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SYSTEMIC RESILIENCE METRICS FOR INTERDEPENDENT INFRASTRUCTURE NETWORKS

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Critical infrastructures such as energy, transport, water, waste and telecommunications exist as geospatial interdependent networks, supplying goods and services that support society and economy. The resilience of infrastructure networks is tested in external shocks, resulting in the potential for widespread cascading failures with catastrophic socio-economic consequences. For efficient resilience planning, there is a need to understand systemic vulnerabilities to prioritize resource allocation for network enhancement. We present a system-of-systems methodology to meet this need, by analysing the systemic resilience in terms of individual asset level and aggregated spatial vulnerability characteristics of interdependent critical infrastructure networks. We characterise the geospatial resilience of networks in terms of: (1) direct and indirect customers disruption potential; and (2) geographic spread of network failure cascades. Case-studies from UK (England and Wales only) and New Zealand demonstrate how these resilience metrics can rank systemic vulnerabilities, which are most critical to maintaining national functionality. Such a ranking provides the basis for prioritizing investment decisions for enhancing the resilience of large scale networks. National scale maps and visualisations are presented to communicate prioritised resilience building measures to stakeholders and decision makers, highlighting wider network vulnerabilities which might not otherwise be identified.

Keywords: infrastructure networks, risk analysis, vulnerability assessment, resilience.

1 Introductions

The resilience of critical infrastructures is crucial for the sustenance of modern day societies. Infrastructures such as energy, transport, water and wastewater, telecommunications in particular provide the lifeline services on which societies rely. During disaster events catastrophic failures of these lifeline infrastructures cause the disruptions of basic services, leading to widespread socio-economic losses and endangering national security (Cabinet Office 2010). Recent events, such as hurricanes in the United States and Caribbean Islands, floods in the United Kingdom and Europe, and earthquakes in Nepal, New Zealand and Mexico have highlighted the widespread nature of critical lifeline infrastructure risks. Among other reasons, during extreme hazard events, critical lifeline infrastructure resilience is eroded due to: (1)

weaknesses in existing systems that make them vulnerable to extreme hazards and climate change impacts; (2) general lack of understanding and accountability for a network-of-networks approach to national infrastructures, with limited knowledge of systemic vulnerabilities and risks across interdependent infrastructures (DfT 2014).

This paper addresses the need for a systemic resilience quantification of the critical lifeline infrastructures outlined above. Resilience here is defined as "the ability of a system or organisation to withstand and recover from adversity" (Cabinet Office 2010). The infrastructure systems we are interested in are modelled as geospatial networks spanning national scales. While different types of modelling approaches could be taken to represent infrastructures (see Ouyang (2014) for detailed review), network science-based models have proven to be popular for multi-scale infrastructure modelling (Thacker et al. 2017b). Infrastructure network resilience can be quantified in terms of (Guthrie and Konaris 2012, Dawson et al. 2016): (1) the *resistance* of individual assets to withstand external threats; (2) the *reliability* of individual assets to continue operations under different states of failures; (3) the *redundancy* of networks to provide alternative connectivity and backups; and (4) the capability of human and organizational systems to *respond* to fix physical assets and *recover* from disruptions. The first three of these dimensions of resilience can be linked to *infrastructure network vulnerability*, which we define as the magnitude of the negative disruption the whole network will sustain due to damage of individual assets from an external shock. Thus infrastructure network vulnerability becomes a function of the lack of resistance and reliability of individual assets, and the inability of the network to provide redundancies when shocked. In this paper, infrastructure resilience is understood through the quantification of systemic vulnerabilities across assets and space.

Recent extensive literature reviews on infrastructure resilience show the progress made in defining and quantifying resilience metrics (Ouyang 2014, Hosseini et al. 2016). These review studies identify a number of key areas where further research progress is needed, including, among others, the need for more studies: (1) with real-world data and applications; (2) representation of more than one or two critical infrastructure networks to capture dependent and interdependent behaviors; and (3) linking infrastructure resilience to the community of regulators, owners, operators and users who rely on them. This paper contributes towards addressing the above research gaps, by building on data and models presented in recent studies on infrastructure vulnerability assessment. These include, among others: (1) a system-of-systems framework outlining how multiple infrastructures exist and interact as multi-scale hierarchical networks that determine systemic vulnerability propagation (Thacker et al. 2017b); (2) mapping of spatially critical infrastructure hotspots using real data of networks and customers England and Wales' interconnected electricity, water, wastewater, and telecoms infrastructures (Pant et al. 2016; Thacker et al. 2017a); and (3) vulnerability analysis using real networks and customer data on interdependent electricity, water, wastewater, and telecoms infrastructures in New Zealand (Zorn et al. 2018).

