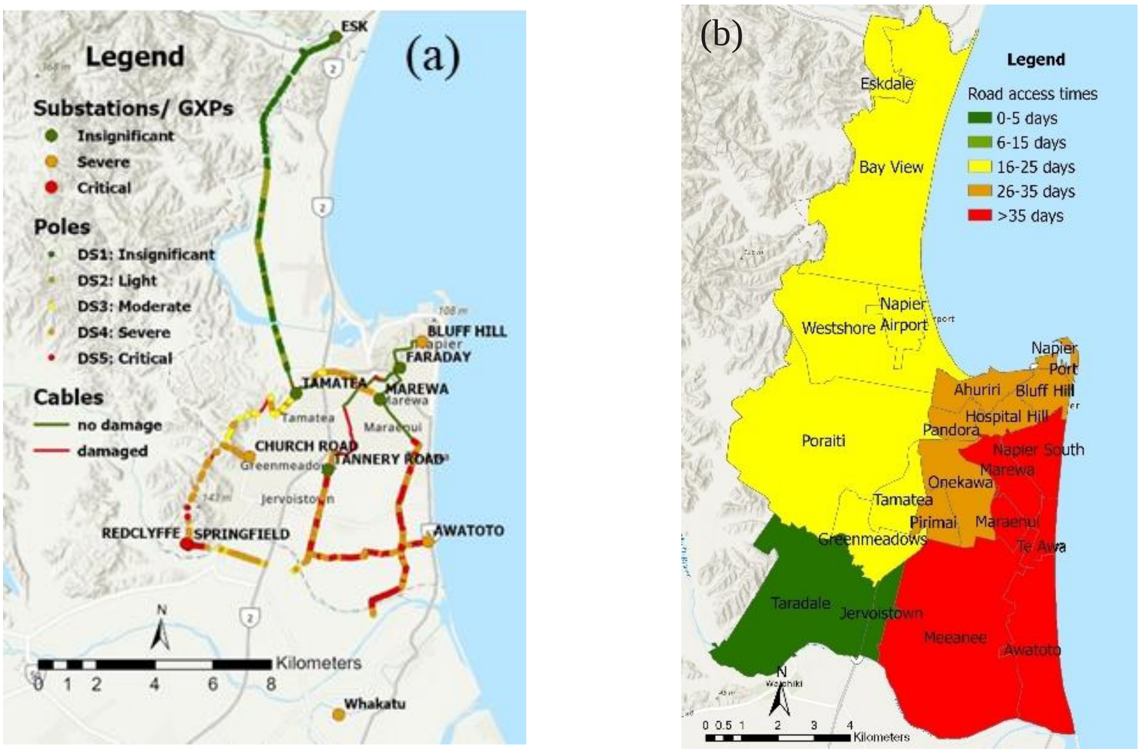

Figure 3 (a) Typical damage scenario of electricity network components; (b) Access time for road zones from the resource location (Taradale)

The electricity assets include substations (>66kV), buried cable, and overhead poles & power lines and the region is identified with 9 supply zones. Two grid-exit points (GXP) namely Redclyffe and Whakatu supplying power to the substations. Note that the damaged components in electricity network could trigger domino effect on the functionality of interconnected components and hence areas beyond the damaged sites could suffer outage of services.

3.1 Modelling intra and inter-dependencies for electricity network

The domino effect of power supply disruption is largely influenced by the connectivity between the components and their functional hierarchy. Therefore, it is necessary to appropriately characterize the intra-dependencies within a network and the interdependencies between components of multiple networks under consideration (Huang et al., 2014; Nan and Sansavini, 2017). We acquired electricity network data of Napier city (Courtesy: Unison company (only for demonstration purposes)), in which the point component within an electricity network e.g., substations, GXPs or poles are modelled as '*nodes*' and linear components, e.g. buried cables are modelled as '*links*' or '*edges*'. 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 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 1.

