Quantitative system dynamics modelling of organisational health/resilience of infrastructure service providers
Research Scoping Report

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Abstract

Despite universal recognition of the importance of the infrastructure services, there has been very little focus on the enabling organisations and how they are affected by major disruptions. The work of Resilient Organisations, in particular, has introduced organisational resilience as a central theme in organisational performance post-disaster. Their work emphasises the roles of leadership, networks/connections, economic and insurance impacts, and regulatory frameworks, on post-disaster operability of any organisation. Most recent research identifies the importance of interacting behaviours of physical (working conditions), human (worker attitudes), and organisational (strategies, plans) elements when understanding organisational resilience.

System dynamics approaches have been used to provide insight into safety systems, which have many similarities to the interactions relating to organisational resilience. The time is ripe for the application of a systems dynamics approach to better understand organisational resilience. Application to the particular issues related to infrastructure service providers would seem a valuable starting point.

Advance in this direction will require the use of qualitative relationships as well as attempts at verification of model reasonableness through analysis of questionnaires. A first step would be the development of causal loop diagrams to identify system archetype diagrams to describe commonly occurring behavioural themes.

Causal loop diagrams can be used to develop quantitative dynamic systems models where the parameters can be varied systematically to identify plausible versus implausible behaviour, helping to constrain uncertainty. This process of refining models to match expected archetypes provides the opportunity to identify critical components or factors that influence the wider system-level behaviour (e.g. resilience).

This direction for research has potentially significant value because it would enable the assessment of an organisation under varied conditions, and the identification of leverage points for intervention to improve performance and avoid failure. The outcomes of such research could valuably interface with the MERIT platform to allow for evaluation of the vulnerability of economic recovery to fragile internal processes of infrastructure service providers. Identification of key components, roles and processes that would cause organisational failure when placed under stress is fundamental to improving performance and resilience.

1. Introduction

This short report examines the literature related to both organisational resilience and systems dynamics modelling while exploring the potential for future research to apply new knowledge to improve the resilience of infrastructure service providers.

The functioning of infrastructure systems is critical to society. Electricity, water (potable, waste and storm), communications and transportation networks provide vital services to communities and business. Widely classified as 'lifeline' systems, their performance is judged to be "intimately linked with the economic wellbeing, security, and social fabric of the communities they serve" (O'Rourke 2007). This importance is amplified when society experiences a major disruption through natural disaster. Infrastructure service continuity has been found to be linked directly to business operation and profitability (Tierney et al. 1997), and has been identified as the key driver for longer term recovery of all business sectors (Kachali 2012).

Infrastructure services have been described as a 'system of systems' containing inherent interdependencies (Tierney 2007) - a characteristic that induces vulnerability that can lead to cascading failure when disrupted by disaster (Leavitt and Kiefer 2006). An example of the fragility of interdependency is illustrated by the country-wide blackout of power and communications systems which happened in Italy in 2003 – the cause of which was the failure of a single power station (Havlin 2010). Figure 1 (taken from Peerenboom et al. 2001) shows the complexity of these interdependencies.

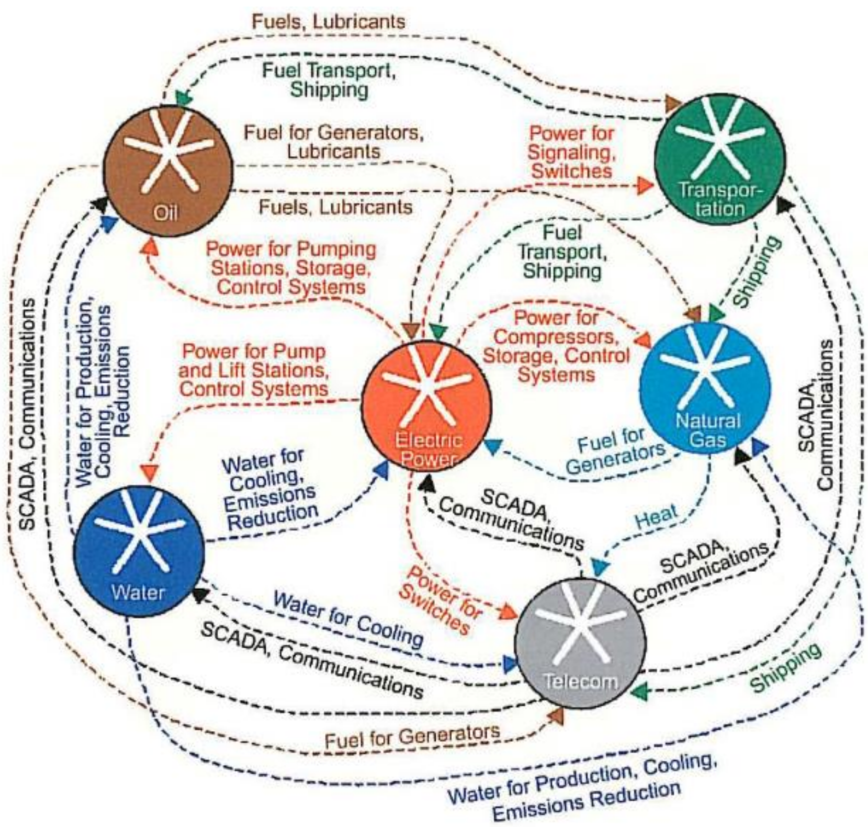

Figure 1: Interdependencies of infrastructure (Peerenboom et al., 2001).

This risk has been well recognised in New Zealand. Aiming to mitigate vulnerability and risk to infrastructure systems, the New Zealand Lifelines Council (NZLC) focuses on "enhancing the connectivity of lifeline utility organisations across agency and sector boundaries in order to improve infrastructure resilience" (NZLC 2018). Resilience is recognised as a key attribute for infrastructure to possess - "the capacity to be flexible and adaptable to changing conditions, both foreseeable and unexpected, and to be able to recover rapidly from disruption" (NZT 2014).

Behind the infrastructure and its service are people and the organisations - their successful operation being fundamental to the service they provide. Just as the infrastructure can fail, so can its enabling organisation. Despite universal recognition of the importance of the infrastructure services, there has been less focus on the enabling organisations and how they are affected by major disruptions. Greater understanding of the interactions of the factors and processes that affect these organisations could not only help the infrastructure organisations themselves, but also the businesses and communities that depend so greatly on the services they provide.

Before the 2010/2011 Canterbury series of earthquakes, there were relatively few studies that examined the effects of disasters on organisations. The older, overseas research has largely centred on small and medium private businesses, and the factors that affect an organisation's performance in response to the event and its longer term adaptation in order to continue operating. More recent research - and particularly the work of Resilient Organisations (Resorgs) - has introduced resilience as a central theme as well as topics such as leadership, networks and connections, economic and insurance impacts, and the effects of regulatory frameworks.