The remainder of this paper is organized as follows: In Section 2 we describe the systemic resilience metrics proposed in this paper. Section 3 presents results demonstrating these metrics through case-study results for the England and Wales only and New Zealand contexts. Section 4 concludes the paper.

2 Systemic vulnerability metrics

Infrastructure network assembly incorporates multiple infrastructure types, with each infrastructure i represented by a connected graph with a node set $N^i = \{n_1^i, \ldots, n_A^i\}$ and edge set $E^{i,i} = \{e_{a,b}^{i,i} = (n_a^i, n_b^i)\}$. The edge $e_{a,b}^{i,i}$ represents a directed connection between adjacent nodes n_a^i and n_b^i in accordance with the direction of service flows. (Inter)dependencies between different infrastructure networks are represented through directed edge set, for example, $E^{i,j} = \{e_{a,b}^{i,j} = (n_a^i, n_b^j)\}$ from the i^{th} infrastructure towards the j^{th} infrastructure. Each node and edge created in the network assembly is geo-located on a 2D plane, with nodes represented by their (x, y)-point-coordinates in space and edges by a collection of line geometries showing their physical extents in space. The resulting geospatial network captures the physical and geographic interdependencies between infrastructures, where physical (inter)dependencies are incorporated through the physical connections (e.g. pipes, cables, etc.) used for service flows and geographic interdependencies are incorporated through the spatial proximity of different types of infrastructures (Thacker et al. 2017a). Together these represent functional dependencies, which trace the flow of resources across the networks (Pant et al. 2016, Thacker et al. 2017b).

Each network node, n_a^i, is assigned a customer demand value c_a^i, which is either obtained from usage statistics or derived from models. These models: (1) identify the network nodes linked directly to customers; (2) assign spatially distributed populations to these nodes based on subdividing the 2D map into node output areas using Voronoi tessellation, which creates an assignment of customers to their nearest geographic nodes; and (3) where nodes are not linked to customers, network functional dependencies are used to create flow pathways between demand nodes and service producing supply nodes – resulting in customers assignments to intermediate network assets. Further details of these techniques are provided in Thacker et al. (2017a, b) and Zorn et al. (2018). Through the (inter)dependency mapping between different infrastructures we are able to infer two types of customer demands on a node n_a^i: (1) direct customer demands – measuring the numbers of customers being directly serviced by the infrastructure to which this node belongs; and (2) indirect customer demands – measuring the numbers of customers from other infrastructures, that indirectly derive their resources from this node. For example, electricity nodes provide electricity directly to customers and also to other assets such as telecoms, water supply that provide service to their customers, thereby creating a direct and indirect customer link with electricity.

Within the network vulnerability assessment, we assume that the failure of individual assets results in total disruption to their services and all the services that connect on them. For dependent systems, alternative network options are taken into account to capture network redundancies. Network vulnerability is measured as: (1) numbers – indicating the magnitude of an asset failure; and (2) spatial extents – indicating the spatial reach of an asset failure. Here the vulnerability assessment is hazard invariant, making it a criticality assessment of 'what if' failure scenarios. Instead of presenting the vulnerability information at the infrastructure asset level, we show combined vulnerability measures in spatially defined hexagonal-grids, across the whole map. Each hexagon area contains multiple assets from multiple sectors. The 'number' and 'spatial' extent measures assigned to each hexagon reflect direct and indirect customer disruptions that would result following failure propagation through the aforementioned functional dependencies. The following section demonstrates this through the case studies for England and Wales and New Zealand. This provides a means to rank systemic vulnerabilities for prioritizing resilience building interventions at specific locations on the networks.

3 Case-study for England and Wales and New Zealand

Using data from previous studies (Thacker et al. 2017a,b, Zorn et al. 2018), we demonstrate the systemic resilience metrics discussed in Section 2 for England and Wales (referred to as UK for brevity) and New Zealand (NZ). For both countries, we have mapped transmission electricity networks and their dependent water, wastewater, and telecoms systems, represented as nodes connected to customers. Table 1 shows the numbers of network assets for the two countries. Details on this data are provided in the cited papers, and are not discussed here.

Table 1. Details of the infrastructure sectors, their assets, and customers served for NZ and UK.

Attribute	**New Zealand (NZ)**	**England and Wales**
Electricity (E)	137 transmission substations	150 transmission substations
Wastewater (WW)	1123 Pump stations & Treatment Plants	1562 Treatment Plants
Water Supply (WS)	1348 Sources, Treatment Plants, Pump stations, or Reservoirs	2566 Water Towers
Telecommunications (T)	4433 Transmitters	5218 Transmitters

We look at the direct and indirect customer disruptions due to electricity failures only. In both contexts electricity network flows are rerouted. The purpose of these case-studies is to: (1) rank customer disruptions of electricity and dependent assets to identify which assets are most critical within the system; (2) highlight locations of concentrations of the most vulnerable assets; and (3) compare results, for both countries, to show that such metrics can be generalized across different contexts.