Table 1. An example of a dependency matrix between nodal components of an electricity network

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

Next, it is needed to model interdependencies by identifying linking components of multiple networks. In our case, we have overlaid the locations of the components of electricity network on road zones (suburbs), so that it is convenient to associate the access time from the resource location (Taradale) to every component sites. The access time from the resource location (Taradale) to all the suburbs is shown in Figure 3 (b). The 'node' type component is associated with one road zone, whereas a 'link' type component (buried cables), may cross multiple road zones. In our modelling process, the input parameters for nodal components include an identifier, component type, and the road zone in which it is located. Whereas, the link components include an identifier, source, destination, material type and the road zones through which they are passing to connect a source node to the destination node. Figure 4 shows a typical scenario of 'nodes' (say substations) in each road zone (A, B, C) and the 'links' crossing different road zones, and there can be multiple paths connecting a given source and destination nodes for redundancy (security). Further, it depicts the possibilities for experiencing varying damage states by the components and their location spread across the region within different road zones. To add to the complexity, there buried cables are of two different materials (XLPE – Cross linked polyethylene; PIAS – Paper insulated Aluminium Sheath) showing different vulnerabilities and needing different repair times. We model with diligence to capture such intricate details of the locations and damage states of the assets to reflect their effects on restoration time.

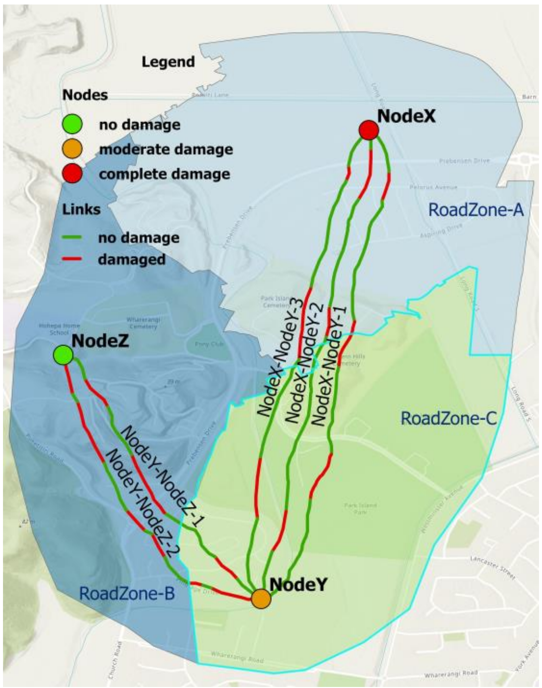

Figure 4. An example depiction of the connectivity (a) between two nodes through multiple links; (b) multiple routes that can be made using these links

3.2 Restoration strategies and time for electricity components

To model restoration of damaged components, we require information on preferred repair strategies and their respective time window. We engaged with asset engineers from an electricity distribution company to draw relationship between damage and the repair time window. For example, repair time for damaged overhead poles ranges between 1 to 7 days; however, substations with severe damage takes about 3 to 7 days and those with critical damage can range between 20 to 80 days. PIAS cables take 15 days for one fault to repair and if the cable has more than one fault, it is abandoned. For XLPE cables with less than 8 faults, it takes between 2 to 13 days and beyond that it is abandoned. The abandoned buried cable links are generally replaced by overhead lines. Using a random number, a repair time (value) was selected from the time window defined for various components and used for estimating restoration time for different supply zones for the considered damage scenario.

3.3 Estimation of restoration (outage) time for supply zones with and without interdependencies on road access recovery

Restoration efforts need to be effective and optimised by choosing the route/path with shortest recovery time from a source (GXP) to a destination node (substation) and consider potential restoration required by other 'link' components such as buried cables or overhead poles/lines connecting the two nodes due to the intra-dependencies within the network. To this purpose, we have applied Dijkstra's optimisation algorithm (Dijkstra, 1959). Dijkstra's algorithm is a useful algorithm to find the single shortest path in terms of recovery time from a source node to all other nodes in the network.