Organisations and their operation can be viewed as complex systems comprising of the interacting behaviours of physical, human and organisational elements. These elements - and their effects on each other - determine the performance of the system as a whole. Despite the increasing quantity of research available covering disasters and aspects of organisations' performance, there is currently no work that combines these elements and assesses the dynamic behaviour of the organisation as it recovers post-disaster.

There is potential to apply system dynamics modelling to investigate the dynamic behaviour of infrastructure service providers in their recovery from major disruptive events such as earthquakes. Using a combination of qualitative sources and methods for data collection and analysis, such research could produce causal loop diagrams (CLD) to describe the performance and resilience of the organisations and develop archetypes of common behaviour patterns. Mapping and quantification of system variables using simulation software could enable dynamic simulation of scenarios.

This potential research could enable the assessment of the system under varying conditions and the identification of leverage points, key drivers of change and success/failure paths. Identification of key components, roles and processes that would cause system failure when placed under stress is fundamental to improving organisational resilience and performance.

We now have enough understanding of resilience components to undertake novel research that combines the differing factors and aspects of resilience - the people, process and physical factors that affect organisations.

In attempting to understand how infrastructure organisations recover from major disruptions through disaster, it is necessary to include multiple theoretical fields. The dynamic nature of the event, the organisation, and their interactions introduce significant complexity and interconnected factors.

2. Disasters, Recovery, and Resilience

Disasters can take many forms and have been described as 'low-probability and high-consequence' disruptions (Park et al. 2011). Natural disasters such as earthquakes and floods are rapid in their onset and can cause extensive damage to communities, infrastructure and businesses. Life and economic losses attributed to disasters are projected to increase due to population growth, greater urbanisation and climate change (UNISDR 2019)(1). A disaster can be defined as 'a serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts.' (UNISDR 2019)(2).

Prominent research by Haas et al. (1977) split post-disaster functions into four distinct time-bound phases - emergency, restoration, plus two phases of reconstruction. More recently, focus has shifted to the concept of disaster management and the adoption of a cyclical approach that includes pre and post-disaster functions - prevention/mitigation, preparedness, response, and recovery (Rubin 1991).

The recovery phase can be defined as 'the restoring or improving of livelihoods and health, as well as economic, physical, social, cultural and environmental assets, systems and activities, of a disaster-affected community or society' (UNISDR 2019). Referred to as "the neglected component of emergency management" (Rubin 2009), recovery was described by Haas et al (1977) as "ordered, knowable, and predictable". This view has since been contradicted, with recovery being seen as complex and dynamic (Blackman et al 2017) and uneven in its actualisation (Chang 2010).

There are differing perspectives on the aims of the recovery phase. Early work highlighted the need to restore communities and services to pre-disaster states. There is a growing consensus that this approach is not optimal as it can re-introduce factors that contributed to the disaster's effects. The theory of "bouncing back" has been largely replaced by "build back better" (UNISDR 2019), which embraces improvement as a necessary focus and goal of recovery.

Resilience is a concept gaining widespread attention within research and many practical application fields, and the building of resilience is seen as a positive and proactive mechanism for better coping with disruptive or damaging events. Resilience theory, measures and practices are now widespread in all areas affected by natural disasters - recent studies have investigated the performance and resilience of the physical infrastructure systems (Giovinazzi et al, 2017, Liu et al, 2017), individual employees (Kuntz et al, 2016), and sector recovery (Kachali et al, 2015). Prominent in this field is Resilient Organisations (www.Resorgs.org.nz) who developed the Benchmarking Resilience Tool (Lee et al, 2013), which has been applied to infrastructure organisations (Brown et al, 2014 and 2017).

Resilience has been described as an inherent capacity (Abdullah et al, 2013), an outcome (Stevenson et al, 2015) and a characteristic (Hollnagel, 2006) of system behaviour. Definitions of resilience are accepted as being contextual - a review of literature by Stevenson et al (2015) accumulated over 120 definitions. The study proposed a 'meta-definition' - "the ability to absorb the effects of a disruptive event, minimise adverse impacts, respond effectively post-event, maintain or recover functionality, and adapt in a way that allows learning and thriving, while mitigating the adverse impacts of future events".

Being a complex property that is not directly observable, research has aimed to classify characteristics and define performance measures of resilience in context. When describing a framework to assess community resilience in response to seismic events, Bruneau et al (2003) introduced four dimensions - technical, organisational, social, economic (TOSE) - and also proposed a quantitative measure. Describing and measuring organisational resilience, Lee et al. (2013) introduced 13 leading indicators under three groups - leadership and culture, change readiness, and networks. Figure 2 shows these indicators (Seville 2017).

Research also highlights the variable nature of resilience. Bruneau (2003) and O'Rourke (2007) indicated clear 'pre' and 'post' disaster states with recovery being based on time to return to pre-disaster levels. This variability leads to the theory of resilience being a dynamic property - which can be increased by positive measures and actions, or eroded by the negative effects of events. This view is reinforced by the work of Lee et al (2013) who describe resilience as having both planned and adaptive elements - with 'planned' addressing the building of capacity, and 'adaptive' responding to and recovering from negative impacts.

The complexity and dynamism of resilience and subsequent difficulties in its quantification have led researchers to acknowledge that there are gaps to be filled, and a more holistic view must be adopted in order to maximise research value. In a review of resilience literature, Bhamra et al (2011) identified that there is a shortfall of research into the interactions between individuals, organisations and infrastructure systems. Additionally, the development of context specific tools and the adoption of a systems perspective were seen to be key requirements for the future of resilience research and its operationalisation in New Zealand (Stevenson et al, 2015).

Figure 2: Indicators of Organisational Resilience (Seville 2017)

3. Organisations and Disasters

3.1 Organisational health, performance and failure

Organisational failure has been defined as "any situation requiring an intervention above-and-beyond normal performance management" (NAO 2015). Three contexts of performance are considered (adapted from PwC 2012):

- Financial: the performance of an organisation in terms of its key financial activities.
- Operational: the efficiency and effectiveness of the delivery of services to end users and the supporting infrastructure of people, processes and systems.
- Strategic: the organisation's overall approach to succeeding in the markets it is serving

This definition would need to be clarified when applied to infrastructure service providers (ISP) in a post-disaster setting---

- Some ISP are public, some private.
- Long-term stress on individuals and hence organisations during recovery phase
- Not much done on failure of ISP.
- Some insight into what an ISP failure might look like during a recovery can be gained by considering the literature on organisational performance.

Where previously research focused on reactive measurement of system performance after an event, there is now significant emphasis placed on pre-emptive risk management and identification of lead indicators of potential failure. Appendix 1 provides an overview of past research into organisational response to disasters, and can serve as an information source for future research.