Figure 1 shows ranked percentages of direct electricity plus indirect water supply, wastewater, and telecoms customers affected due to individual electricity transmission substations vulnerabilities in NZ and UK.

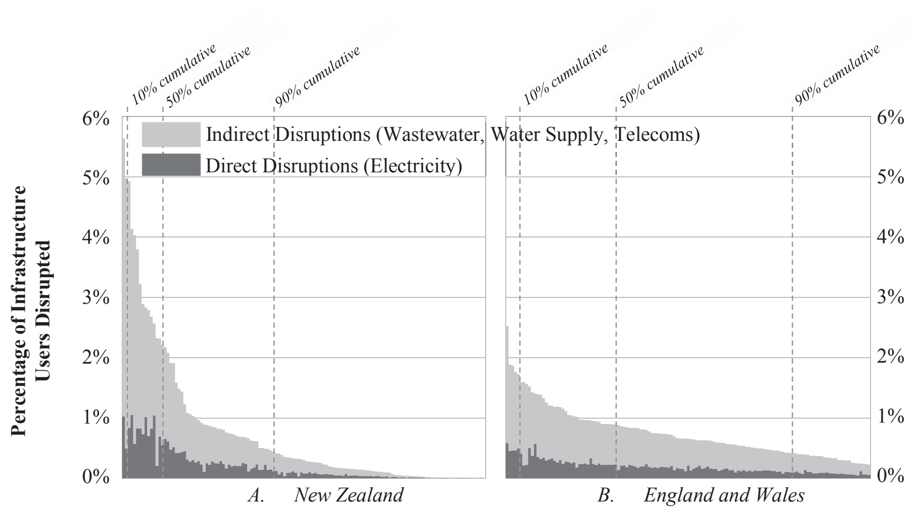
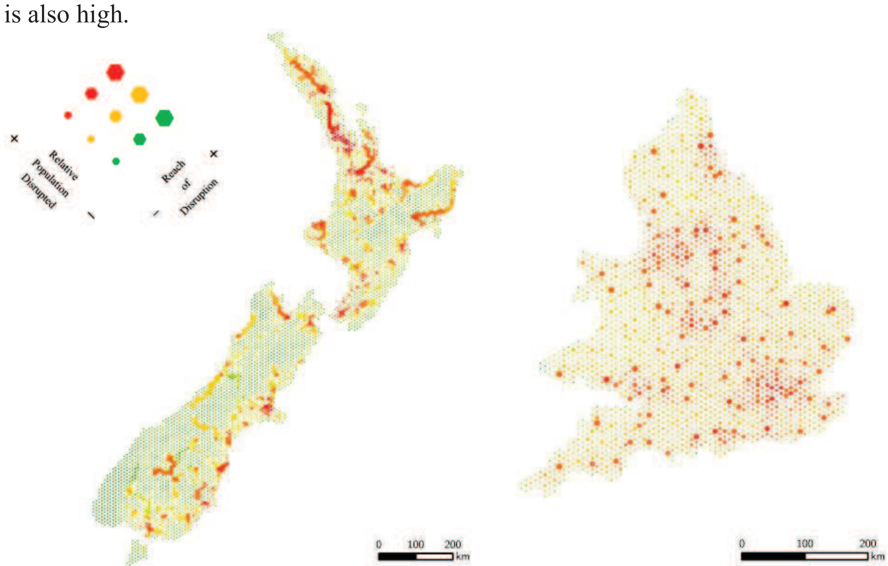


Figure 1. Ranking percentages of direct electricity and indirect wastewater, water supply, and telecoms customers disrupted due to electricity transmission asset disruptions. The results show the spread from A. New Zealand (NZ), and B. England and Wales.

We see a greater spread of customers across UK than NZ, because the populations and electricity substations in UK are more spatially distributed. Both NZ and UK have a large number of customers assigned to a small number of assets with 10% cumulative customer demand concentrated in top 2 (1%) assets for NZ and top 5 (5%) assets for UK. Subsequently, 50% cumulative customer demand are concentrated in the top 15 (11%) assets for NZ and top 40 (27%) assets for UK, and 90% cumulative customer demand are concentrated in top 56 (41%) assets for NZ and top 103 (67%) assets for UK. Due to the high concentration of demands at relatively few assets in NZ, we also see a greater magnitude of dependent failures, as indicated by the higher indirect to direct customer disruption ratios in NZ in comparison to UK. For the top 50% cumulative customer demand ranked assets in NZ, this ratio is 4 on average and 3 in average for UK. For lower ranked assets, we see higher cascading effects in the UK network. Overall, this shows that NZ has a less resilient electricity dependent infrastructure network compared to the UK when looking at potential systemic vulnerabilities of assets.