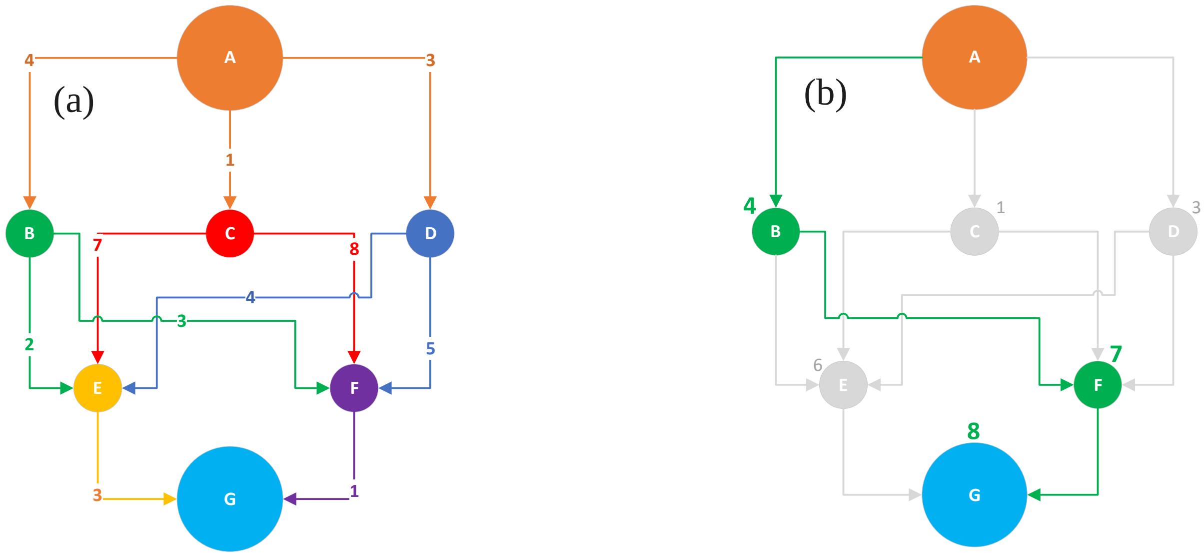

Figure 5 (a) Paths with restoration time between different nodal components; (b) Resulting shortest path using Dijkstra's optimisation algorithm

An example scenario for estimation of electricity network outage is shown in Figure 5. The path can be represented with restoration time between the nodes (accounting for all the intermediate components) with or without considering interdependencies on road network. When road interdependencies are considered, the restoration time of a damaged component equals the sum of its own functional restoration time and the road access time to the suburb where the component is located. For this scenario, the goal is to find the shortest route from node A (e.g., a GXP) to node G (e.g., a substation) and there are multiple paths passing through different nodes and links (buried cables) in between. Each path connecting a set of two nodes has been assigned the restoration time. In this example scenario, from the start node 'A' to reach the node 'B', we need 4 days, and similarly, node 'C' to 'E' takes 7 days. After applying the Dijkstra's algorithm, the shortest path from node A to node G is determined as A → B → F → G and the optimum time to reach node G from node A is 8 days. This algorithm underpins the estimation of optimal restoration times for all 9 supply zones of Napier City.

3.4 Outage time results and discussion

Given a damage scenario of the electricity network and the road zone access time to account for interdependencies, we applied the above-described steps to estimate outage time for the supply zones and are shown in Figure 6 without and with interdependencies. For illustration purpose, this exercise has considered one single realisation of damage and adopted one randomly picked repair time for the damaged components and hence arrived at one single value of outage (restoration) time for each supply zone. For map representation, we have grouped the supply zones having outage time within a specific range for clarity. It is clear that the road interdependencies extend the restoration time of supply zones for obvious reasons. The reasons for longer outage time for supply zones can be attributed to: (i) severity of damage (for example, Redclyffe substation in 'critical' damage state, even though it was near the resource location (Taradale) and not affected by any access delay; (ii) increased road access time influenced by road damage (e.g. Meeanee with liquefaction prone zone) for Tanner Road substation.