Organisational failure can be seen as occurring from internal processes only. For example, issues such as understaffing, poor leadership attitude ('deny, deflect, defend') and unfamiliar response policies were significant contributing factors to failure in the response to Hurricane Katrina (Gall, 2011). Reason (1995) concluded that organisational error was due to the interactions of human and organisational factors.

Interactions between the organisation and its social environment are also important for analysing success/failure. D'Aveni (1989) combined human (managerial) and economic elements into his study of organisational decline, and identified threat-rigidity response to circumstances as a key factor.

Relationships and connections between businesses are an asset in resilience (as identified by ResOrgs), but interdependencies and reliance on other organisations can be factors in both success and failure, for example, "No organisation today has direct control over every aspect of its operations or reputation" (ILM 2014).

One potential conceptual framework for better communicating issues associated with organisational success/failure is an analogy to the health of a person. Xenedis and Theocharous (2014) adopted a definition of organisational health from life sciences - "health is the state of complete physical, mental and social wellbeing and not only the absence of disease or disability". As with health, failure can occur from individual parts, from internal interactions, or from some combination of internal and external factors. In all cases, the existing literature points to a recognition of the system-level interactions. Surprisingly, there has been little research of using systems modelling of organisational resilience/failure.

3.2 Factors Relevant to Organisational Response to Disasters

From the literature reviewed for this report, a number of prominent factor classifications have been identified that contribute to the performance of the organisation post-disaster, as listed below.

- Type of disaster
- Scale of disaster
- Property / Infrastructure condition and capacity
- Organisation characteristics
- Leadership and experience
- Adaptation and decision making
- Financial measures, stability and capacity
- Staff competency, wellbeing and support
- Organisation culture and learning
- Customer retention and support
- Resources available
- Networks and relationships (internal and external)

These factors are complex and inter-related, with the scale or performance of one factor area determining the effect on another. The inter-related nature of these factors supports the need for a systems approach to understanding their relationships.

3.3 Infrastructure Organisations

There is significant focus within New Zealand on the continued service provision of lifelines utilities after disasters in order to support the recovery of communities and businesses. The Civil Defence and Emergency Management (CDEM) Act 2002 has established clear imperatives for service continuity, and regional lifelines groups have been formed with the aim of improving inter-organisational collaboration and system resilience.

The particular characteristics of infrastructure organisations and their interdependence raises questions around their particular behaviour patterns. At this stage the following questions are apparent:

a. How does the organisations' criticality to society affect its behaviour during post-disaster recovery, particularly regarding leadership and decision-making?
b. How does the organisational structure affect its performance?
c. Which factors affecting organisational performance are specific to particular provider types?

4. Organisations and disasters - a systems approach

There is an opportunity to understand better the behaviour of organisations after disasters by considering organisations as dynamic systems. Based on the concept of causal linkages between factors forming interconnected loops - the structure of a complex system is derived from its interacting feedback loops (Sterman 2000), which in turn drives system behaviour (Meadows 1997). These concepts fall under the general approach of systems thinking - "the art and science of making reliable inferences about behaviour by developing an increasingly deep understanding of underlying structure" (Richmond, 1994). A holistic viewpoint should be adopted - the modelled organisation should be subject to technical, organisational, human and economic factors.

The use of systems theory to describe organisations and their behaviour has been identified as a dominant theoretical perspective (Millet 1998). Systems theory and methodology has been applied to organisational research in areas such as learning and culture (Cooke et al, 2006, Jiang et al, 2012), risk and safety management (Leveson et al. 2005), and organisational collapse (Rudolph and Repenning, 2002).

It is an established viewpoint that organisations can be classified as complex adaptive systems (CAS), with systems theory becoming prominent in the areas of managerial behaviour and organisational analysis (Millet, 1998). Definitions of organisations and systems have conceptually similar foundations - a grouping of entities (people, processes and physical elements) and a shared purpose. Acknowledged as having external relationships and dependencies, organisations are defined as open systems (Katz, 1978).

Feedback loops - whether balancing or reinforcing - have been shown to be evident in many areas related to organisational effectiveness. Lindsley et al (1995) reviewed reinforcing feedback loops as applied to efficacy and performance, and Masuch (1985) described the actions of individuals being transformed into performance based system behaviour loops - deviation counteracting loops and vicious circles. Just as the system is dynamic, so to are the properties contained within the system - behavioural factors such as experience (Burg et al 2013) and motivation (Bouloiz et al 2013) have been incorporated into system models.

Complex organisations may have many abstract relationships, but they are still constitute of individuals, and systems analysis of organisations have considered that success or failure is dependent on the actions of the people involved (Cook 1998). The importance of the actions and decisions of actors within the system has been highlighted as key to process success in fields such as safety science (Bouloiz et al, 2013) and enterprise risk management (Arena et al, 2010). Bouloiz concludes that "operators, through their behaviour, affect the quality and success of all operations and actions relating to risk control in the system". Van Burg and Van Oorschot (2012) use system dynamics modelling to integrate current situation conditions with the perceptions of key organisation personnel to show how the dynamic nature of relationships and perceptions affect business performance over time.

Perhaps the literature most relevant to the topic of ISPs during disaster recovery would be the literature on safety and failure analysis. Work by Leveson (2005) and Cooke (2003) contributed to SD being viewed as an effective methodology for investigating differing factor types and their interactions as contributing to system failure. In the case of Leveson, the manifestation of failure was the Space Shuttle Challenger loss (see Figure 3); and Cooke's work focused on the Westray mine disaster. As such, SD has become an established methodology in safety science, fostering the view that significant events such as accidents are judged to be a failure of the system caused by the interaction of several smaller failure points (Cooke 1998). Bouloiz et al (2013) developed a quantitative system dynamics model that integrated technical, organisational and human aspects. The model was based on interacting components - operators, procedures and safety devices.