Figure 2 shows spatial concentrations of vulnerabilities in NZ and UK combined for all assets within hexagonal grids into which the whole maps are divided. For both countries the hexagonal grid areas are the same (~65km^2). Each hexagon shows: (1) numbers of the direct and indirect customers as depicted by the color scheme, and (2) range of spatial impact as depicted by the size of the color fill within the hexagon. The maps are valuable in identifying locations where the most numbers of customers are affected and the spatial coverage of impacts is also high.



A. New Zealand *B. England and Wales*

Figure 2. Concentrations of spatial infrastructure vulnerabilities for A. New Zealand (NZ), and B. England and Wales. The maps show hexagonal grids whose color indicates relative magnitude of customers (direct electricity plus indirect water supply, wastewater and telecoms) impacted and the size indicates the spatial reach of disruption.

In concentrations of dense infrastructures and populations, especially around cities (e.g. London in UK and Christchurch in NZ) the magnitudes of customer impacts are high, but the spatial coverage is low. The opposite happens in sparsely populated rural areas supported by more spatially distributed infrastructures. Comparing the two countries we see that: (1) NZ tends to show a lot of points at the extremes – as on one hand there as lots of red/darker orange (clearly mark urban areas that main infrastructure connections i.e. water pipelines and transmission grid supplying regions with a single connection (with no/little redundancy), and on the other hand there are lots of green areas (implying low populations relative to urban areas); (2) UK tends to show the bulk of the impacts in the middle band (orange) showing comparatively more evenly spread populations outside of the (high population red zones), and more redundancies built into UK transmission network through the more meshed network and larger numbers of external connections (to mainland Europe, Scotland, Ireland).

4 Conclusions

In this paper we have presented systemic resilience metrics for multiple infrastructure networks in terms of vulnerabilities of interdependent critical infrastructure networks. We specifically quantify the: (1) physical and geographic network failure propagations; (2) direct and indirect customers disruptions. Case-studies from UK and NZ, show electricity networks and their dependent water supply, wastewater and telecoms networks, demonstrating how the systemic vulnerability metrics are used: (1) to rank individual electricity assets based on their systemic direct and indirect failure impacts, (2) identify area locations where large number of assets and customer disruptions are concentrated. Such analysis provides the basis for prioritizing investment decisions for enhancing the resilience of large scale networks. The analysis shows that NZ has a less resilient system when compared to the UK.

Further analysis will also include: (1) incorporating hazards such as earthquakes in NZ and flooding in UK to characterize hazard risks; (2) incorporate recovery and adaptation characteristics of assets and networks to provide a more complete understanding of resilience.

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References

Cabinet Office, *Strategic framework and policy statement on improving the resilience of critical infrastructure to disruption from natural hazards*, Whitehall, London, UK, 2010.

Dawson, R.J., Thompson, D., Johns, D., Gosling, S., Chapman, L., et al., *UK Climate Change Risk Assessment Evidence Report: Chapter 4, Infrastructure*, Report prepared for the Adaptation Sub-Committee of the Committee on Climate Change, London, UK, 2016.

Department for Transport (DfT), *Transport Resilience Review: A review of the resilience of the transport network to extreme weather event*, London, UK, 2014.

Guthrie, P. and Konaris, T., Infrastructure and resilience, *London, UK: Foresight, Government Office for Science*, 2012.

HM Treasury, *National Infrastructure Plan 2013 – Infrastructure UK*, UK Treasury, London, 2013.

Hosseini, S., Barker, K. and Ramirez-Marquez, J.E., A review of definitions and measures of system resilience, *Reliability Engineering & System Safety*, *145*, 47-61, 2016.

Ouyang, M, Review on modeling and simulation of interdependent critical infrastructure systems, *Reliability Engineering & System Safety*, *121*, 43-60, 2014.

Pant, R., Thacker, S., Hall, J.W., Barr, S., Alderson, D., et al., Analysing the risks of failure of interdependent infrastructure networks. *The Future of National Infrastructure: A System-of-Systems Approach*, 241, 2016.

Thacker, S., Barr, S., Pant, R., Hall, J.W. and Alderson, D., Geographic Hotspots of Critical National Infrastructure, *Risk Analysis*, *37*(12), 2490-2505, 2017a.

Thacker, S., Pant, R., and Hall, J.W., System-of-Systems Formulation and Disruption Analysis for Multi-Scale Critical National Infrastructures, *Reliability Engineering & System Safety*, *167*, 30-41, 2017b.

Zorn, C., Thacker, S., Pant, R., and Shamseldin, A., Evaluating the magnitude and spatial extent of disruptions across interdependent national infrastructure systems. *In Review*, 2018.