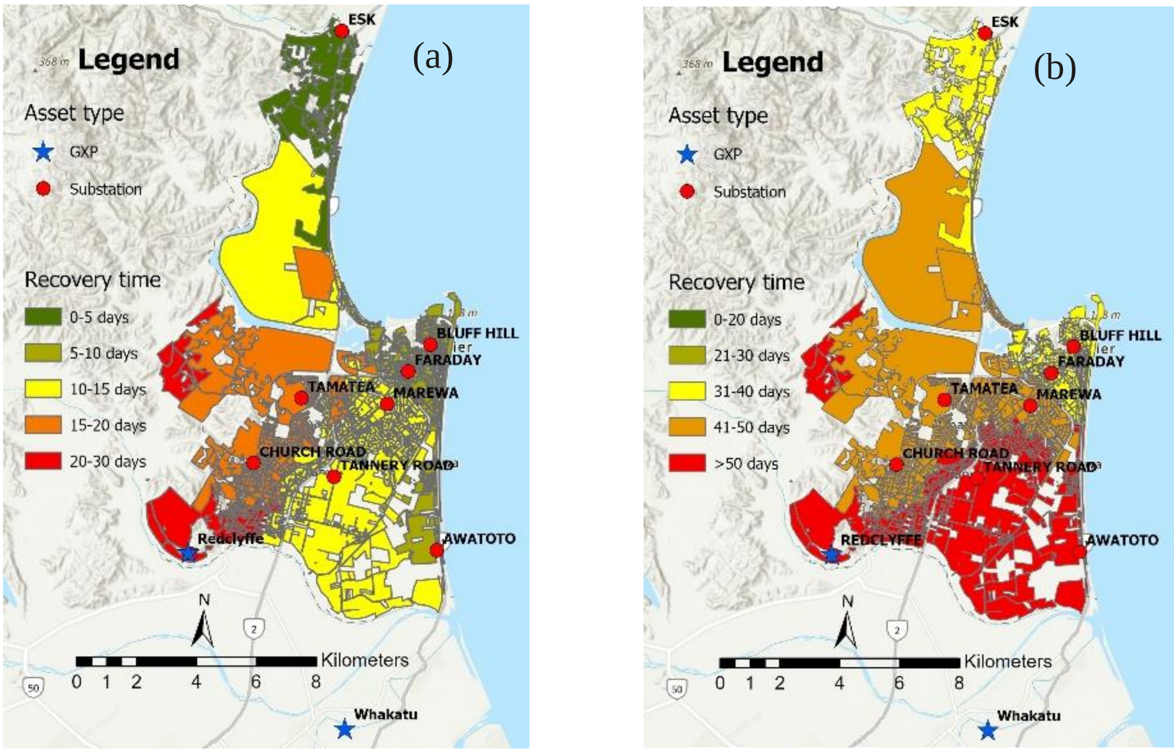

Figure 6: Supply zones outage maps (a) without road interdependencies; (b) with road interdependencies

4 CONCLUSIONS

In a complex and distributed infrastructure when subjected to cascading hazards of different types and with spatially varying intensities, it is important to give due attention to the details of disruptions caused in the network and its interdependencies. This research has presented a pragmatic approach, to estimate restoration time for infrastructure network services considering interdependencies, that can be integrated within a probabilistic cascading hazard risk framework. The approach has been demonstrated through a single damage realisation of Napier City electricity network along with potential road access time for its components from a resource location. Effort has been taken to describe the intricacies involved in modelling intra-dependencies within the network and interdependencies between the networks. An optimisation algorithm has been used to find the quickest recovery path for every supply zone providing effective restoration (outage) time. The key results in terms of outage maps highlights the influence of interdependency on road access times leading to an extended restoration time for the affected supply zones.

Work is underway to integrate the method in a simulation environment where earthquake triggered cascading hazards are modelled to create different damage scenarios for the networks and with derived road access times to generate thousands of outage maps. Advanced artificial intelligent techniques such as clustering methods are planned to be used to process the results for quantifying uncertainties.

5 ACKNOWLEDGEMENTS

We acknowledge the funding support granted by two projects, namely, End-to-End Flagship project and Performance of Built-environment under Strategic Science Investment Funding (SSIF) scheme. We are thankful to Dr Sanjay Bora, GNS Science and the anonymous reviewer for their helpful review comments. We appreciate support from Unison Contracting Services, Hastings in sharing the GIS data of electricity network in Napier City and Wellington Electricity, Lower Hutt for the consultation on restoration times for electricity assets.

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