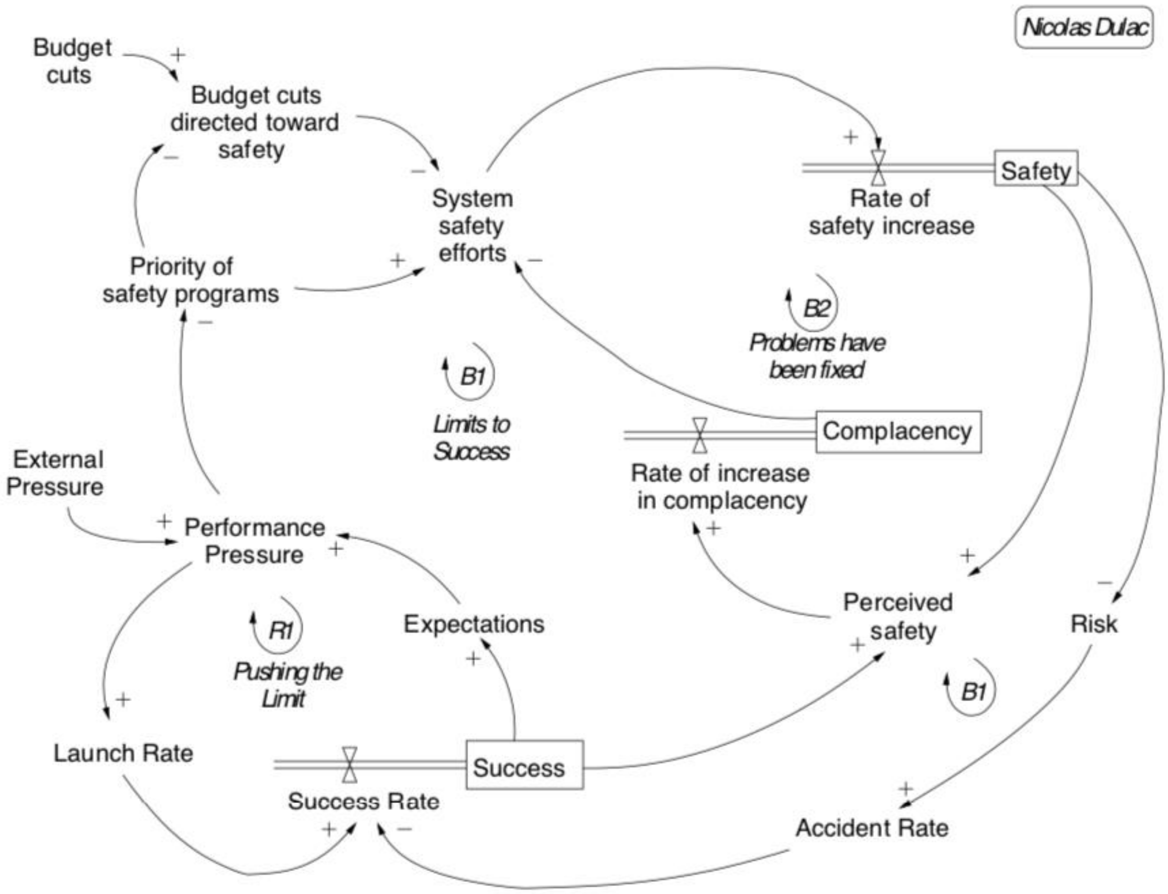

Figure 3: Simplified Model of the Dynamics Behind the Shuttle Columbia Loss (Leveson et al. 2005)

Very little research has been conducted on the study of infrastructure service providers as systems. The closest would be the work of Armenia et al (2014) who used system dynamics modelling to investigate the interdependencies of critical infrastructure services. This research was part of CRISADMIN (Critical Infrastructure Simulation of ADvanced Models on Interconnected Networks resilience) - a European Union project to design a Decision Support System to support reaction to catastrophic events and their effects on critical infrastructure systems. Figure 4 shows a part of the system dynamics model derived to show Telecommunications network behaviour - this subset illustrates a positive feedback loop that could lead to system overload. While including the organisational stresses associated with responding to disruptive events, the research did not model the internal dynamics of organisations in response to those stresses.

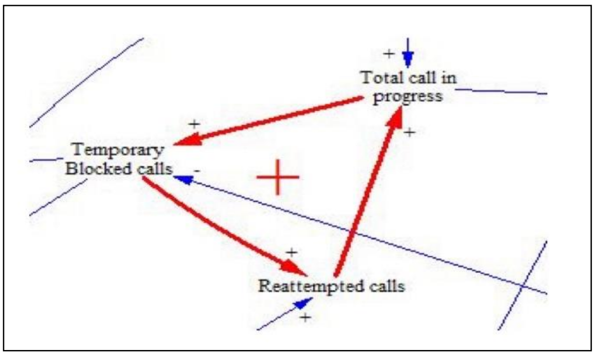

Figure 4: Feedback Loop in Telecommunications Network performance (Armenia et al. 2014)

General systems theory has also developed in ways that can aid in a study of organisations as systems. For example, research into networked systems (Havlin et al. 2010) indicated that interdependence through common components introduces additional fragility to system performance under stress. Networked systems showed increased chance of cascading failure and also a lower failure threshold in comparison to isolated systems. The interdependencies between ISPs can thus be analysed for additional fragility, and the potential for cascading failure needs to be evaluated in any risk management process for each individual organisation. The established method for this type of analysis is a systems dynamics model.

5. Systems Modelling of Infrastructure Service Organisations within the New Zealand Decision-Making Context

Systems modelling presents an opportunity to improve the resilience of infrastructure service organisations. It would also provide a modelling approach that could enrich other risk modelling approaches in development and use in New Zealand, namely, Merit and RiskScape.

RiskScape can be used to estimate the risks to specified pieces of infrastructure to specified disasters. This makes it useful for evaluation of the economics of resilience investments (e.g., new sewer connections in liquefaction prone areas) by infrastructure service organisations. It also can be used to evaluate the amount of damage from specific disaster scenarios, which can help infrastructure service organisations to plan their response strategies, including their likely labour demands over a time scale from weeks to years after an event. RiskScape could be valuable to generate scenarios that could then be used as inputs into systems models of the internal dynamics of an infrastructure service organisation. The output of a systems model of an infrastructure service organisation would not interface with RiskScape because the platform is not able to estimate or predict the rate of repair of infrastructure at present.

MERIT, and the broader suite of related models, is a modelling method developed to examine the recovery path, in particular its economic impacts. Because the modelling is focused on the post-disaster dynamics, there is great potential to interface future systems dynamics models of infrastructure service organisations with the MERIT platform. Since its initial development as a model of economic recovery, the model has been increasingly refined to include social variables related to recovery, including behavioural adaptation following an event (Brown et al., 2015). A good example of this broader application of MERIT is McDonald et al. (2018). In that paper, they examine the economic impact of an Alpine Fault earthquake on the west coast of the South Island. The economic impact is estimated while considering infrastructure outages and their impact on local businesses, e.g., dairy factories. The current version of the model uses simplistic models of how infrastructure service organisations respond to the increased demand for repairs (e.g., increased in labour, increase in costs) without considering the risks of rapid growth or work overload for these organisations. The proposed research for systems modelling of the internal dynamics of these organisations could be readily interfaced with the systems models of MERIT to enhance the current capacity of the MERIT platform.

Decision-making related to infrastructure service providers are made by the providers themselves, but they are influenced by direction and financial support from central government. Civil Defence and Emergency Management has increasingly seen its role as continuing beyond immediate response to providing a basis for long-term recovery. The April 2019 National Disaster Resilience Strategy describes multiple ways that central government will look to support improved resilience through the Ministry of Civil Defence. The document provides tangential references only to a need to improve the resilience of infrastructure service organisations; these references are in specific objectives:
"11. Build the capability and capacity of the emergency management workforce for response and recovery.
13. Enable and empower … organisations … to build their resilience….
16. Address the capacity and adequacy of critical infrastructure systems …."

Unfortunately, the discussion of "what success looks like by 2030" for each of these objectives does not acknowledge the importance of understanding and reducing the challenges faced internally within infrastructure service organisations. This lack of direction in the national strategy will impede uptake of any new research insights into the fragility of organisations. On the other hand, the lack of emphasis shows the need for research into this topic to improve the ability to make the case to central government to place greater future emphasis on this hidden vulnerability to recovery.

6. Research Scoping

This report is intended to provide a recommended direction for future research following from its supporting analysis.

6.1 Research Goals

Future research on this topic should be structured around the following research objectives:

a. To investigate the behaviour and performance of infrastructure organisations during the recovery from major disruptive disaster events using a dynamic systems perspective.
b. To develop dynamic models in order to identify positive and negative patterns of organisational behaviour.
c. To define possible interventions and practices that could improve the resilience of the organisations.

That research would be guided by the following questions:

- What are the key factors and processes that influence the performance of infrastructure service provision organisations during society's recovery from major disruptive events?

- How does the dynamic interaction of these factors and processes influence organisational behaviour?
- What changes in behaviour could positively influence the resilience of the organisation when under stress from major disruptive events?

6.2 Research Methodology Overview

System dynamics (SD) has been chosen as the methodology foundation for the project. Introduced by Forrester (1961) as a means to describe industrial processes, SD has since seen increasingly diverse application and is extensively described as a methodology in its own right. A strength of SD is its ability to successfully integrate factors related to people, process and physical elements in the same model - factors inherent in the structure and operation of organisations. Figure 5 shows a research methodology framework applicable to research on this topic.

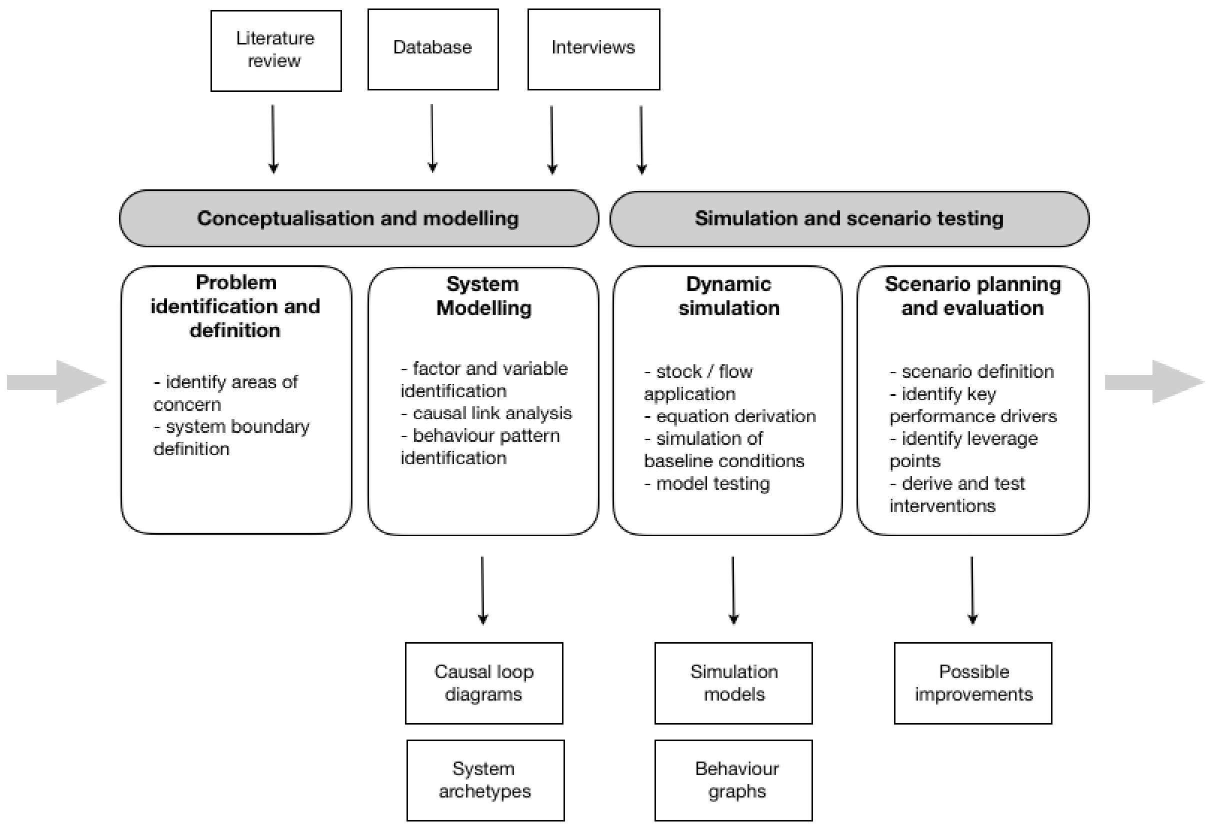

Figure 5: Methodology framework diagram (adapted from Sterman 2000, Maani and Cavana 2007)

6.3 Conceptualisation and modelling

Model conceptualisation has been described as a general theory building process (Goh et al 2015) derived of data from mental and written databases (Sterman, 2000). This has led to the adoption of established qualitative methods for data collection and analysis. Literature reviews (Dulac, 2005) and interviews (Bouloiz, 2013, Armenia, 2014) are now common data collection methods used in the model conceptualisation stages.

Literature relevant to the project includes published journal articles, government and organisational reports, and books. The database held by Resorg contains significant empirical data of organisational behaviour and response to earthquakes, much of which has been published in its original context. The database held by Resorgs is the raw questionnaire data results from several studies and is able to be interrogated in many ways - thus it can be utilised in the context of this particular project to possibly provide evidence of additional previously unidentified factors and causal links.

This work should be supplemented by the results from interviews with industry practitioners. A questionnaire could be distributed in order to gain initial feedback and guide a more focused follow-up for purposely-selected interviews. Sampling could initially use convenience methods based on available participants. It is likely that previous relevant participants of Resorgs projects will be used as a base, and that snowball sampling will enable the inclusion of additional participants. It will be attempted to gain participation from multiple infrastructure organisations, and a spectrum of roles within these organisations through purposeful selection. Interviews will be semi-structured, to enable the discussion of the existing models while also encouraging exploration of further topics and collection of additional data.

The aims of this stage of data collection would be to -
- assess the structure of the models
- gain insight to the derived factors and causal links
- elaborate on behavioural processes identified during the modelling process
- identify any additional relevant data for inclusion

Before data collection from participants there would be proper vetting for any ethical concerns.

Data that are collected should be analysed through established coding techniques. Open coding can identify key theme areas, and subsequent selective coding can be used to establish links between factors and variables to expose the structure of the system. These techniques also facilitate the grouping of factors and behaviour patterns for inclusion in themed archetype diagrams. Research memos can be written throughout to aid the extraction of themes from the data and tracking of analysis findings.

6.4 Simulation and scenario testing

Factors, variables and causal links, supported by thorough conceptualisation, can be mapped within simulation software to enable dynamic simulation of system behaviour and testing of scenarios. Simulation will require quantification of relevant system variables to form stocks, derivation of behaviour equations and quantified delays. The initial values for stock variables can be derived from the data collected to date. If this approach does not give sufficient coverage due to developing theory, then an additional questionnaire can be distributed to enable gathering of data specific to the stock variables. Established tests such as extreme behaviour testing and sensitivity analysis can be applied to the models at this stage.

Scenarios can be developed in order to test behaviour of the models under differing conditions. This will enable the identification of key processes and the formation of intervention strategies. Seeking improvement in the organisational system behaviour may require a design perspective and changes in model structure.

7. Conclusion

The functioning of infrastructure systems is critical to society. Behind the infrastructure and its service are the organisations—their successful operation being fundamental to the service they provide. Despite universal recognition of the importance of the infrastructure services, there has been very little focus on the enabling organisations and how they are affected by major disruptions.

The work of Resilient Organisations, in particular, has introduced organisational resilience as a central theme in organisational performance post-disaster. Their work emphasises the roles of leadership, networks/connections, economic and insurance impacts, and regulatory frameworks, on post-disaster operability of any organisation. Most recent research identifies the importance of interacting behaviours of physical (working conditions), human (worker attitudes), and organisational (strategies, plans) elements when understanding organisational resilience. Stevenson et al. (2015) see the development of context-specific tools and a systems perspective as key requirements for future organisational resilience research and its operationalisation in New Zealand.

Dynamic systems modelling examines interacting variables using causal linkages between causes and effects forming feedback loops. The combination of feedback loops can determine whether a system is tending to equilibrium, or will undergo change (for good or bad). System dynamics approaches have been used to provide insight into safety systems, which have many similarities to the interactions relating to organisational resilience. The time is ripe for the application of a systems dynamics approach to better understand organisational resilience. Application to the particular issues related to infrastructure service providers would seem a valuable starting point.

Advance in this direction will require the use of qualitative relationships as well as attempts at verification of model reasonableness through analysis of questionnaires. A first step would be the development of causal loop diagrams showing the relationships between factors affecting performance and resilience of infrastructure service organisations. Literature reviews and interviews are now common methods used in model conceptualisation. Casual loop diagrams can then be used to identify system archetype diagrams to describe commonly occurring behavioural themes.

The causal loop diagrams, in turn, can be used to develop quantitative dynamic systems models. This step will require parameterisation. Though rigorous validation of all parameters for a model is not practical, the parameters for quantitative models can be varied systematically to identify plausible versus implausible behaviour, helping to constrain uncertainty. This process of refining models to match expected archetypes provides the opportunity to identify critical components or factors that influence the wider system-level behaviour (e.g. resilience).

This direction for research has potentially significant value because it would enable the assessment of an organisation under varied conditions, and the identification of leverage points for intervention to improve performance and avoid failure. Identification of key components, roles and processes that would cause organisational failure when placed under stress is fundamental to improving performance and resilience.

The study of the interaction of processes affecting physical, human, and organisational spheres in this case has the potential to improve our general understanding of organisations, with benefits beyond those attributable to improving the resilience or health of infrastructure service providers.

References

Abdullah, N. A. S., Noor, N. L. M., & Ibrahim, E. N. M. (2013). Resilient organization: Modelling the capacity for resilience. Paper presented at the Research and Innovation in Information Systems (ICRIIS), 2013 International Conference on.

Arena, M., Arnaboldi, M., & Azzone, G. (2010). The organizational dynamics of enterprise risk management. Accounting, Organizations and Society, 35(7), 659-675.

ARMENIA, S., CARLINI, C., Saullo, A., & Assogna, P. (2014). From theory to practice: taking up a theoretical framework on critical infrastructures modelling through a system dynamics approach. In: EURAM.

Bhamra, R., Dani, S., & Burnard, K. (2011). Resilience: the concept, a literature review and future directions. International Journal of Production Research, 49(18), 5375-5393.

Blackman, D., Nakanishi, H., & Benson, A. M. (2017). Disaster resilience as a complex problem: Why linearity is not applicable for long-term recovery. Technological Forecasting and Social Change, 121, 89-98.

Bouloiz, H., Garbolino, E., Tkiouat, M., & Guarnieri, F. (2013). A system dynamics model for behavioral analysis of safety conditions in a chemical storage unit. Safety science, 58, 32-40.

Brown, C., Seville, E., & Vargo, J. (2014). Bay of Plenty Lifelines Group Resilience Benchmark Report (ISSN 1178-7279).

Brown, C., Seville, E., & Vargo, J. (2017). Measuring the organizational resilience of critical infrastructure providers: A New Zealand case study. International Journal of Critical Infrastructure Protection.

Brown, C., Stevenson, J., Giovinazzi, S., Seville, E., & Vargo, J. (2015). Factors influencing impacts on and recovery trends of organisations: evidence from the 2010/2011 Canterbury earthquakes. International Journal of Disaster Risk Reduction, 14, 56-72.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., . . . Von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. Earthquake spectra, 19(4), 733-752.

Burg, E., & Oorschot, K. E. (2013). Cooperating to commercialize technology: A dynamic model of fairness perceptions, experience, and cooperation. Production and Operations Management, 22(6), 1336-1355.

Chang, S. E. (2010). Urban disaster recovery: a measurement framework and its application to the 1995 Kobe earthquake. Disasters, 34(2), 303-327.

Cook, R. I. (1998). How complex systems fail. Cognitive Technologies Laboratory, University of Chicago. Chicago IL.

Cooke, D. L. (2003). A system dynamics analysis of the Westray mine disaster. System Dynamics Review, 19(2), 139-166.

Cooke, D. L., & Rohleder, T. R. (2006). Learning from incidents: from normal accidents to high reliability. System Dynamics Review, 22(3), 213-239.

D'aveni, R. A. (1989). The aftermath of organizational decline: A longitudinal study of the strategic and managerial characteristics of declining firms. Academy of Management journal, 32(3), 577-605.

Dulac, N., Leveson, N., Zipkin, D., Friedenthal, S., Cutcher-Gershenfeld, J., Carroll, J., & Barrett, B. (2005). Using system dynamics for safety and risk management in complex engineering systems. Paper presented at the Proceedings of the 37th conference on Winter simulation.

Forrester, J. (1961). Industrial Dynamics. Cambridge, Mass.: MIT Press.

Gall, M. (2011). Dynamics of Disaster. Chapter 9, Social Dynamics of Unnatural Disasters: Parallels between Hurricane Katrina and the 2003 European Heat Wave. Earthscan publishers. ISBN 978 1 84971 143 2.

Giovinazzi, S., Austin, A., Ruiter, R., Foster, C., Nayyerloo, M., Nair, N.-K., & Wotherspoon, L. (2017). Resilience and Fragility of the Telecommunications Network to Seismic Events: Evidence after the Kaikoura (New Zealand) Earthquake. New Zealand Society for Earthquake Engineering, 50(2), 318-328.

Guo, B. H., Yiu, T. W., & González, V. A. (2015a). A system dynamics view of safety management in small construction companies. Journal of Construction Engineering and Project Management, 5(4), 1-6.

Guo, B. H., Yiu, T. W., & González, V. A. (2015b). Identifying behaviour patterns of construction safety using system archetypes. Accident Analysis & Prevention, 80, 125-141.

Haas, J. E., Kates, R. W., & Bowden, M. J. (1977). Reconstruction following disaster. In Reconstruction following disaster: US The Massachusetts Institute of Technology.

Havlin, S., Araujo, N., Buldyrev, S. V., Dias, C., Parshani, R., Paul, G., & Stanley, H. E. (2010). Catastrophic cascade of failures in interdependent networks. arXiv preprint arXiv:1012.0206.

Hollnagel, E. (2011). RAG-The resilience analysis grid. Resilience engineering in practice: a guidebook. Ashgate Publishing Limited, Farnham, Surrey, 275-296.

Hollnagel, E., & Woods, D. D. (2006). Epilogue: Resilience engineering precepts. Resilience Engineering–Concepts and Precepts, Ashgate, Aldershot, 347-358.

Jiang, H., Onkham, W., Zeng, E., & Rabelo, L. (2012). System Dynamics Application in Organizational Learning Evaluation. Paper presented at the IIE Annual Conference. Proceedings.

Kachali, H., Whitman, Z., Stevenson, J., Vargo, J., Seville, E., & Wilson, T. (2015). Industry sector recovery following the Canterbury earthquakes. International Journal of Disaster Risk Reduction, 12, 42-52.

Katz, D., & Kahn, R. L. (1978). The social psychology of organizations (Vol. 2): Wiley New York.

Kuntz, J. R., Näswall, K., & Malinen, S. (2016). Resilient Employees in Resilient Organizations: Flourishing Beyond Adversity. Industrial and Organizational Psychology, 9(2), 456-462.

Leavitt, W. M., & Kiefer, J. J. (2006). Infrastructure interdependency and the creation of a normal disaster: The case of Hurricane Katrina and the city of New Orleans. Public works management & policy, 10(4), 306-314.

Lee, A. V., Vargo, J., & Seville, E. (2013). Developing a tool to measure and compare organizations' resilience. Natural hazards review, 14(1), 29-41.

Leveson, N. G., Barrett, B., Carroll, J., Cutcher-Gershenfeld, J., Dulac, N., & Zipkin, D. (2005). Modeling, Analyzing and Engineering NASA's Safety Culture: Phase 1 Final Report. Cambridge, MA, Massachusetts Institute of Technology.

Lindsley, D. H., Brass, D. J., & Thomas, J. B. (1995). Efficacy-performing spirals: A multilevel perspective. Academy of management review, 20(3), 645-678.

Liu, Y., Nair, N.-K., Renton, A., & Wilson, S. (2017). Impact of the Kaikoura Earthquake on the Electrical Power System Infrastructure. New Zealand Society for Earthquake Engineering, 50(2).

Maani, K., & Cavana, R. Y. (2007). Systems thinking, system dynamics: Managing change and complexity: Prentice Hall.

Management, I. o. R. (2014). Extended Enterprise: Managing Risk in complex 21st century organisations.

Masuch, M. (1985). Vicious circles in organizations. Administrative Science Quarterly, 14-33.

McDonald, G.W., Smith, N.J., Kim, J-H, Brown, C., Buxton, R., & Seville, E. 2018. Economic systems modelling of infrastructure interdependencies for an Alpine Fault earthquake in New Zealand, *Civil Engineering and Environmental Systems*, 35: 57-80, doi: 10.1080/10286608.2018.1544627.

Meadows, D. H. (2008). Thinking in systems: A primer: chelsea green publishing.

Millett, B. (1998). Understanding organisations: the dominance of systems theory. International Journal of Organisational Behaviour, 1(1), 1-12.

New Zealand Ministry of Civil Defence and Emergency Management, National Disaster Resilience Strategy, 2019.

O'Rourke, T. D. (2007). Critical infrastructure, interdependencies, and resilience. BRIDGE-WASHINGTON-NATIONAL ACADEMY OF ENGINEERING-, 37(1), 22.

Office, N. A. (2015). Principles Paper: Managing provider failure. Retrieved from London: http://www.nao.org.uk/wp-content/uploads/2015/07/Principles-paper-managing-provider-failure.pdf

Park, J., Seager, T. P., & Rao, P. S. C. (2011). Lessons in risk- versus resilience- based design and management. Integrated environmental assessment and management, 7(3), 396-399.

Peerenboom, J., Fischer, R., Whitfield, R. (2001). Recovering from disruptions of interdependent critical infrastructures. Pro. CRIS/DRM/IIIT/NSF Workshop Mitigat. Vulnerab. Crit. Infrastruct. Catastr. Failures, 2001.

PwC. (2012). Under Pressure: Securing success, managing risk in public services. Retrieved from London: http://www.pwc.co.uk/industries/government-public-sector/insights/under-pressure-securing-success-managing-failure-in-public-services.html

Reason, J. (1995). A systems approach to organizational error. Ergonomics, 38(8), 1708-1721.
Richmond, B. (1994). System dynamics/systems thinking: Let's just get on with it. Paper presented at the International systems dynamics conference, Sterling, Scotland.

Rubin, C. B. (1991). Recovery from disaster. Emergency Management: Principles and Practice for Local Government. Washington DC: International City Management Association, 224-259.

Rubin, C. B. (2009). Long term recovery from disasters--The neglected component of emergency management. Journal of Homeland Security and Emergency Management, 6(1).

Rudolph, J. W., & Repenning, N. P. (2002). Disaster dynamics: Understanding the role of quantity in organizational collapse. Administrative Science Quarterly, 47(1), 1-30.

Seville, E. (2017). Resilient Organisations. Kogan Page publishers. ISBN 978 0 7494 7855 1

Sterman, J. D. (2000). Business dynamics: systems thinking and modeling for a complex world.

Stevenson, J., Kwok, A., Hamilton Skurak, H., Davies, A., Hatton, T., Sajoudi, M., . . . Bowie, C. (2015). Multi-Capital Resilience Annotated Bibliography.

Stevenson, J., Vargo, J., Ivory, V., Bowie, C., & Wilkinson, S. (2015). Resilience Benchmarking & Monitoring Review.

Tierney, K. J. (1997). Business impacts of the Northridge earthquake. Journal of Contingencies and Crisis Management, 5(2), 87-97.

Tierney, K., & Bruneau, M. (2007). Conceptualizing and measuring resilience: A key to disaster loss reduction. TR news, (250).

Treasury, N. Z. (2014). Forging a Common Undestanding for Critical Infrastructure.

UNISDR (2019) (1). United Nations Office for Disaster Risk Reduction. Global Assessment Report on Disaster Risk Reduction. https://gar.unisdr.org/sites/default/files/gar19distilled.pdf

UNISDR (2019) (2). United Nations Office for Disaster Risk Reduction. Terminology on Disaster Risk Reduction. https://www.unisdr.org/we/inform/terminology

Van Burg, E., & Van Oorschot, K. E. (2013). Cooperating to commercialize technology: A dynamic model of fairness perceptions, experience, and cooperation. Production and Operations Management, 22(6), 1336-1355.

Xenidis, Y., & Theocharous, K. (2014). Organizational health: definition and assessment. Procedia Engineering, 85, 562-570.

Appendix 1: Overview of past research into organisational response to disasters

Author (Year)	Type and Location of Event or Disaster	Type of Organisation	Focus of research	Methods
Alesch et al. (2001)	Earthquake - Northridge Floods - Tar River, Red River, Flint River Fires - Los Alamos Tornado - Minnesota	Small business and non-profit	How businesses cope after disasters – long- term adaptation and recovery. Identification of key success and failure factors.	Longitudinal study Unstructured interviews
Anderson (1969)	Earthquake - Alaska	Public service organisations - police, fire, port, schools, public works etc	Long-term organisational change due to effects of event.	Longitudinal study Unstructured and semi-structured interviews
Brown et al. (2013)	Earthquake - Canterbury	Insurance service companies and small business owners	Effectiveness of insurance on aiding recovery.	Interviews of key personnel Literature review
Brown et al. (2015)	Earthquake – Canterbury	Multiple sector, type and size	Factors influencing recovery of organisations.	Survey Literature review
Brown et al. (2017)	N/A	Infrastructure organisations	Organisational resilience factors and indicators.	Benchmarking study

Author (Year)	Type and Location of Event or Disaster	Type of Organisation	Focus of research	Methods
Chang-Richards et al. (2013)	Floods - Alberta, Queensland Earthquake -Canterbury, Wenchuan and Japan	N/A	Labour market policy responses to natural disasters.	Comparative case studies
Chang-Richards et al. (2013)	Earthquake - Canterbury	Small / medium businesses	Economic effects on businesses, resilience measures, intervention strategies.	N/A
Chang-Richards et al. (2013)	Earthquake - Canterbury, Japan, Wenchuan Floods - Queensland and Alberta	Multiple sector, type and size	Inter-sector linkages and interdependencies.	Literature review **Case studies**
Comfort (1994)	Earthquake - Northridge	Government agencies	Inter-organisational communication and learning	Case study
Corbacioglu & Kapacu (2006)	N/A	Organisations involved in response and recovery – public and private	Factors that inhibit or facilitate organisational learning and adaptation as part of the disaster operation system.	Exploratory case study Questionnaire Semi structured interviews
Dahlhmer & Tierney (1998)	Earthquake - Northridge	Private sector, multiple sizes	Determinants of recovery and non-recovery.	Survey

Author (Year)	Type and Location of Event or Disaster	Type of Organisation	Focus of research	Methods
Doerfel et al. (2010)	Hurricane - Katrina	Multiple types & sizes	Inter-organisational communication and social capital and their effect on recovery.	Longitudinal study Semi structured interviews
Dynes et al. (1990)	Earthquake - Mexico City	Multiple types & sizes. Also covers individual level	Individual and organisational response.	Survey Structured interviews
Ferreira et al. (2010)	N/A	Transport network organisations	Operations planning and decision making.	Case study based on event simulations
Kachali et al. (2015)	Earthquakes - Canterbury	Sector level, multiple. Includes Infrastructure organisations	Direct and indirect impacts on organisations. Recovery process.	Questionnaire
Kroll et al. (1991)	Earthquake - Loma Preta	Small businesses	Economic impacts	Literature review Survey
Liu et al. (2016)	Earthquake - Canterbury	Infrastructure	Factors of success for infrastructure recovery	Case study Archival study, observations, semi structured interviews
Nilakant et al. (2013)	Earthquake - Canterbury	Large organisations	Leadership and human resource issues post-disaster	Semi-structured interviews

Author (Year)	Type and Location of Event or Disaster	Type of Organisation	Focus of research	Methods
Nilakant et al. (2014)	Earthquake - Canterbury	Infrastructure organisations	Factors that aid organisational response, recovery and renewal post-disaster.	Interviews and focus groups
Pedroso et al. (2015)	Earthquake - Canterbury, Japan	Response organisations and facilities	Information sharing and decision making during the response phase	Case studies
Porfiriev (1996)	Earthquake - Sakhalin	Official response organisations	Social and organisational response	Unknown
Rotimi et al. (2006)	Floods - New Zealand	General	Regulatory framework effectiveness during reconstruction.	Case study
Rubin (2009)	General	General	Perspectives on long-term recovery	Review paper
Seville et al. (2014)	Earthquakes - Canterbury	Multiple sectors and types	Economic effects on business, disruption and resilience factors	Survey
Stevenson et al. (2014)	Earthquakes - Canterbury	Multiple	Organisational networks, response and short-term recovery phase.	Review of multiple case studies
Stevenson (2014)	Earthquakes - Canterbury	Multiple	Connections and resilience	Surveys, Interviews Field observations
Tierney (1997)	Earthquake - Northridge	Small businesses	Direct impacts and losses.	Survey

Author (Year)	**Type and Location of Event or Disaster**	**Type of Organisation**	**Focus of research**	**Methods**
Wasileski et al. (2009)	Earthquake - Loma Prieta Hurricane - Andrew	Small/medium businesses	Short to mid-term impacts on business - closure and relocation.	Surveys
Webb et al. (2000)	Earthquake - Northridge, Loma Prieta Floods - Midwest Hurricane - Andrew	Multiple businesses, plus community level	Factors of preparedness, disruption and recovery. Long term study.	Surveys
Whitman et al. (2014)	Earthquake - Darfield	Multiple sectors, type and size	Resilience and recovery focus - challenges, impacts and reflections.	Survey